# Stimulation of Waves and Instabilities in Response to Irradiation of Electromagnetic Fields into Plasmas

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**ABSTRACT:**
Plasma is a unique phase of matter constituting positively or negatively charged atoms, excited atoms, neutral atoms, electrons, radicals, etcetera displaying a unique role in the nuclear fusion research besides studying electrical discharges in the domain of switching devices and biomedical applications lately. We discuss in this extensive proposition the fundamental plasma characteristics such as Debye length, plasma oscillations, plasma sheath and condition for sustainability and confinement of plasmas, besides examining the elementary waves in plasmas namely zero waves, electron plasma wave and ion plasma wave. The inherent electron plasma wave and ion plasma wave is associated with the driving of plasma currents which in turn depends upon the density perturbation and thermal velocities of the electrons and ions. The application of external electromagnetic radiation such as laser (pump wave) into the plasma modifies the dispersion relations of electron and ion plasma wave, respectively. The laser stimulates a plethora of waves in the plasma and undergoes remarkable physical phenomena such as self-focusing and filamentation of laser beams. The excitation of sideband waves of the laser beams into the plasma plays a key role in imparting ponderomotive force on the electron plasma waves leading to turbulence in the plasmas due to coupling of the waves. The oscillatory velocity of the electron due to pump wave, plasma density perturbation, ponderomotive force and current densities are associated with the excitation of instabilities in the plasma. Conclusively, such waves and instabilities in unmagnetized and magnetized plasma is comprehensively studied and concluded by proposing the investigation of unexplored twisted electromagnetic wave-plasma interaction.

**KEYWORDS:** Debye Length, Plasma Frequency, Langmuir Wave, Magnetized Plasma, Unmagnetized Plasma, Parametric Instabilities.

## 1. INTRODUCTION

Plasma is a ubiquitous phase of matter, though not plentiful but abundant outside the planet, such as outer space. Each Star is made of Plasma, the solar winds that are constantly being radiated outward from the sun are essentially Plasma, and the Blockhole's accretion disk is made of Plasma.

Plasma, often known as the fourth state of matter, is a gas of ionized particles generally containing ions and electrons, achieved by raising the temperature of the gas in total. Due to this increase in temperature, the electrons in the atoms of the gases get enough energy to get free from the atoms and, in addition, provoke others to do the same by continuously striking them and transferring energy. This process is known as ionization. The various ways to ionize gases are: photoionization and electric discharge. In photoionization we use light as the source to excite atoms. Here actually, the atoms absorb the incident photons to get energized, and then if the photon has sufficient energy, the gas atoms will get ionized. But in electric discharge when electric field is applied across the ionized gas, it accelerates the free electrons to high energies and hence by collision it ionizes other atoms [1, 2].

Additionally, Plasma is treated as a fluid because Plasma acts as a fluid in macroscopic view. It shows various properties similar to that of fluids, mostly like gas. In macroscopic view, the Plasma seems neutral, because though there are charged particles, the number of positive ions is equal to the number of electrons. However, in microscopic view, the story is different. Due to the formation of charged particles in Plasma they interact with nearby particles simultaneously. Other particles also interact with those others leading to a collective behavior. These collective behaviors lead to



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various collective effects that distinguish Plasma from other fluids [1].

Charge-charge interaction and charge-neutral interaction are two forms of particle interactions in plasma. The kind of charged Plasma, weak or strong, is determined by interactions. In a lightly ionized plasma, charge-neutral interactions dominate over numerous Coulomb interactions. However, as particle ionization grows, so does the Coulomb interaction, such that all particles in a fully ionized plasma are susceptible to numerous Coulomb interactions [1].

Plasma exhibits a variety of physical phenomena as a result of its unique plasma activity. Plasmas are good conductors of electricity and heat due to the presence of ions and electrons, as well as their tremendous mobility. Because of the size difference between electrons and ions, it may appear that electrons will travel faster than ions when a density gradient forms in plasma. However, as a result of the charge separation, a polarization electric field is formed. As a result, the ions begin to migrate, and the rate of electron movement slows, until both electrons and ions diffuse at the same rate. Ambipolar diffusion [1] is the name given to this sort of diffusion.

