WHY STUDY PLASMA SCIENCE

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ABSTRACT

Plasma is an essential stage in the process of formation of matter from elementary particles up to condensed matter. Plasma science is a rapidly growing research field with its natural inter-disciplinary connections from ultrashort scale nanoscience to gigantic scales of astrophysics. The technological applications of plasma science have been ingenious and its influence on scientific progress is significant. That is why the fascinating paradigm of many-body (plasma) physics in classical, as well as quantum mechanical regimes is on the forefront of research nowadays. This article aims to overview the main features of this versatile field with description of its potential technological applications and future promises. It will also help to understand the main reasons of growing interest in plasma science and provide motivation to students to opt it as a future research area.

1. INTRODUCTION

1.1 Plasma: the Fourth State of Matter

The world is undergoing a new revolution fueled by rapid progress in science and technology of the past decades. Principles of fundamental physics which have been known before, from abstract theory, are now suddenly becoming accessible to direct experimental observations and evidences. There are examples of various physical phenomena whose impact on the society has become so vital that these have became separate disciplines of research in physics.

Plasma science encompasses a variety of science disciplines ranging from plasma physics to aspects of atomic and molecular physics, chemistry, and material science. Its broad, interdisciplinary nature also includes ionized gases that range from classical to quantum, cold to hot, weakly ionized to highly ionized, and from collisional to collisionless. These types of plasmas underlie variety of applications and natural phenomena. However, many fundamental considerations dictate the range of parameters from man-made plasmas in laboratories to natural plasma in the universe. The subject is difficult to characterize keeping in mind the diversity of what is included in 'plasma science'. However, its vital contribution to a broad range of applications in scientific & technological developments are due to the same diversity.

Sir William Crookes, an English physicist, identified plasma in 1879. The word 'plasma' was first coined by I. Langmuir and L. Tonks in 1929 for description of oscillations of ionized gases in an electrical discharge. Later on, the definition was broadened to define a state of matter (also known as 'the fourth state of matter') occurring naturally in the cosmos. Generally, plasma is referred to as 'a statistical system of the charged, excited, and neutral assemblies, including some or all of the following: electrons, positive and/or negative ions, atoms, molecules, radicals, and radiation exhibiting collective motion — a joint ping-pong game'. As a whole, a plasma is electrically neutral, because any unbalance of charges would result in the long range electric and magnetic fields. It will, in turn, move the charges in a way it would neutralize charges of opposite sign [1-3].

Plasmas are characterized by various regimes depending upon the distribution of energy and density, which can be described by classical or quantum mechanical models. For instance, the (common) space (e.g., interplanetary and interstellar media) or laboratory (e.g., gas discharges) plasmas are rarefied ionized gases in random thermal motion. On the other hand, the electron gas in metals and semiconductors also behaves very similar to gaseous plasmas. However, there is a basic difference: the relevant statistics changes from (classical) Maxwell-Boltzmann to (quantum) Fermi-Dirac. The quantum electron gas in metals is globally neutralized by the lattice ions whose properties are governed by various control parameters. Similarly, dense low temperature plasmas also obey the Bose-Einstein statistics with no restrictions on the number of particles in the same energy state. Various plasmas found in nature and laboratory can be shown by a simple density–temperature phase diagram (Figure-1) which illustrates regime of density and temperature of different plasma systems[†].

The historical developments and familiar types of plasmas are briefly described as follows.

1.2 Historical Developments

There has been a firm belief that plasma existed since the beginning of the universe. At extremely high

