1
Plasma, an Overview

1.1
Introduction

This chapter introduces the different areas of plasma, the unique aspects of the subject, definitions, the use of simple ballistic and statistical models and the defining characteristics of plasmas.

The influence of plasma technology has penetrated almost every aspect of human activity during the last few years. Some of the different areas of plasma technology, applications and areas of operation are shown in Table 1.1. Despite the widespread use of many of the applications, the subject of plasma has developed a mystique which has given it a reputation of being complex and impenetrable. Aspects of plasmas which make the subject different from many other areas of physics and engineering are introduced in this chapter.

Plasma comprises, in its simplest form, the two elementary particles that make up an atom: electrons and ions. Over 99% of the universe is believed to be plasma, as opposed to condensed matter (solids, liquids and gases) such as comets, planets or cold stars. The term *plasma* was first used by Langmuir in 1927 and derives its name from the Greek to shape or to mould and the analogy with biological plasma, which is an electrolyte, and describes the self-regulating behaviour of plasma in contrast to the apparently random behaviour of fluids.

The science of plasma encompasses space plasmas, kinetic plasmas and technological plasmas and ranges over enormous variations of parameters such as pressure, distance and energy. One method of distinguishing different areas of plasma technology that is often used is as hot or cold plasmas (Table 1.2) depending on the relative value of the ion temperature T_i to the electron temperature T_e. Although widely and conveniently used to describe individual areas, they accentuate the differences, and the anomaly of a plasma at several thousand degrees kelvin being described as cold is not always helpful! Other common descriptions used are glow, corona, arc and beams. These artificial definitions often present obstacles to those entering the field or to those already engaged in it. The subject of plasma is better described as a continuum in terms primarily of the potential energy of electrons T_e and ions T_i and the electron number density n_e, and one of the objectives of this book is to emphasize the similarities rather than the differences.

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Table 1.1 Some applications of plasmas.

Low-pressure non-equilibrium plasma	Atmospheric non-equilibrium plasmas	High-current equilibrium plasmas
Plasma processes used in electronics fabrication	Atmospheric pressure discharges	Arc welding
Glow discharge diode	Corona discharges	Metal inert gas welding
Magnetron	Corona discharges on power lines	Tungsten inert gas welding
Induction coupled plasmas	Electrostatic charging processes	Submerged arc welding
Electron cyclotron resonance reactor	Electrostatic precipitators	Plasma torch
Helical reactor	Electrostatic deposition	Electric arc melting
Helicon reactor	Dielectric barrier discharges	Three-phase AC arc furnace
Low-pressure electric discharge and plasma	Manufacture of ozone	DC arc furnaces
Lamps	Surface treatment using barrier discharges	Electric arc smelting
Low-pressure mercury vapour lamp	Partial discharges	Plasma melting furnaces
Cold cathode low-pressure lamps	Surface discharges	Vacuum arc furnaces
Electrodeless low-pressure discharge lamps	Atmospheric pressure glow discharges	Arc gas heaters
Plasma display panels	Surface treatment of films and textiles to change surface properties	Electric discharge augmented fuel flames
Gas lasers	Sterilization of medical equipment and disinfection	Induction coupled arc discharges
Free electron and ion beams	Surgery	High-pressure discharge lamps
Electron and ion beam evaporation	Diesel exhaust treatment	Ion lasers
Ion beam processes	Biomedical applications	Arc interrupters
High-power electron beams	Surface modification to improve adhesion, hydrophobic properties, wetting	Vacuum circuit breakers and contactors
Glow discharge surface treatment		Magnetoplasmadynamic power generation
Propulsion in space		Generation of electricity by nuclear fusion
		Natural phenomena
		Lightning
		Applications in space

The reason for plasmas' unique characteristics and relevance to high-energy processes is apparent from Figure 1.1, where the electron temperature T_e is shown for different plasma processes as a function of electron number density of the electrons. Energy and temperature are related by the Boltzmann constant, k_B:

$$\frac{1}{2}mu^2 = k_B T$$

where $k_B = 1.38 \times 10^{-23}$ J K^{-1} [2]. In a cold plasma such as a neon lamp, the kinetic energy equates almost entirely to the electron energy and, although the mean electron temperature may be several times room temperature, the number of hot electrons is only a tiny fraction of the total and their thermal mass is small

Table 1.2 Temperature and pressure ranges of hot and cold plasmas.