An essential characteristic of Plasma is to sustain a wide variety of waves. In low frequency waves in magnetized Plasma is known as Alfven wave and magnetosonic waves. Each wave depends on wave frequency, wave number, and its polarization. Dissipative properties like collision produce damping in the wave's amplitude, which means energy is transferred from wave field to plasma particles. Non-collisional mechanism such as Landau damping also causes damping. Here some plasma particles get trapped in the energy potential well of the wave, the net result being the transfer of energy from the wave to the particles [1].

When plasma has energy, it also sustains various forms of wave. That energy also gets emitted. The mechanisms of emitting or absorbing radiation can be grouped into two categories: radiation from emitting atoms or molecules, and radiation from accelerated charges. When ions and electrons also recombine energy is liberated. These energy radiations constitute the line of spectrum of the plasmas. An accelerated charged particle also liberates energy. Whenever a charged particle is deaccelerated due to some kind of collision then the radiation emitted is called Bremsstrahlung. If the charged particle remains unbound, both before and after the encounter, the process is called free-free bremsstrahlung. If the originally unbound charged particle is captured by another particle, as it emits the radiation, the process is called free-bound radiation [1].

We discuss the plasma characteristics in section 2 followed by examining the elementary waves in magnetized and unmagnetized plasmas in section 3. Section 4 focuses on investigating important instabilities in plasma. We conclude by proposing future research aspects on plasma in section 5.

## 2. PLASMA CHARACTERISTICS

The three utmost essential characteristics of the Plasma are stated as below:

Debye Length- It is the distance or radius of the sphere up to which the influence of an individual charged particle is felt. The charged particles arrange themselves to effectively shield any electrostatic field at a distance equal to the Debye length. This electrostatic field shielding is a consequence of the collective effects of the plasma particles.

$$\lambda_D = \left((\varepsilon_0 kT) \,/\, (n_e e^2)\right)^{1/2} \tag{1}$$

Where $\lambda_D$ is the Debye length, T is temperature and $n_e$ is the electron number density [1].

Plasma Sheath- The sphere of radius of Debye length inside which the concept of electrical neutrality does not hold is known as Debye sphere and the layer is known as Plasma Sheath [1].

Plasma Frequency- The production of a restoring force occurs when the plasma density is perturbed from its equilibrium position, resulting in the oscillation of plasma density from its equilibrium position. However, when the perturbed particles find equilibrium, they do not stop there; because of the inertia, they continue to travel, resulting in an oscillation kind of motion. The plasma frequency is a natural frequency of oscillation that characterizes these collective movements. Collisions between electrons and neutral particles tend to extinguish and diminish the amplitudes of these collective oscillations [1].

To define the term Plasma in scientific terms, a few conditions need to be fulfilled. The First criterion, Plasma is macroscopically neutral; the second criterion, if $L$ is the characteristic dimension of the Plasma then $L \gg \lambda_D$[1,2]. The number of electrons $N_D$ inside the Debye sphere is given by

$$N_D = (4\,/\,3)\pi\lambda_D^3 n_e = (4\,/\,3)\pi\left((\varepsilon_0 KT)\,/\,(n_e^{1/3}e^2)\right)^{3/2} \tag{2}$$

Where, $\lambda_D$ is debye sphere radius, $n_e$ is the electron number density in Plasma, e is the electron's charge, $k$ is the Boltzmann constant, $T$ is temperature. Here we can say that $n_e\lambda_D^3 \gg 1$ if we take the rest part to be constant [1, 2]. This is the third condition. It is necessary that the electron-neutral collision frequency ($\nu_{en}$) be smaller than the electron plasma frequency.

$\nu_{pe} > \nu_{en}$ implies $\omega\tau > 1$, where $\tau > 1/\nu_{en}$ and $\nu_{pe} = (\omega_{pe}\,/\,2\pi)$, where $\omega$ is the angular frequency of typical Plasma Oscillation. This indicates that the average period between electrically neutral collisions must be long in comparison to the typical time when the physical properties of the plasma change. This is the fourth criterion [1,2].