[†] For more details see Ref. 4, 5 & 6

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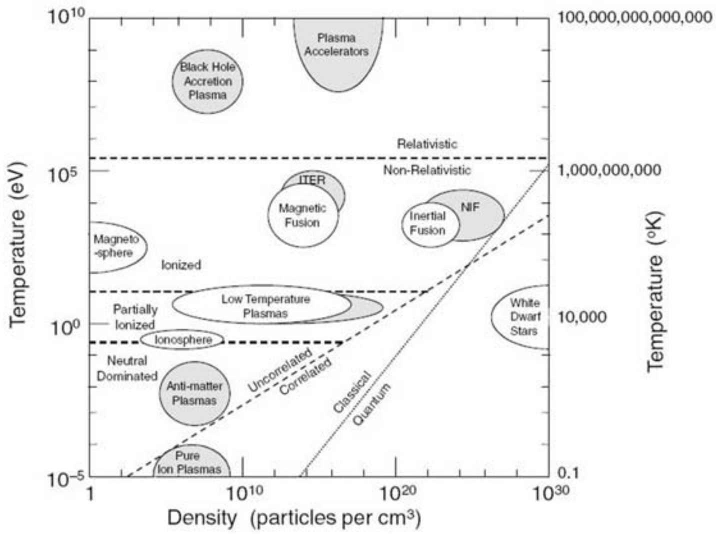

Figure-1: Some Phenomena in the range of plasma physics. Regimes that are new areas of study since 1990 are indicated in gray, including the future regimes of the National Ignition Facility (NIF) and the International Thermonuclear Experimental Reactor (ITER) [Ref. 7]

nuclear densities ($\sim 10^{39}\ cm^{-3}$), the physical process like Mott transitions in compressed matter leads to quark-gluon plasma (QGP), a very special kind of plasma interacting via a (color) Coulomb potential. Such plasmas are believed to have existed immediately after the Big Bang and seen in Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) experiments. Ionized matter found naturally in dense astrophysical objects (e.g., stellar cores, white and brown dwarfs, neutron stars, etc.) and interior of giant planets in the solar system (e.g., Jovian planets) constitutes plasma under extreme conditions of density. Here, the electrons may be non-relativistic or relativistic depending upon the electron energy. However, on a terrestrial scales, the developments in plasma physics dates back to early 1920s when plasma started getting recognition with major contributions from the Nobel Prize winning scientist Irving Langmuir, who first used the term plasma to describe the charge dynamics in ionized gas. Langmuir was inspired by the blood plasma which carries red and white corpuscles in the way an ionized gas carries electrons and ions. Langmuir, Tonks, and others also started its first technological inception by finding the ways to extend the lifetime of tungsten-filament light bulbs greatly. In the process, they developed the Theory of Sheaths in Plasmas and well known theory of Electron Plasma Oscillations (now called Langmuir Wave Theory. The field was somehow established in 1930s, and got impetus in 1940s when another Noble Laureate, Hannes Alfven, developed a theory of hydromagnetic waves (now called Alfven en Waves) and revealed its significance in astrophysical settings. This later led to the explanation of some complex phenomena like solar coronal heating, the solar wind interactions in space, the magnetohydrodynamics (MHD) of laboratory systems, and so on. The significance of plasma in the description of theory and experiments on thermonuclear, the creation of thermonuclear bomb, and the idea of sustainable controlled thermonuclear reaction for energy production generated a great deal of interest in the field of plasma physics since 1950s. At first, USA was the main contributor in the research with secrecy due to the observations of the devastative potential of the fusion. In parallel, the work continued independently in the USSR and the UK. In short time, the world recognized the importance of joint efforts in the field, with major emphasis on the peaceful use of fusion for energy discouraging its destructive uses. The institutions like International Atomic Energy Agency (IAEA) were established for coordinated efforts in the right directions. Progress in plasmas again accelerated with the development of tokamak machine by Russians by the end of 1960s. By 1970s and 1980s many tokamaks with improved performance were constructed and fusion breakeven had been achieved in tokamaks[†].

Various new applications of plasma physics appeared

[†] For further details, see Ref. 8.

in 1970s, and were developed as critical technique for the fabrication of the tiny, complex integrated circuits used in modern technology. Plasma processing and plasma treatment are vital technologies used in a large number of industries with hundreds of applications, some of which are described in the next section.

On the other hand, plasma is a natural medium in space and astrophysics. Plasma has been one of the priority area of research in space astrophysics, which has significantly contributed in our current knowledge of planetary and space science. Plasma is operative from very small scales of highly compressed degenerate stars to interstellar and intergalactic scales. The research activities in stellar bodies are the main source of development in space technology, which made possible to launch space missions and satellites for various purposes. The main players of the space game in 1970s were USA, Russia, Europe and China. On the technological side, plasma is the backbone of huge projects like plasma-based space missions, High Frequency Active Auroral Research Program (HAAPRP), Radiation Belt Storm Probes (RBSP), etc., and one of the major areas of observations on board by NASA, International Space Station (ISS), European Space Agency (ESA), etc. [9].