Low-temperature thermal cold plasmas	Low-temperature non-thermal cold plasmas	High-temperature hot plasmas
$T_e \approx T_i \approx T < 2 \times 10^4$ K	$T_i \approx T \approx 300$ K $T_i \ll T_e \leqslant 10^5$ K	$T_i \approx T_e > 10^6$ K
Arcs at 100 kPa	Low pressure ~100 Pa glow and arc	Kinetic plasmas, fusion plasmas

From Ref. [1].

compared with an atom or molecule, so that the average temperature increase is small. The potential and energy of most plasma processes are several orders of magnitude greater than those of most other processes; for example, the energy of molecules at room temperature is about 0.025 eV and at 4000 K it is 0.35 eV.

It is usually necessary to consider plasma parameters on an atomic level, including particle sizes, length and time scales, particle number densities, forces between particles and many other parameters, with respect to each other. Atomic particles resonate and the difference in resonant frequencies between electrons and ions due to their different masses adds a further layer of complication, together with the fluid nature of a plasma and the ability to affect it with static and fluctuating

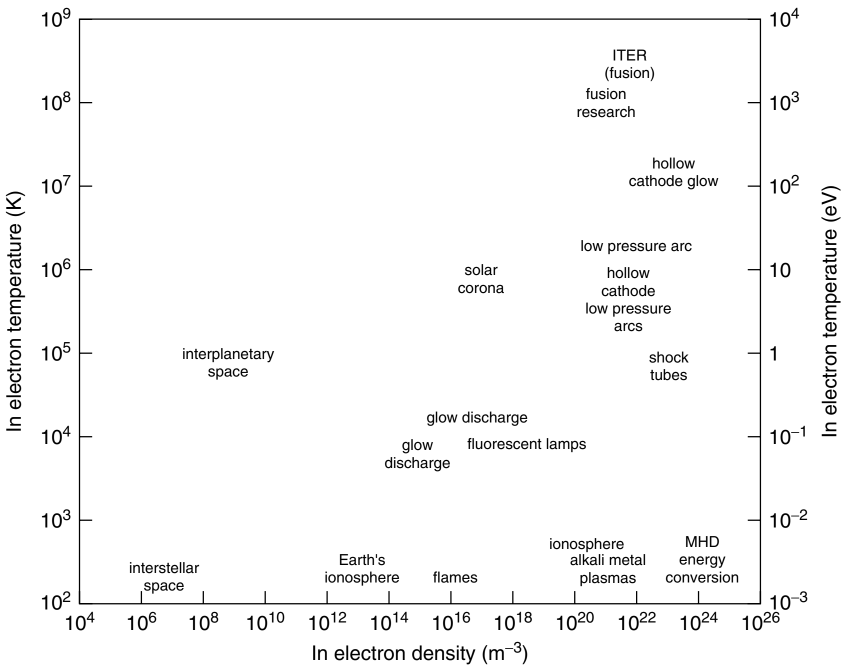

Figure 1.1 Plasma applications at different currents and gas pressures.

magnetic fields. To this we may also add the ranges of conditions encountered, such as current and gas pressure.

1.2
Plasma

1.2.1
Space Plasmas

Space plasmas [3] vary from very hot ($T > 30\,000$ K), dense plasmas at the centre of stars, corona flares and sunspots, to cold, less dense plasmas such as the aurora borealis and the ionosphere within the Earth's gravitational system.

Space is not a perfect vacuum but the gas pressure in interstellar space may be as low as about 3 fPa (22.5×10^{-18} Torr), at which pressure has little meaning. [The parameters of neutral particles scale approximately with number density (gas pressure) over wide ranges.] The corresponding particle density in interstellar space may be as low as 10^6 m^{-3}, less than 1×10^{-19} of the particle density at atmospheric pressure on Earth. The diameter of a hydrogen atom is of the order of 10^{-10} m with a nucleus of diameter about 10^{-15} m; the chance of a collision is very low, and electrons and ions travel through space at high velocities over large distances.