The Plasma is investigated through the velocity, continuity and Poisson's equation [3] expressed below as

$$(\delta\rho/\delta t) + \vec{\nabla}.(\boldsymbol{\rho}\vec{\boldsymbol{u}}) = 0 \quad (3)$$

Where, $\rho$ is the Plasma density, $t$ is time, $\vec{\boldsymbol{u}}$ is the flow velocity vector field.

$$\nabla^2\phi = 4\pi e\,(n_e - n_i) \quad (4)$$

Where, $\phi$ is the electric potential, $e$ is the electronic charge, $n_e$ is the electron number density in the Plasma, $n_i$ is the ion number density in Plasma.

The Vlasov equation [4] are a set of equations which describes the time dependence of distribution function of Plasma. Below are two of the Vlasov-Maxwell equations.

$$\frac{\partial f_e}{\partial t} + \vec{\boldsymbol{u}}_e \cdot \vec{\boldsymbol{\nabla}} f_e - e\left(\vec{\boldsymbol{E}} + \frac{\vec{u}_e}{c} \times \vec{\boldsymbol{B}}\right) \cdot \frac{\partial f_e}{\partial \vec{\boldsymbol{p}}} = 0 \quad (5)$$

$$\frac{\partial f_i}{\partial t} + \vec{\boldsymbol{u}}_i \cdot \vec{\boldsymbol{\nabla}} f_i - Z_i e\left(\vec{\boldsymbol{E}} + \frac{\vec{u}_i}{c} \times \vec{\boldsymbol{B}}\right) \cdot \frac{\partial f_i}{\partial \vec{\boldsymbol{p}}} = 0 \quad (6)$$

Where, $f_\alpha(\vec{\boldsymbol{p}}, \vec{\boldsymbol{r}}, t)$ is the distribution function of species $\alpha$ (electrons and ions) described as the number of particles of the species $\alpha$ having approximately the momentum $\vec{\boldsymbol{p}}$ near the position $\vec{\boldsymbol{r}}$ at time $t$. $\vec{\boldsymbol{E}}$ is the Electric field, $\vec{\boldsymbol{B}}$ is the Magnetic field, $e$ is the charge of the electron, $Z_i$ is the number of ions, $\vec{\boldsymbol{u}}$ is the flow velocity vector field.

The Navier-Stokes equation is also of significant importance in Plasma and the basic equation corresponding to it is expressed as,

$$\rho\left[(\delta\vec{\boldsymbol{u}} \,/\, \delta t) + \left(\vec{\boldsymbol{u}} \cdot \vec{\nabla}\right)\vec{\boldsymbol{u}}\right] = -\vec{\boldsymbol{\nabla}}p + \rho\nu\boldsymbol{\nabla}^2\vec{\boldsymbol{u}} \quad (7)$$

Evidently, we can observe that the first two equations of Vlasov-Maxwell's equation and Navier-Stokes equation are similar kind of equation. Thus, not always, but the majority of the time, Plasma can be described using fluid equation showing that for specific situations, Plasma can be treated as fluid of charged particles without much deviation from the actual result. One of the most prominent situations when fluid theory is a good approximation for Plasma is the movement of charged particles perpendicular to Magnetic field B.

## 3. ELEMENTARY WAVES IN PLASMAS

### 3.1. Plasma Oscillations

When electrons in Plasma are displaced intentionally a restoring force acts on them to bring them back to equilibrium position. When the force acts on the electron and accelerates it in the opposite direction to the electron's movement due to inertia, the electron moves to the other side of the equilibrium point. So again, a restoring force gets created and accelerates the electron back. This motion of electrons across its equilibrium point is known as plasma oscillation. Such oscillations have a characteristic frequency known as plasma frequency (stated earlier). These oscillations are so fast that the more significant components like the ions do not get enough time to respond and are considered static [3].

The formula given below gives the plasma frequency:

$$\omega_p = \left((n_0 e^2)\,/\,(\varepsilon_0 m)\right)^{1/2} \quad (8)$$

Which can be approximated to as

$$f_p = 9n^{1/2} \quad (9)$$

This shows us that the plasma frequency depends only on the plasma density [3]. It also shows that ω does not depend on k so$d\omega/dk = 0$, which means that the disturbance does not propagate.

When laser is propagated through Plasma, various types of phenomena can be encountered depending on the plasma conditions. Fig.1. displays the schematic of physical phenomena and associated waves excited in Plasma under the influence of external electromagnetic waves (pump wave).