1.3 Occurrences of Plasmas

The existence of plasma and its various types can easily be categorized on the basis of density and temperature parameters, relevant to laboratory and astrophysical regimes. The density-temperature phase diagram (Figure-1) helps in defining two major types of plasmas, laboratory based or astrophysical. It includes low-density plasmas (following classical physics laws) and high-density plasmas (following quantum statistics). Both of these types are found in the universe, including:

i. Aurorae;
ii. Ionospheres, magnetospheres, and interior of planets;
iii. Solar and stellar winds;
iv. Solar atmosphere;
v. Solar and stellar shock regions;
vi. Flux ropes;
vii. Coronal mass ejections in the Sun and stars;
viii. Interstellar media;
ix. Intergalactic media;
x. Supernovae remnants (SNRs);
xi. Astrophysical jets;
xii. Lightning, and ball lightning; and
xiii. Matter in degenerate stars (white dwarf, neutron stars, magnetars).

There are also many types of plasmas produced in laboratory, including:

i. Gas discharge plasmas;
ii. Radiation-beam produced plasmas;
iii. Processing plasmas;
iv. Micro and nano plasmas;
v. Degenerate plasmas;
vi. High-energy-density plasmas;
vii. Complex plasmas;
viii. Fusion plasmas; and so on.

The laboratory plasmas are of particular interest from a technological standpoint (Box-1).

1.4 Description of Plasma

Plasma is truly a many-particle systems with its description in the framework of classical and/or quantum mechanical laws. The mean particle distance is a key parameter in plasmas, which is large in most of the abundant space and astrophysical plasmas. That is why the thermal de Broglie wavelength of plasma species (electron) is negligible as compared to the interparticle distance. So the plasma motion is not influenced by quantum effects and the plasma behavior is classical. Such plasmas can be described by classical physics and classical statistical laws. On the other hand, if it is of the order of or smaller than de Broglie wavelength, the plasma is (quantum) degenerate. In this case, few important and unusual effects like overlapping of the wave functions, Mott-transitions, etc., take place. For classical systems, the Coulomb coupling parameter is the ratio of average potential energy and the average kinetic (thermal) energy. If it is much smaller than unity, the plasma behaves as an ideal gas of charge carriers, otherwise the plasma is collisions dominated and the dynamics of plasma is more complex in nature. For sufficiently cold and dense plasmas, the role of thermal energy is taken over by the Fermi energy, the representative of the degeneracy temperature. The strength of particle correlations is measured by quantum Coulomb coupling parameter or Brueckner parameter. The ideal behavior is reached when Fermi energy is much larger than the (potential) interaction energy, otherwise strong correlations exist and plasma in a system of mutually interacting quantum particles. Since the Fermi energy is density dependent quantity, the quantum plasma state is commonly known as the Low Temperature State as evident from Figure-1. Modeling of quantum (degenerate) plasma is done in the framework of well know quantum physics models e.g., Schrodinger or Heisenberg models, density matrix theory, quantum field theory, and quantum electrodynamics because strong interparticle interactions at de-Broglie length scale impede the use of conventional classical theoretical models [4, 5, 10, 11]. The computational methods for many-particle problems like classical and quantum Monte Carlo schemes, Path Integral Monte Carlo (PIMC) methods, (time dependent) Hartree-Fock (HF,TDHF) theory, density functional theory (DFT) are very popular models. Its applicability varies from atoms, molecules, solids to classical and quantum fluids, and generalized to deal with many different situations.

The standard description of non-equilibrium plasmas is based on kinetic theory, and classical and quantum kinetic equations (KEs) have been developed. The KEs are the most reliable methods for description of plasmas [12]. Many other methods like non-equilibrium Green's function (NEGF), Kadanoff–Baym (KB) equations, etc., are also able to extract the information on plasma dynamics. Finally, the theoretical progress is significant, however the solution and detailed analysis of KEs or the full description of manyparticle systems have been major challenges from a theoretical perspective for the last several decades.