The fundamental theory of space plasmas is the same, however, as in other areas of plasma technology, although the conditions such as pressure, boundaries and energies may be very different. Space propulsion shares terrestrial technology such as plasma torches, electron cyclotrons or helicons, also used for making computer chips.

1.2.2
Kinetic Plasmas

Kinetic plasmas are generally described as hot plasmas since the ion temperature which is approximately equal to the electron temperature ($T_e \approx T_i$), is high although the gas is not necessarily in thermal equilibrium since the neutral atoms and molecules may be at a much lower temperature. In a kinetic plasma, the mean free path of a particle (λ) is long (i.e. the time between collisions τ is long and the collision frequency ν is low), electrons and ions tend to behave separately and their behaviour can be described in terms of individual particles in both space and time. Beams of electrons and ion beams at low pressures are used in semiconductor manufacture and for welding and melting can be regarded as kinetic plasmas.

At higher pressures, such as those used in atomic fusion [4], although the collision processes can be described as kinetic, the effects of diffusion gradients, collisions and the fluid and electromagnetic properties also affect the process, and they may also be described as magnetoplasmadynamic (MPD) [5]. Very high energy densities are possible and kinetic plasmas are the subject of areas such as fusion and particle research.

1.2.3
Technological Plasmas

Technological plasmas are normally supplied with energy from electric power sources, although excitation from shock waves and chemical plasmas is possible, and operate in the region from atmospheric pressure down to about 10 Pa (75.2×10^{-3} Torr) [6]. Gas pressures as low as 10^{-11} Pa (7.52×10^{-14} Torr) are obtainable in the laboratory, but the use of plasmas is limited by the energy density at low pressures to about 100×10^{-3} Pa (0.752×10^{-3} Torr), at which the mean free path is of the order of 100 mm.

Technological plasmas are often referred to as *cold plasmas*, since the neutral particle and ion temperatures are often much lower than the electron temperature. If the length and time scales of changes of the electric field are long compared with the mean free path and collision frequency, the effects of collisions in a plasma result in a statistical distribution of velocities and energy. At gas pressures above about 0.133 Pa (10^{-3} Torr), corresponding to particle densities of 10^{19} m^{-3}, plasmas can be considered statistically as a quasi-continuous fluid; below this there is a substantial separation between particles and the behaviour is more accurately described by the behaviour of individual particles (free electrons or ions), such as those in electron and ion beams.

1.3
Classical Models

1.3.1
Simple Ballistic and Statistical Models

It is difficult to comprehend the complexity of the numerous subatomic particles and their interactions, but fortunately simple models adequately explain the behaviour of most plasma processes.

Models using ballistic equations to describe atoms and electrons are a simple way of understanding the events that occur in a plasma at an atomic level. Many plasma processes can be treated using classical mechanics, such as the velocity equations:

$$s = ut + \frac{1}{2}ft^2, v^2 = u^2 + 2fs$$

momentum equations:

$$m_1 u_1 = m_2 v_2$$

conservation of energy:

$$\frac{1}{2}m_1 u^2 = \frac{1}{2}m_2 v^2$$

the continuity equation and basic electromagnetic theory [7].

The atoms or molecules comprising a gas are in a continual state of movement due to thermal diffusion caused by temperature differences in the gas. Thermal diffusion affects the behaviour of plasmas, except at very low pressures, and it is necessary to superimpose a statistical model on the ballistic model using mean values and probabilities. The transport properties of the parent gas (density, velocity, viscosity and pressure) have a major effect on the plasma where the degree of ionization is low and the number of collisions is high.

The effects of the large numbers of collisions drive the number distribution of velocities towards a statistical distribution such as a Maxwellian distribution (see Section 1.3.2). A kinetic solution that describes the velocity and position as a function of time is appropriate where the time scales of significant functions such as waves, propagation, instabilities and other non-Maxwellian effects are much shorter than the time for relaxation or thermal equilibrium. Particle beams, some low-pressure plasmas and, for example, toroidal (tokomak) fusion reactors fall into this area.