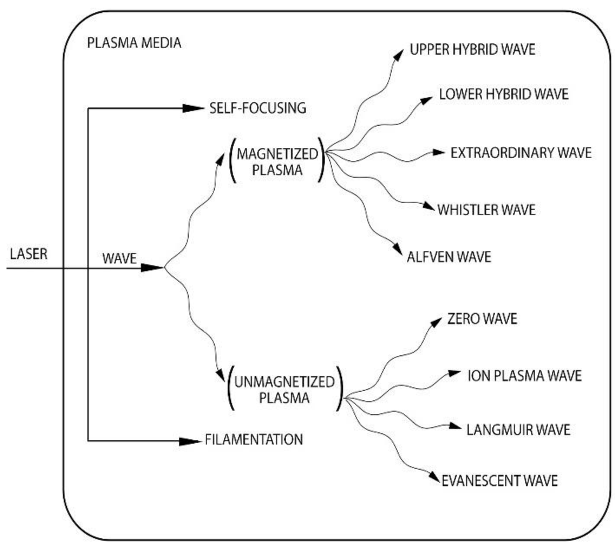


**Fig. 1.** The physical phenomenon and excitation of waves under the influence of pump waves.

In the case of non-uniform heating of the Plasma there is the creation of thermal pressure gradient which pushes the Plasma, causing density depression which again acts as a guide and leads to self-focusing of electromagnetic waves (EM waves). This is known as self-focusing of laser. The focusing continues until the duct is nearly depleted and then it starts diverging [7]. When a radiation intensity profile for which self-focusing and the diverging effect properly balance each other, however, a slight fluctuation occurs in the intensity distribution. Such fluctuation gets amplified by the same process leading to filamentation [7]. We have discussed about this in details later in the paper.

Besides, the laser in Plasma can produce a plethora of waves depending on the presence of an external magnetic field. Such waves are summarized in the subsequent section.

### 3.2 Unmagnetized Plasma

#### 3.2.1. Zero waves

As we have studied that in Plasma, waves are generally due to the interaction of the charged particle with each other and the forces experienced by them due to the rest of the charges. For this thing to happen in a particular environment, more specifically a proper temperature is required. However, when the temperature is relatively low, then the particles do not have enough thermal energy and gradually freeze out hence ordinary sound waves cannot propagate.

However, it was discovered by Landau [5] that even in low temperature medium not an ordinary wave but a density wave can flow, known as zero sound or zero wave. It can be represented by the dispersion relation

$$\omega_0 = \nu_0 k \tag{10}$$

Where, $\nu_o$ is the speed of the zero wave. The speed of zero wave is greater than the speed of sound by a factor of $3^{1/2}$.

#### 3.2.2. Ion plasma wave (acoustic wave)

Waves in ordinary air, which on simplification gives us

$$(\omega / k) = (\gamma p_0 / \rho_0)^{1/2} = c_s \tag{11}$$

Where, $c_s$ is the speed of sound in air, $p_0$ is the pressure, $\rho_0$ is the density and $\gamma$ as the specific heat ratio. Ion acoustic wave, or simply ion wave, is a type of wave observed in plasma that has no neutrals and few collisions.

With very few collisions, sound cannot propagate, but ions can still transmit vibrations because of their charge in Plasma. Since these oscillations includes ions, which are massive hence the frequency is very low [6].

In the absence of magnetic field [2], we get

$$(\omega / k) = \left((kT_e + \nu_i kT_i) / M\right)^{1/2} \tag{12}$$

Which gives us vs that is the speed of sound in Plasma, where $T_e$ is the temperature of the electron and $T_i$ is the temperature of the ions, M is the mass of the ion and $\gamma_i$ is taken as 3. The main difference between ion plasma wave and plasma oscillation is Plasma oscillations that are basically constant-frequency waves, with a correction due to thermal motions. Ion waves are constant-velocity waves and exist only when thermal motions [3].

#### 3.2.3. Electron Plasma Wave (Langmuir wave)

Apart from intentional displacement, another factor that triggers plasma electrons to oscillate and propagate is their thermal motion. Due to their thermal velocities, the electrons oscillate and carry information about the oscillating region by streaming into the adjacent layers of the Plasma. So, this actually can be called a plasma wave.