Owing to the analytical complexity of the quantum kinetic approach, drastically simplified macroscopic models like hydrodynamics are often adopted, which can reproduce the salient features of plasma. However, one has a choice with the alternative of studying a physical problem microscopically with inherent difficulties or macroscopically with less cluttered and simpler approach[†].

1.5 Basic Plasma Science

Plasma science has spawned new avenues of basic science. Notably, plasma physicists were among the first to open up and develop the new and profound science of chaos and nonlinear dynamics. Plasma physicists also have great contribution in the study of aerodynamics and turbulence, playing important role in safe air travel and other applications. The vibrant science of plasmas also has a key role in recent new discoveries that have occurred in plasma medicine, engineering and technology fields, thus bringing the plasma science on the forefront of basic sciences. As plasmas are highly conductive and their response to electric and magnetic fields is rapid, they have been a priority area of research, and plasma science a potential field of interest in future.

2. AREAS OF PLASMA TECHNOLOGY

2.1 Fusion Plasmas

2.1.1 Magnetic Confinement Fusion

Fusion is one of nature's most spectacular processes. Billions and billions of fusion furnaces, the Sun among them (Figure-2), are flaring in the universe, creating light and energy. Through the efforts of scientists over the past seventy years, the physics behind this wonder is now well understood. This provides us the

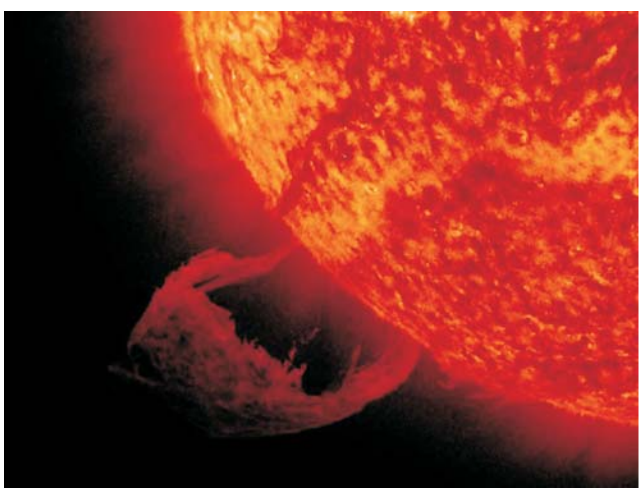

Figure-2: Exploding plasma on the Sun the natural fusion furnace. The eruption is lifting plasma above the Sun s surface. [NASA, www.nasa.gov]

[†] Interested readers of plasma physics can see Ref. 1, 4, 5 & 13 for more details on the description of plasmas.

information of transmutation of the matter in the Sun and stars, which are transforming hydrogen nuclei into helium atoms and releasing tremendous amounts of energy during the process. With this knowledge at hand, the ambition increased to reproduce on Earth a sustainable physical process similar to the ones operative in stars here. But harnessing the energy of the stars was to prove a formidable task, more complex and arduous than anticipated.

Fusion in laboratory demands very small confinement time and very large densities (Lawson criterion) [8]. History of fusion, the experiments started in the 1930s and fusion physics laboratories were established in almost every industrialized country. By the mid 1950s 'fusion machines' were operative on experimental basis in the Union of Soviet Socialist Republics USSR, the USA, UK, Germany, France, and Japan. This helped as similar in understanding of the fusion and associated processes and technologies.

A major breakthrough was achieved in 1968 when researchers in USSR were able to build a doughnut-shaped magnetic confinement device called 'tokamak'. The success was at two levels – achievement of high temperature and plasma confinement times – two of the main criteria to achieving fusion that had never been observed before. It made the tokamak most feasible concept in fusion research and such devices were built in many parts of the world.