1.3.2 Statistical Behaviour

Where there are a very large number of particles in thermal and charge equilibrium in an isotropic (uniform) medium, the velocity distribution can be determined statistically and is given by the Maxwell equation [2]:

$$f(u) = \frac{\mathrm{d}n_u}{\mathrm{d}u} = \frac{4n}{\pi^{\frac{1}{2}}}\left(\frac{m}{2k_B T}\right)^{\frac{3}{2}} u^2 \exp\left(-\frac{mu^2}{2k_B T}\right) \tag{1.1}$$

where T is the average temperature and u the velocity over the range $\mathrm{d}u$, n is the particle number density, m the particle mass, and k_B Boltzmann's constant, $k_B = 1.38 \times 10^{-23}$. The kinetic energy of a particle is

$$\frac{mu^2}{2} = k_B T \tag{1.2}$$

The Maxwell velocity distribution (Figure 1.2) relates the normalized number probability of neutral particles which have a specific value of velocity [7].

The most probable velocity is the maximum of the velocity distribution:

$$u_m = \left(\frac{2k_B T}{m}\right)^{\frac{1}{2}} \tag{1.3}$$

The average velocity is

$$\overline{u}_{av} = \left(\frac{8k_B T}{\pi m}\right)^{\frac{1}{2}} \tag{1.4}$$

and the r.m.s. velocity is

$$\overline{u}_{rms} = \left(\frac{3k_B T}{m}\right)^{\frac{1}{2}} \tag{1.5}$$

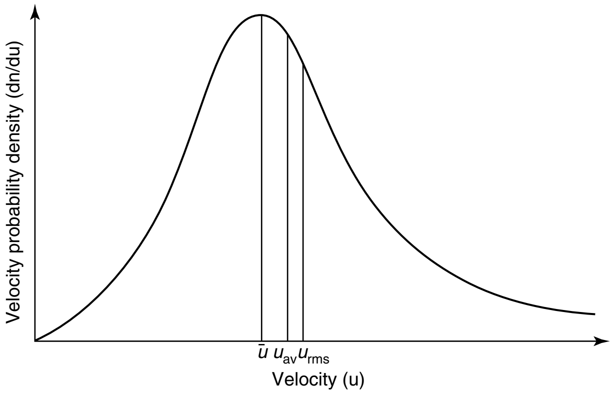

Figure 1.2 Maxwellian velocity distribution showing average, r.m.s. and peak values of probable velocities.

Although there is a wide distribution of velocities, nearly 90% are between half and double the average velocity and the probability of a molecule having a very high or very low velocity is extremely small; however, small numbers of high-velocity particles with high kinetic energy exist in the tail of the distribution.

The Maxwell–Boltzmann energy distribution $f(w)$ [1] (Figure 1.3) as a function of the probable particle distribution derived from the velocity distribution is

$$f(\mathbf{w}) = \frac{\mathrm{d}n_w}{\mathrm{d}w} = \frac{2n}{\pi^{\frac{1}{2}}} \frac{w^{\frac{1}{2}}}{\left(2k_B T\right)^{\frac{3}{2}}} \exp\left(-\frac{w}{2k_B T}\right) \tag{1.6}$$

The velocity distribution of charged particles tends to be non-Maxwellian, due to the effect of the electric field and neighbouring charged particles. However, it may be applied with caution in weak electric fields:

1) The electric field strength is low enough that inelastic collisions can be ignored but high enough for $T_e \gg T_i$.

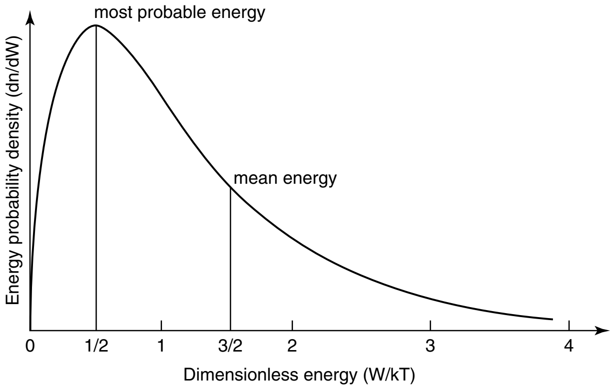

Figure 1.3 Maxwell–Boltzmann energy distribution.