Bohm and Gross worked on these waves in 1949, and gave a detailed theory on the wave propagation and how to produce it [7]. The dispersion relation of electron plasma wave is given by the equation:

$$\omega^2 = \omega_p^2 + (3/2)k^2 v_{the}^2 \tag{13}$$

Where, $\omega$ is the total frequency, $\omega_p$ is the plasma frequency and $v_{th} = ((2k_B T)/m)$, the thermal velocity [2]. Now the group velocity is given by

$$v_g = (3/2)\left(v_{th}^2 / v_\phi\right) \tag{14}$$

Where, $v_{th}$ is the thermal velocity and $v_\phi$ is the phase velocity [2].

#### 3.2.4. Evanescent wave

It is observed that propagation of EM waves in Plasma depends upon the type of EM wave and the plasma frequency. The dispersion relations tell us about the relation between these. If plasma frequency is greater than the EM, wave will not propagate, there will be damping. Such wave with damping is called Evanescent wave [8].

### 3.3 Magnetized Plasma

#### 3.3.1. Upper Hybrid Wave

Upper hybrid waves are the electrostatic waves across $B_0$ with frequency $\omega_H$ where regions of compression and rarefactions are formed in electron wave. The Lorentz force creates an elliptical trajectory because the magnetic field B is perpendicular to the motion. The frequency is higher than that of plasma oscillation due to enhanced restoring forces acting on electrons, electrostatic field, and Lorentz force. Since the higher hybrid oscillations are generated and energy is absorbed from the beam as the plasma density is changed, the transmission through the plasma decreases, making $\omega_H$ equal to the applied frequency. Microwave transmission along a magnetic field is used to confirm the upper hybrid frequency [2,10,11].

The dispersion relation of upper hybrid wave is given by the equation:

$$\omega^2 = \omega_p^2 + \omega_c^2 \quad (15)$$

Where, $\omega_p$ is the plasma frequency and $\omega_c$ is the electron gyro frequency.

### 3.3.2. Lower Hybrid Wave

Lower Hybrid waves are the waves that propagate almost perpendicular to the magnetic field. The charge neutrality is not preserved by along the lines of force. They obey the whole equation of motion instead of Boltzmann's relation [12]. The frequency of lower hybrid waves can be given by

$$\omega_L = (\omega_C \cdot \Omega_C)^{1/2} \quad (16)$$

Where, $\omega_c$ is the electron gyro frequency and $\Omega_c$ is the ion gyro frequency. The dispersion relation is given by

$$\omega^2 = [(\Omega_c^2 \omega_c)^{-1} + \omega_i^{-2}]^{-1} \quad (17)$$

Where, $\Omega_c$ is the photon gyrofrequency, $\omega_c$ is the electron gyrofrequency and $\omega_i$ is the ion plasma frequency. Lower hybrid waves are in resonance with both magnetized and unmagnetized electrons at the same time, allowing them to provide the necessary electron acceleration for the plasma heating mechanism [12].

The k vector in these waves is rather huge. This makes them ideal for radiofrequency fusion plasma heating. Lower hybrid wave tests need a strong magnetic plasma. These waves are utilized in a variety of astrophysical scenarios [13].

### 3.3.3. Extraordinary Wave

Extraordinary waves are electromagnetic waves that travel in the direction $E_1$ perpendicular to $B_0$ and are partly transverse and partly longitudinal. The waves become elliptically polarized rather than plane polarized when the electric field $E_1$ becomes perpendicular to the magnetic field $B_0$. As these waves propagate in the plasma, they generate an $E_x$-component along the wave vector $\vec{\boldsymbol{k}}$, making them partially longitudinal and partly transverse. Due to the presence of static magnetic field perpendicular to the wave, vector and oscillating magnetic field of electromagnetic wave allow the wave to propagate in a plasma whose density is above a critical value [14].