Experiments with actual fusion fuel – a mixture of hydrogen isotopes deuterium and tritium started in early 90s in the Tokamak Fusion Test Reactor (TFTR) in Princeton, USA, and Joint European Torus (JET) in Culham, UK, which carried out the World's first controlled fusion power experiment. Sufficiently long-duration controlled fusion was later on achieved in a EURATOM-CEA installation in France and the TRIAM-1M tokamak in Japan and some other machines. JT-60 machine in Japan achieved the highest values of three key parameters in fusion - the plasma density, temperature and confinement time. In these efforts, the scientists have approached the long-sought 'breakeven' point where a device release as much energy as is required to produce fusion.

2.1.1.1 International Thermonuclear Experimental Reactor (ITER) Project: The availability of limitless fusion fuel all over the world; no greenhouse gases; safety; no radioactive waste; large-scale energy production, and above all, the success in getting 'breakeven' point, are the factors that have led to the concept of International Thermonuclear Experimental Reactor (ITER), the world's largest multibillion-euro international nuclear fusion collaborative tokamak project [14]. ITER is a mega-science project of seven stakeholders namely, China, India, Japan, Korea, Russia, USA, as well as European Union aiming to build the tokamak at the Cadarache facility in the South of France. Construction began in 2007, scheduled to be completed in 2020, with first plasma produced in the same year. After resolving all the engineering and science problems (the complicated geometry of machine is evident from Figure-3), the first nuclear fuel – a plasma of two heavy hydrogen isotopes, deuterium and tritium (DT) is scheduled to

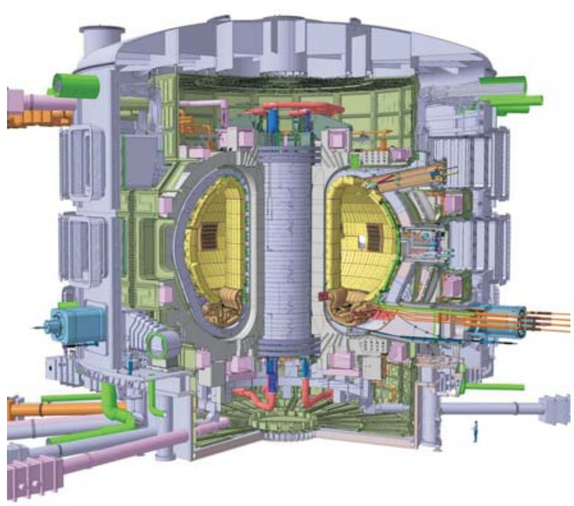

Figure-3: The ITER machine is based on the tokamak concept of magnetic plasma confinement, in which the fusion fuel is contained in a doughnut-shaped vessel. With a height of 29 meters and a diameter of 28 meters, ITER will be the world s largest tokamak. [Ref. 14]

Figure-4: The National Ignition Facility (NIF) is the world s largest laser for inertial fusion purpose. Three football fields could fit inside the NIF Laser and Target Area Building. NIF s 192 intense laser beams can deliver to a target more than 60 times the energy of any previous laser system. NIF became operational in March 2009 and is capable of directing nearly two million joules of ultraviolet laser energy in billionth-of-a-second the target chamber center producing compressed plasma for fusion. [Ref. 15]

be injected into the reactor by 2027 and commercial power production is expected in 2028. Estimated construction, operation and decommissioning cost is 15 billion Euro (~20.3 USD) with design to produce 500 megawatt of fusion power for 50 megawatt of input power for 20 years. If ITER is successful, it could be the first tokamak based power plant to produce more power than it consumes. The ITER team of physicists and engineers has done tremendous job so far and the ITER is hoped to be a game-changing solution for the future energy needs.

In addition to tokamak, alternate plasma confinement and fusion concepts are also hot areas of research nowadays. Some of such concepts include:

- Colliding Beam Fusion;
- Electric Tokamak;
- Floating Multipole;
- Dense Plasma Focus (DPF);
- Heavy Ion Fusion;
- Electrostatic Confinement;
- Matter-antimatter systems;
- Reversed Field Pinch;
- Field Configuration;
- Spheromak;
- Stellarator;
- Spherical Torus;
- Magnetized Target Fusion;
- Tandem Mirror;
- Z-pinch, and more.