2) The supply frequency is much lower than the collision frequency.
3) The collision frequency is independent of the electron energy T_i.

Figure 1.4 shows the energy levels for different atomic and molecular transitions. The energy gained by an electron (charge 1.6×10^{-19} C) accelerated through a potential of 1 V is 1 eV or 1.6×10^{-19} J. The Maxwell–Boltzmann distribution indicates the small number of particles available with sufficient energy for ionization.

One electronvolt corresponds to an average velocity of a proton of 1.38×10^4 m s^{-1} and for an electron 593×10^6 km s^{-1}, or a temperature of 11 600 K. The units of energy in electronvolts are small but the overall energy transfer may be large since the numbers and collision frequency are very high. On a molecular level, the energy required to change a molecule of a solid to a liquid is about 10^{-2} eV, but to ionize a gas molecule requires at least 1 eV. At room temperature, the kinetic energy of a proton (the nucleus of a hydrogen atom) is about 0.04 eV and only 0.5 eV at 4000 K. The energy required to detach an electron from a single proton to ionize it is 13.6 eV, so that the probability of a neutral particle having a high enough energy to ionize even at high temperatures is very low.

1.3.3
Collisions Between Particles

Collisions between particles may be elastic, in which case momentum is preserved, or inelastic, where momentum is transferred to potential energy; in both cases, energy is exchanged. The energy per collision and the collision frequency between atomic particles affect the rate at which energy can be coupled with or released from a plasma. The mass of an electron, m_e, is 9.11×10^{-31} kg. The atomic weight of the nucleus of a hydrogen atom (proton), m_p, is 1.67×10^{-27} kg.

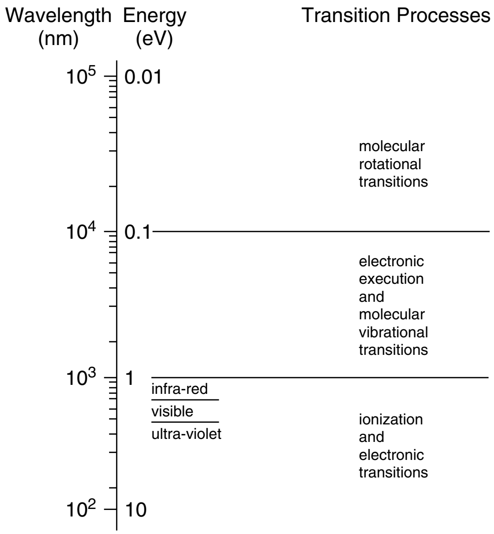

Figure 1.4 Atomic and molecular energy associated with different energy transitions.

The small mass of the electron results in only a negligible exchange of kinetic energy from electrons in an elastic collision and both particles preserve the magnitude of their momentum but its direction will be changed.

The fraction of energy k transferred in an elastic collision from a particle of mass m to a stationary particle of mass M can be derived from the momentum and kinetic energy equations. For impact on the axis of the two particles

$$k = \frac{\frac{4m}{M}}{\left(1 + \frac{m}{M}\right)^2} \tag{1.7}$$

Where $m \gg M$ such as an electron neutral collision

$$k \approx \frac{4m}{M} \tag{1.8}$$

If m and M are similar, the energy is approximately equally shared. In a collision between an electron and a stationary hydrogen atom or proton, $k = 2\,m/M$ and the energy transferred is 10.9×10^{-4} or about 0.1% of the initial electron energy; if the collision is inelastic, the fraction of energy converted may be as high as $M/(m + M)$, and over 99% of the initial electron energy may be transferred.

The collision frequency of a proton in air at atmospheric pressure is of the order of $7 \times 10^9\ \mathrm{s}^{-1}$. The mean free path λ (distance between collisions) of an atom or molecule in air at atmospheric pressure is approximately 6×10^{-8} m and decreases approximately inversely with pressure, so that at 0.1 Pa (0.752×10^{-3} Torr), the mean free path is of the order of 60 mm [8].

1.3.4
Coulomb Forces

The Coulomb force is the electrostatic force between electric charges; opposite charges attract, like charges repel. Electrons can be considered as point charges; ions may also be considered in the same way by assuming that their charge is concentrated at their centre.