### 3.3.4. Whistler Wave

Whistler waves are intermediate frequency plasma waves with their frequency ranging between $\Omega_{LH} < \omega < \Omega_{ce}$, where $\Omega_{LH}$, $\Omega_{ce}$ are the lower hybrid and electron cyclotron frequencies, respectively. In solar-terrestrial processes, these waves are critical for controlling electron energy [7,9,15]. Whistler waves are created during thunderstorms and are steered along the earth's magnetic field via ducts to magnetic conjugate sites. They are known as short whistlers when they are discovered at this phase. Short whistlers can be reflected and steered back to their original location, which is known as a long whistler [3,16]. According to results of magnetohydrodynamic, the whistlers can be defined on time scales of $(2\pi / \Omega_{ce}) < t < (2\pi / \Omega_{LH})$ and spatial scale of $L < \lambda_i$. The ions here are assumed to be motionless neutralizing background. The whistler wave follows the dispersion relation [7]:

$$\omega = \lambda_e^2 \Omega_{ce} k^2 \cos\theta \quad (18)$$

### 3.3.5. Alfven waves

The Alfvén wave is a low frequency wave mode of magnetized Plasma [2,17]. Considering a magnetic field of intensity $B_0$ and the magnetic stress equal to the tension $B_0^2 / \mu_0$ along the magnetic field lines. The isotropic hydrostatic pressure, given by, $B_0^2 / \mu_0$ is combined with the kinetic fluid pressure. The plasma particles act as though they are tethered to the magnetic field lines, causing the force lines to behave like mass loaded strings under strain. When magnetic field lines are perturbed from their equilibrium position, they vibrate transversely [3,18,19]. As a result, ions in a plasma oscillate in response to the restoring force generated by magnetic field line tension [23,24]. These waves propagate in non-uniform plasmas in real life. This allows them to be reflected, transmitted, or absorbed. The amplitude of Alfvén surface wave eigenmodes decays roughly exponentially in each direction away from the surface [21,22]. These waves are crucial for heating and transmitting energy in laboratory, space, and astrophysical plasmas. [2,6,20]. The dispersion relation is given by the equation:

$$\omega^2 = k^2 v_A^2 \quad (19)$$

Where, $v_A$ is the Alfen velocity given by:

$$v_A = B / \sqrt{\mu_0 \rho} \quad (20)$$

Where, $B$ is the applied external magnetic field, $\mu_0$ is the permeability of vacuum, $\rho$ is the mass-density [2].

## 4. INSTABILITIES IN PLASMAS

Instabilities in Plasma refer to those regions in the space where some kind of turbulence occurs due to the change in plasma properties like density, electric field, temperature, etc. [7].

Fig. 2 shows the schematic of the instabilities in Plasma that can be stimulated by propagating electromagnetic waves through Plasma. Investigations on such instabilities are comprehensively documented.

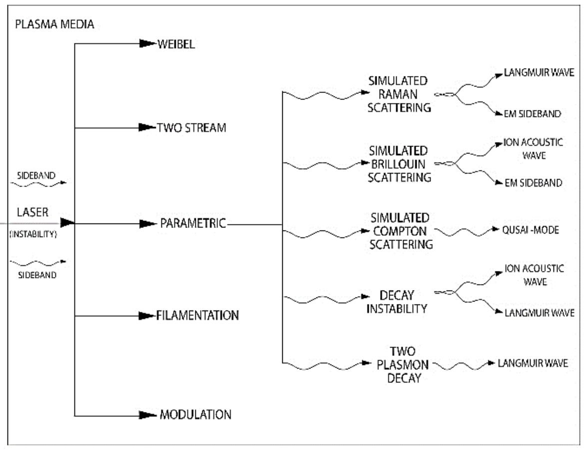


**Fig. 2.** The instabilities stimulated due to propagation of electromagnetic waves in plasmas.

### 4.1. Weibel Instability

Weibel instability occurs inhomogeneous Plasma when there is an anisotropy in momentum space. In other words, Weibel instability is a superposition of counter streaming waves. Weibel instability is almost similar to two-stream instability with the difference that in Weibel instability the disturbance is electromagnetic which leads to filamentation [7] whereas in two-stream the disturbance is electrostatic, which results in charge accumulation [25].

In standard limit, Weibel instability causes exponential growth of Electromagnetic fields in Plasma leading to restoration of momentum space isotropy.

### 4.2. Two-Stream Instability

Two Stream instability occurs when the main two components of Plasma, i.e., ions and electrons start to move with different drift velocities. Such situations can be created by inducing high velocity particles or by setting a current along the Plasma. When these high energy particles collide with the components of the Plasma due to the size difference, the electron gets more excited and starts moving with higher velocity than ions which are far bigger in size than the electron. Because of this reason, there is a net change in the drift velocity of the electrons and ions leading to this instability. In two-stream instability, when an electron stream is injected to the plasma, the particles' velocity distribution function has a bump (cf. fig. 3).