The scientists have been pursuing fusion for almost 50 years now. The research in fusion has increased key fusion plasma performance parameters by a factor of 10,000 over 50 years. This in turn leads us to safely say that the progress is now less than a factor of 10 away from producing the core of a fusion power plant. Although the goal of energy production from plasma fusion is somewhat distant, much of the associated science and technologies are being used for commercial purposes today or will be used in a foreseeable future. The current world market for such applications exceeds 100 billion USD per year with a noticeable increase every year.

2.1.2 Inertial fusion

The inertial fusion scheme is based on compressing the gas of deuterium and tritium into a small pellet of glass, or other appropriate material, less than or about one millimeter in size. The pellet is heated by super intense lasers arranged in appropriate geometries. Laser being the highly coherent radiation source has the advantage of being easily focused onto very small spot sizes. In the process of shining laser on a suitable target, some of the laser energy is absorbed by the pellet and a plasma is formed from the outer surface material. This plasma blows out like the gases of a rocket, and causes the remains of the pellet to move inwards with a very high speed. As a result, the deuterium–tritium mixture at the center of the pellet is highly compressed, in turn rapidly igniting the fusion reaction. The pressure generated in this process is tremendously large which explode the pellet. To sustain the reaction, new deuterium–tritium pellets are then introduced inside the vacuum chamber where the process is repeated again and again. The larger part of the energy in this reaction is carried by the neutrons which are absorbed by some suitable liquid fluid. This fluid is heated by the neutron energy and then is removed by a suitable mechanism to operate a turbine generator for production of electricity.

The inertial confinement fusion (ICF) was first proposed in the early 1970s and now believed to be a practical approach for fusion power generation [16]. Throughout 1980s and 1990s, many experiments around the world took place to understand the complex interaction of intense laser and compressed plasma. However, due to limitations in laser technology, the progress could not result in a practical fusion reactor. Recent advancements in peta and exawatt laser technology like the mega-project of National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL, aerial view shown in Figure-4) [15, 16], Laser Megajoule (LMJ) in France, GSI Germany, and Institute of Laser Engineering (ILE) in Japan has accelerated the progress and hopes for the commercial laser-plasma fusion reactor in future.

2.2 INDUSTRIAL AND COMMERCIAL APPLICATIONS

Plasmas span from laboratory systems of nanometer and even smaller scales to astrophysical and cosmological scales underlying numerous important technological applications for the benefit of mankind as well as our understanding of much of the universe around us. Thus, the long list of plasma applications from electron scale ultrafast phenomena to plasmatechnology-based projects on fusion, aerodynamics, and space probes are not easy to cover in a simple way, for an overview, (Figure-5). The strong links between scientific progress, development, social security, and quality of life are well documented. The contribution of advancement of plasma science in current technology is undoubtedly tremendous and critical to many future developments. The importance of plasma science is evident from huge plasma technology based commercial activity worldwide. In the near past, new plasma technologies

Box-1: Various Types and Applications of Plasmas

Major Areas of Plasma Technology
Plasma processing and thin films
Plasma materials
Plasma diagnostics
Industrial plasmas and applications
Environmental and health applications
Radiation sources and display applications
Space and astrophysical applications
Micro and nanoscale engineering
Plasma health care Plasmonics technology
Plasma chemistry and plasma medicine
High Energy-Density Physics (HEDP)

Space, Astrophysics and Cosmology
Space Weather technologies
Zero gravity plasma probing
Auroral research technology
Radiation Belt probing
Space stations experimentation
Radiation monitoring technology in space missions
Solar and magnetosphere activity monitoring
Space stations observations
Plasma-technology based space probes
Near-planetary and interplanetary data missions
Plasma Jet thrusters for space flights
Propulsion
Electromagnetic and Solar wind measurements
Engineering and technical support projects

Plasma Sheath Phenomena
Spacecraft charging
RF heating
Sheath dynamics
Plasma ion implantation
Plasma probe interactions