The electrostatic force between two point charges q_1 and q_2 separated by a distance r is given by Coulomb's law [2] as

$$\frac{q_1\, q_2}{4\pi r^2 \varepsilon_0} \tag{1.9}$$

For two charges of opposite polarity, the particles attract although forces due to other charged particles may prevent collision. The Coulomb force between particles in close proximity is strong and may be much greater than the effect of the applied electric field.

Displacement of a charge from a position of charge equilibrium results in oscillation of the charge at the electron or ion resonant frequency (see Section 1.4). When a large number of collisions occur at high pressure and an electron charge of depth equal to the Debye radius λ_D develops, this screens the effect of the electric field and reduces its potential (see Section 3.2.1.3). Ambipolar diffusion, in which the drift velocities of electrons and ions are affected by the electric field between them, retards high-velocity electrons. At low pressures and, for example, in electron and ion beams an external electric field may have a greater effect than Coulomb forces.

1.3.5
Boundaries and Sheaths

Technological plasmas have boundaries defined by the walls of a vessel, electrodes or the ambient gas and energized particles give up energy by collisions at the boundaries. Insulated surfaces or boundaries rapidly acquire a charge, forming a sheath, and repel like charges. Figure 1.5 illustrates the variation of plasma potential in a plasma sheath with distance from a boundary.

A local charge concentration of positive ions forms over a region of a few tens of microns comparable to the mean free path of the particles. The ion sheath causes a potential gradient between the plasma and the boundary and screens the plasma, which remains approximately charge neutral. The ability of the sheath to screen the plasma from a disturbance is known as the *Debye radius* [1]. The Debye radius is normally small compared with the principal dimensions of a process except at very high values of T_e or very low values of n_e except for example on a nanometre scale (as in etching and similar processes).

1.3.6
Degree of Ionization

The degree of ionization [1] is a measure of the number of ionized atoms or molecules (which is normally equal to the number of electrons n_e or ions n_i) as a fraction α of the total number n_t of atoms or molecules:

$$\alpha = \frac{n_e}{n_t} \tag{1.10}$$

Only a small fraction of the atoms in an electric discharge are ionized, typically 1 in $10^5 - 10^6$, which at a gas pressure of 133 Pa (1 Torr) corresponds to a particle density of 10^{22} m^{-3} and an electron density of 10^{16} m^{-3}. The variation of the degree of ionization with temperature is illustrated in Figure 1.6.

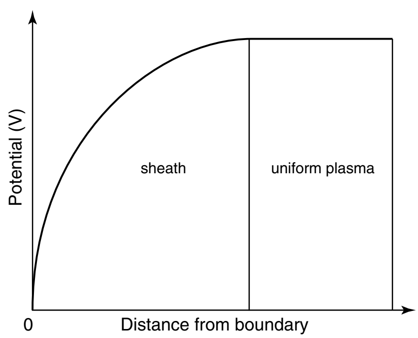

Figure 1.5 Illustration of the voltage distribution in a sheath at a boundary.

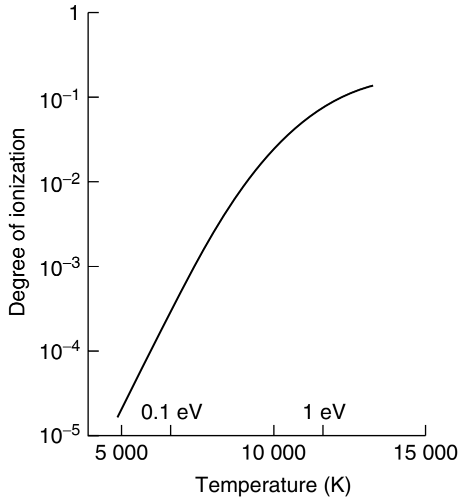

Figure 1.6 Characteristic variation of the degree of ionization of an atomic gas at atmospheric pressure.