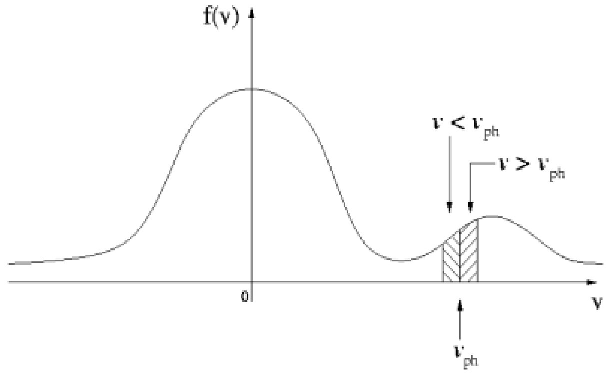


**Fig. 3.** Velocity distribution function of Plasma [27].

$v_{ph}$ represents the wave drift velocity of the wave and $v$ is velocity of a specific section of a wave. When $v = v_{ph}$ slope is positive, there is a greater number of faster particles than slower particles, which means there is a greater amount of energy being transferred from the fast particles to the wave. This phenomenon is giving rise to exponential wave growth [26].

### 4.3. Filamentation Instability

The growth of filamentation instability is triggered when a diluted cold electron beam passes through a cold plasma [28]. The disintegration of an incident Electromagnetic wave into two high frequency Electromagnetic waves, dispersed due to the connection of the incident laser wave with the ion-acoustic mode of the Plasma, is known as filamentation instability [7, 29]. Due to filamentation, various variations can be seen in the environment of the Plasma. The nonlinear processes such as stimulated Raman scattering and Brillouin scattering result from filamentation processes [29].

### 4.4. Modulational Instability

When an intense laser pulse is made to go through ionized Plasma, the refractive index gets altered. Due to this process, a critical interaction arises known as Modulation interaction. This interaction causes a non-linear shift in the group velocity of the laser pulse. This shift occurs such that it leads to spatial modulation of the wave amplitude, hence leading to modulation instability [30]. In general, modulation instabilities are caused by the interplay between (anomalous) group velocity dispersion and self-phase modulation [31].

### 4.5. Parametric Instability

Parametric instability is a common form of wave-wave interaction which can also be seen in nonlinear resonances like in plasma sheath. This instability occurs when a nonlinearity couple waves. A very common parametric wave instability arises from the decay of a strong electromagnetic wave, the "pump", into two electrostatic waves, an electron plasma wave and an ion acoustic wave. It is called a "decay" instability when the pump excites a lower frequency sideband, the electron plasma wave, and the ion-acoustic wave's difference mode. These three modes are the only ones in an unmagnetized plasma [7, 32].

#### 4.5.1. Stimulated Raman Scattering

Raman scattering is the nonlinear excitation of perturbed waves in resonance with the coupled waves' beat frequency [7], [33]. Stimulated Raman Scattering (SRS) is one of the most well-known instabilities in inertial confinement fusion [33]. The pump electromagnetic wave excites a Langmuir wave and sideband wave [3].The daughter electromagnetic wave can elude the Plasma and manifest as an increased dispersion of the original electromagnetic wave [7], [33].

#### 4.5.2. Stimulated Brillouin Scattering

Simulated Brillouin Scattering (SBS), like Raman scattering, is a non-linear excitation of disturbed waves that fluctuate in resonance with the linked waves' beat frequency. When the requirement of resonance for energy and moment is met, the SBS process involves the coupling of a high amplitude electromagnetic wave, a dispersed electromagnetic wave, and an ionic acoustic wave [35]. Ion acoustic waves in SBS have a substantially lower frequency than Langmuir waves in SRS [7, 36]. In general, electrostatic and pressure factors impact the ion acoustic wave, although electrostatic terms dominate for SBS [36]. The resulting electron density fluctuations modulate the transverse current induced by the pump, scattering energy into the seed and producing an amplified seed pulse with central frequency down-shifted by the ion wave frequency [36].