Plasma Sources
Laser-produced plasma
Beam-generated plasma
Ion beam sources
Free electron lasers (plasma based)
plasma-generated electron sources
Electron cyclotron (for materials processing)
Parallel plate discharges (materials processing)
Free electron plasma radiation sources
X-ray production (for lithography)
RF sources, electronic (e.g., materials processing)
Coherent microwave sources
Arcs (e.g., steel processing, welding, toxic waste)
Ion engines for space propulsion
MHD thrusters for space propulsion
Neutron production
Plasma production for industrial engineering
Cold atmospheric pressure (CAP) plasmas
One atmosphere gun and filamentary discharges

Plasma Diagnostics
Ion and neutral beam diagnostics
Spectroscopy (mass, photon) and imaging
Probe measurements for density-temperature study
Scattering for remote sensing
Laser-induced fluorescence
Laser transmission diagnostics (e.g., interferometry)
Charged-particle spectrometers

Magnetic field measurements
Electric field measurements
Neutral particle analysis
Diagnostics at one atmosphere pressure

Plasma-Based Devices
Plasma opening switches
High-power tubes (thyratrons, ignitrons, klystrons)
Pulsed power systems
Plasma-based light sources
Vacuum electronics
Thin panel displays
Relativistic electron beams (intense X-ray sources)
Plasma channels for flexible beam control
Free electron lasers (tunable)
Gyrotrons (high-power short wavelength)
Backward wave oscillators
Traveling wave tubes
Helicon antennas
Laser self-focusing
Plasma lenses for particle accelerators
Dense plasma focus or pinch plasmas for X-rays and beams
Compact X-ray lasers
Cerenkov grating amplifier
Photon accelerators
Incineration of hazardous materials
Plasma armature railguns
Electron cyclotron resonance reactors
Gas lasers
Arc lamps
Torches and film deposition chambers
Ignition and detonation devices
Meteor burst communication
High-power light sources
Plasma accelerators by relativistic space-charge wave

Wave and Beam Interactions Applications
Externally driven waves
Waves as plasma sources
Waves as diagnostics
Waves as particle accelerators
Beam instabilities (FEL; gyrotrons)
Parametric instabilities
Solitons
Wave-particle interactions
Charged particle trapping
Wave physics research (e.g., electron plasma, upper hybrid,
Low and high frequency mode detection
Ionospheric modification
Light ion beam/plasma interactions
Solar power satellite microwaves
Nonlinear waves
Turbulence, stochasticity and chaos
Striation formation and transport

Plasma Based Computational Resources
Fundamental studies of many-body dynamics
Fundamental studies of Hamiltonian systems
Kinetic theory
Nonlinear systems; nonequilibrium systems
Reconnection
Double layers
Self-organization and chaos
Turbulence
Linkage of micro-, meso-, and macroscale processes

Industrial Plasmas
Thermionic energy converters
MHD converters
Engines, Metallurgy
Catalysts, Spectroscopy
Transformers, Motors, Relays
Reactors, Isotopes
Transistors, IC's
Field-emitter arrays
Lasers, Flashlamps, displays
Plasma surface treatment
Plasma etching
Plasma thin film deposition (e.g.,superconducting film)
Ion interaction with solids
Synthesis of materials (e.g., arc furnaces)
Destructive plasma chemistry
Destruction of chemical warfare agents
Thermal plasmas
Isotope enrichment and separation
Electrical breakdown, switch gear, and corona
Plasma lighting devices
Meat pasteurization
Instrument sterilization
Water treatment systems
Gas treatment
Electron scrubbing of flue gases in substances
Ion beams for fine mirror polishing
Plasma surface treatment
Electron beam-driven fuel injectors
Sterilization of medical instruments
Chemical synthesis
Synthetic diamond films for thin-panel television systems
Plasma chemical processing
low-energy electron-molecule interactions
Low-pressure discharge plasmas
Production of fullerenes
Plasma polymerization
Heavy ion extraction from mixed-mass gas flows
Deterioration of insulating gases

One-atmosphere glow discharge plasma reactor for surface treatment of fabrics (enables improved wettability, wickability, printability of polymer fabrics and wool)