1.4
Plasma Resonance

Resonance occurs in a plasma at high frequencies at different frequencies corresponding to the electron and ion frequencies. The electron frequency is independent of the mass of the atom or molecule and is sometimes referred to as the *plasma frequency*. The resonant frequency defines one of the characteristic properties of plasmas at high frequency, namely the cut-off frequency at which an electromagnetic wave will not be transmitted through a plasma. The conditions for this will be dealt with in Chapter 3 but can be considered in terms of the Debye radius (see Section 1.3.5). The Debye radius is the distance that an electron has to move to screen the plasma from radiation. If the period of the frequency of the radiation is such that it is shorter than the average time for an electron to move through the Debye radius, the energy will be transmitted since the electrons in the limit will not have time to absorb energy, whereas if it is longer energy will be absorbed. This accounts for the variation of the transmission of electromagnetic waves with frequency in the ionosphere; however, in the case of technological plasmas the distances involved are short and absorption within a narrow depth is normally required.

1.5
The Defining Characteristics of a Plasma

The high temperature and energy density of plasmas are illustrated in Figure 1.7, which also shows different methods of energizing plasmas. The defining

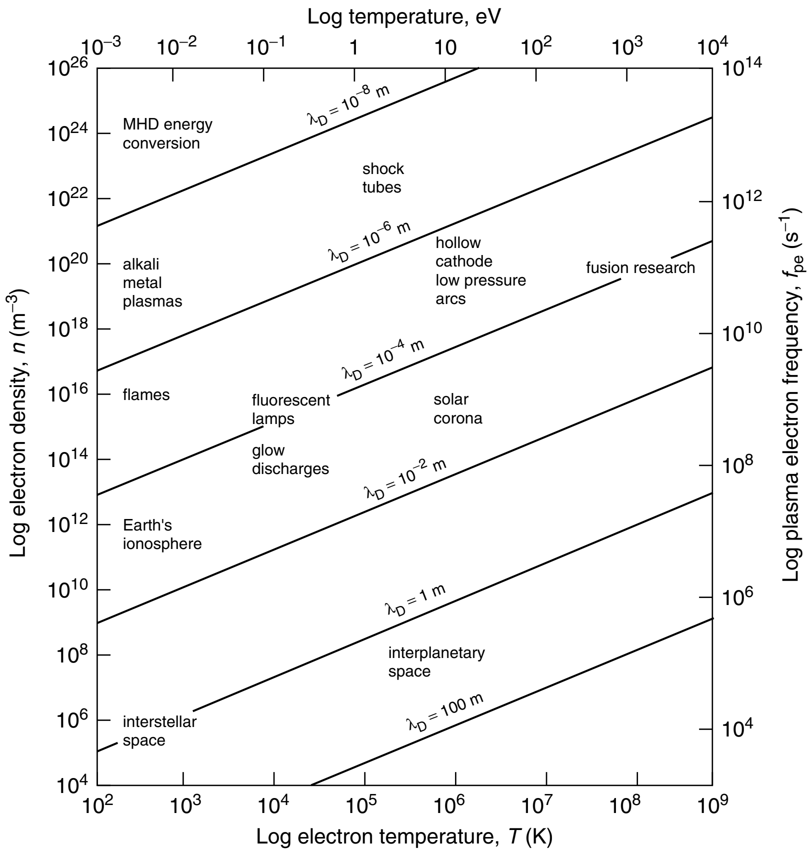

Figure 1.7 Variation of electron number density with electron energy at different values of Debye radius for different plasma processes.

characteristics of a plasma are shown in Figure 1.7, together with some characteristic ranges of plasma applications. The plasma conditions can be determined if any two parameters are known.

In addition to charge equilibrium, some additional defining characteristics of a plasma are as follows:

1) Sufficient charged particle density so that the plasma is not discontinuous.
2) Debye radius greater than the distance between particles and smaller than the characteristic length of the plasma, that is, the size of the vessel should be much greater than the Debye length.
3) The plasma electron frequency $\omega_{pe} = 2\pi f_{pe}$ should be much higher than the collision frequency if a signal is to propagate.

There are many examples of plasmas which do not meet the strict definition of charge equilibrium, such as in the electrode regions of electric discharges, and electron and ion beams, which are otherwise similar, or contribute to the production of a plasma; many plasma processes themselves are generated using electron and ion beams from the cathode or anode fall regions of a discharge.

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