#### 4.5.3. Stimulated Compton Scattering

When the nonlinear forces of Plasma interact with the plasma-charged particles instead of the coherent waves, it results in simulated Compton electron instability [7, 37]. When an intense electromagnetic wave is scattered by bare matter particles, simulated Compton scattering instability is induced. The condition for such scattering is that the nonlinear force either has a small spatial period compared to electron Debye length or a larger frequency as compared to the screening time. The energy absorbed by the Plasma depends on the frequency difference between the pump wave and reflected wave [7, 37].

#### 4.5.4. Decay Instability

The decay in which an incident electron plasma wave scatters off fluctuations in plasma density and decays into an ion acoustic wave and a secondary electromagnetic wave is called Langmuir decay. The scattering process becomes unstable for sufficiently small damping of electron plasma wave and ion-acoustic wave. This results in continuous energy transfer from the incident wave to the scattered waves. If the electron plasma wave is itself a result of unstable parametric decay process, then Langmuir decay instability saturates the growth. The amplitude of the incident electron plasma wave plays a vital role in determining the growth rate of decay instability. [7, 38]

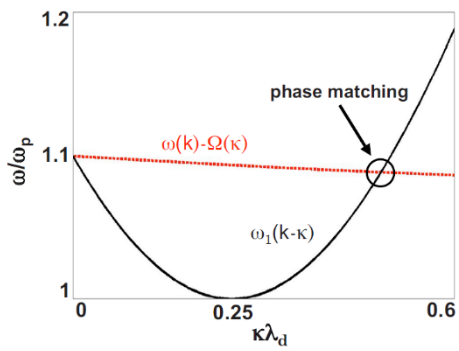


**Fig. 4.** Phase matching for the Langmuir decay in one dimension [38].

#### 4.5.5. Two-Plasmon Decay

The paramagnetic decay of electromagnetic waves into two electrostatic plasma waves is called the two plasmon decay. This instability occurs in the corona region of the Plasma. The conversion of electromagnetic waves to electron plasma waves occurs at electron density $n_e$ equal to one fourth of the critical density of the EM wave [39,40]. The Two plasmon decay instability results in the Langmuir wave and $\omega_0$ radiation spectra which happen to be in semi-quantitive agreement as per Meyer [3].

## 5. CONCLUSION AND FUTURE WORK

The fourth state of matter, plasma, is made up of a vast number of charged particles that reach overall charge neutrality. Plasma is capable of sustaining a wide range of waves. The many sorts of waves maintained by magnetized and non-magnetized plasmas were explored in this work. Frequency, wave number, and polarization all affect the waves. By dampening in amplitude, energy is transferred from waves to plasma particles. Instabilities in plasma are areas where turbulence arises as a result of changes in plasma parameters such as density, electric field, and temperature. Many different forms of instabilities exist, including Weibel, two-stream, filamentation, modulation, decay instability, and so on.

Plasma has a wide range of uses, some of which are worth exploring here. The magnetohydrodynamic energy generator (MHD) uses electricity to transform the kinetic energy of a dense plasma moving through a magnetic field. Plasma propulsion systems for rocket engines are based on a process that converts electricity into Plasma kinetic energy, which is the polar opposite of the MHD generation process and many others, which are primarily used in the medical field for the treatment of various types of tumors such as skin, head and neck, blood, cervical, and others[3]. Plasmas are employed in biomedical applications for disinfection and sterilization of various medical devices [41]. Plasma's employment in such procedures makes work far more accessible and practical. Plasma is also employed in controlled thermonuclear fusion, where it is contained in a Tokamak, a toroidal chamber.

The energy and momentum of electromagnetic waves emitted by antennas may be separated into linear and angular momentum. The angular momentum can be divided into spin and orbital angular momentum. The circular and elliptical polarization associated with spin momentum can be utilized to send two different signals on the same frequency over a long distance. However, it is presently claimed that by modulating particular modes utilizing the angular momentum property, it is feasible to broadcast signals on the same frequency. Twisted Waves [42] is the name for this. Because the number of modes that may be transmitted in an unbounded medium is almost infinite, communication based on these independent modes would substantially boost the information-carrying capacity of a frequency band, revolutionizing the wireless communications industry [42].

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