Laser ablation plasmas; precise drilling
Plasma cutting, drilling, welding, hardening
Ceramic powders from plasma synthesis
Impulsive surface heating by ion beams
Metal recovery, extraction, scrap melting
Plant growth
Waste handling, paper, and cement industries
Laser ablation plasmas
Laser and plasma wave undulators for femtosecond pulses of X-rays and gamma rays
Tunable and chirpable coherent high-frequency radiation from
Low frequency radiation by rapid plasma creation
DC to AC radiation generation by rapid plasma creation
Infrared to soft X-ray tunable free-electron laser (FEL)
Optoelectronic microwave and millimeter wave switching
Plasma source ion implantation (PSII)

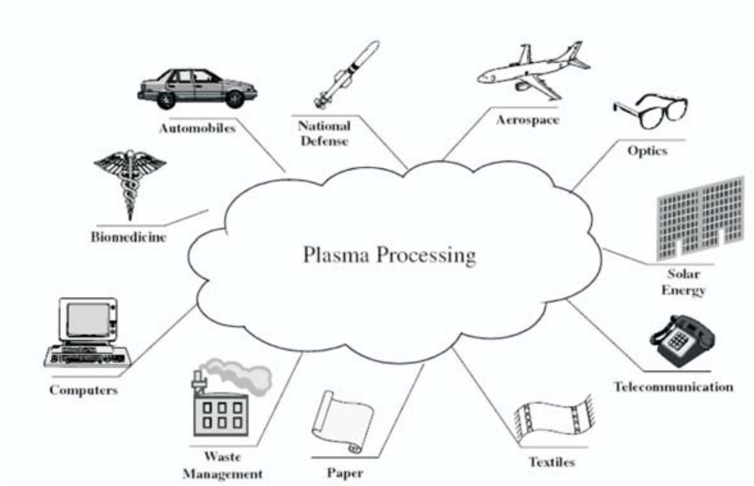

Figure-5: Few Plasma Processing Applications in Industry

Figure-6: Plasmas in the kitchen. Plasmas and the technologies they enable are pervasive in our daily life. We all touches or are touched by plasma-enabled technologies every day. Various products from microelectronics industry, large-area display systems, lighting, packaging, and solar panels to jet engine turbine blades and bio compatible human implants either directly use or are manufactured with plasmas. They in many cases would not exist without plasmas. The result is a better quality of life and economic competitiveness. Note: CVD, chemical vapor deposition; HID, high-intensity discharge; LED, light emitting diode; LCD, liquid crystal display. [Ref. 7]

have entered our homes, offices, and around (Figure-6).

In the absence of plasma technology, more than 3 trillion USD global telecommunications and semiconductor industry would arguably not exist [7]. Here, we provide a bird's eye view of some of these applications where plasma science is essential ingredient[†].

3. CONCLUSIONS

On Earth, we live on an island of "ordinary" matter which has connections with plasmas in different ways. We have learned to work, play, and rest using the familiar states of matter solid, liquid, and gas but plasma is least known. When considered inclusively, it is clear that plasma science and technology encompasses immense diversity, pervasiveness and potential. Diversity through numerous topical areas; pervasiveness by covering the full range of energy, density, time and spatial scales; and potential through innumerable current and future applications. Thus leading contribution of plasmas in science and technology of 21st century is obvious.

In this article, we have presented an overview of the vast field of plasma science and its technological imprints on society with a brief description of historical developments and occurrences of plasmas. Rather than going into the rigorous discussion on various aspects of plasmas, the basic concepts of plasmas in fusion and other major technological applications have been pointed out. The tremendous activities show that plasma science is on the cusp of a new era making significant breakthroughs in the next decade possible. For example, the giant projects on burning plasmas like ITER, NIF, HiPER, ILE, are expected to take critical steps on the road to commercial fusion. Low-temperature plasma industrial applications are already changing everyday lives. Plasma scientists are on call to help crack the mysteries of exotic universe. This make the dynamic future of the field exciting but challenging at the same time.

The significant contribution of plasmas in technology has made it important to nurture fundamental knowledge of plasma science across all of its subfields. It will make possible to advance the science and to create opportunities for a broader range of science-based applications. Such advancements will play a key role in future national and global priority goals such as fusion energy, economic competitiveness, and industrial activities. The vitality of plasma science also demands transnational efforts for joint ventures on crosscutting plasma research [7].

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