



A Study on Instabilities and Nonlinear Wave Energy Exchange Process in Terrestrial Ionospheric Plasma

S. J. Gogoi^{1*}

¹Department of Physics, Tinsukia College, Assam-786125, India.

Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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ABSTRACT

From ground and satellite based observatories, various forms of nonlinear effects and plasma waves instabilities are observed in the Earth's ionosphere. In this paper we present a brief review on nonlinear wave-particle interaction energy exchange mode *plasma maser instability* and on probable growth rate of high frequency non-resonant waves at different regions of the Earth's ionosphere.

Keywords: Ionospheric plasma; wave-particle interaction; plasma maser effect; growth rate.

1 INTRODUCTION

Initially, research on ionospheric physics was focussed on origin of the ionosphere, its different layers and variability of its physical parameters with local time, latitude, and seasons; and on radio wave propagation. For development of experimental based observatories and theoretical frameworks, current ionospheric research is mainly concerning on dynamics of

this region and on ionospheric plasma physics [1].

In 1901 after successfully transmitted radio signals across the Atlantic, G.Marconi had experimentally established existence of electrically conductive layer in the upper terrestrial atmosphere and in 1902, a theoretical model of this medium was put forwarded by O. Lodge [2]. The name '*Ionosphere*' was proposed

*Corresponding author: E-mail: satyajyotitsk@gmail.com;

by R.A. Watson-Watt for this layer in a letter to the United Kingdom Radio Research Board [3].

By using ground based and with rocket and satellite based observatories combined with remote sensing data, pictures of terrestrial ionosphere were obtained for different aspects [4, 5, 6, 7]. In presence of sources of ionizations, upper atmosphere of Earth has a weakly ionized ionospheric zone. Range of ionospheric altitude of the Earth starts from about 50 km to 1000 km. Characteristics of this region are known by reflection and refraction properties of electromagnetic wave. Major ingredients of this radio wave reflected region are electrons ($< 1eV$), ions and few neutral particles. In daytime, Earth's ionosphere ionization occurs mainly from solar photons of *extreme ultraviolet* and ultraviolet wavelength range ($10 \times 10^9 m - 100 \times 10^9 m$). Energetic precipitating charged particle fluxes ($\geq 1KeV$) which are coming from the sun, the galaxy, the magnetosphere and additionally local accelerated charged particles, are taking part in this upper atmospheric region to produce ionization by coulomb collisions. Behaviour of this partially ionized open system is controlled by processes and external entities like diffusions, chemical reactions, turbulences, instabilities, confining fields like electric and magnetic fields, gradients of pressure, temperature, density and so on [8, 9, 10].

Earth's ionospheric region can be characterised as a weakly collisional or collisionless, low plasma beta and cold plasma. Long term stability, lack of confinement walls, constant circulating around the Earth and wide region of parameter space are few major characteristics of ionospheric plasma. In this region, interactions among electrostatic and electromagnetic resonant and non-resonant plasma modes and with plasma particles may develop different types of instabilities [5, 11].

For theoretical and experimental investigations on wave-wave and wave-particle interactions on various observational nonlinear phenomena and instabilities in different regions of Earth's ionosphere, ionospheric plasma can consider as a natural laboratory to gather better understanding of the upper atmosphere. Due

to low plasma graininess parameter ($g \rightarrow 0$) in the Earth's ionosphere, it is contemplating ionospheric plasma as collisionless and the collective effects are dominating the whole system [12].

In presence of energy and momentum fluxes from diverse free energy sources, inhomogeneities are developed in the ionosphere due to spatial gradients of physical parameters like density, temperature, pressure etc. Perturbations are taking place in equilibrium state and for the growth of these perturbations, plasma system become unstable and can accumulate energy. To redistributing this accumulated energy, plasma instabilities are the general way leads to transitions, of this nonequilibrium thermodynamical state and turbulence [5, 13, 14].

In nonuniform ionospheric plasma, both electrostatic plasma waves, like ion sound wave [15, 16], lower hybrid wave [1], Langmuir wave [17, 18, 19, 20], drift wave [1, 21], and electromagnetic plasma waves, like O-mode [16, 22, 23], are prevailing. These plasma waves can perturb physical properties in the ionosphere. As a result, large scale macro-instabilities and small scale micro-instabilities are observing in different altitudes and regions of the ionosphere. It had been found that ion sound instability, beam driven instability and cyclotron maser instability at auroral ionosphere, lower hybrid instability at E- and F- layers of ionosphere, universal drift instability for all kinds of electrostatic and electromagnetic plasma waves at all conditions in ionosphere, wind-driven instability and Perkins instability at E-regions, Kelvin-Helmholtz instability at F-regions, $\vec{E} \times \vec{B}$ instability and auroral electrojet instability at high latitude ionosphere; were observed [1, 14].

Nonlinear effects and turbulences are observing in nonlinear ionospheric plasma for the energy exchange among collective modes and among plasma particles and plasma waves. According to weak turbulence theory, 3- types of nonlinear interactions are occurring in wave energy exchange process in plasma medium which are wave-wave interaction, wave-particle interaction and wave-particle-wave interaction respectively. In this study, we concern only on nonlinear wave-

particle energy exchange process in momentum space.

In 1976 Ronmark and Stenflo [24] had explained generation mechanism of high frequency plasma waves in presence of low frequency waves via waves- particles interaction through the theory of plasma turbulence. In 1983, Nambu [25] had studied on nonlinear interactions of waves and particles and this study had formed the foundation of plasma maser effect. Wave energy up conversion of high frequency waves takes place through this effect and it is a high frequency modes and low frequency modes coupling effect.

Nambu [25] also had proposed a modulated electric field which was developed due to nonlinear coupling between high frequency and low frequency plasma modes and plasma particles were accelerated by the modulated electric field through a nonlinear force. These accelerated resonant particles transfer their energy to the high frequency non resonant modes. From this effect, unstable radiation phenomena are possible in presence of macroscopic inhomogeneity of density gradient, temperature anisotropy, pressure gradients and magnetic field gradients [26] and the efficiency of wave energy up conversion through this effect decreases as difference in wavelengths increases [27].

In Space Physics, plasma maser effect had explained generation mechanism of ULF modulated ELF emissions , Auroral kilometric radiation(AKR),Chorus related electrostatic

bursts, Whistler mode in the solar wind and Type III solar radio bursts [28, 29, 30]. To explain Jupiter's narrow band kilometric radiation , in 1989 Khound et al.[31] had explained this with the help of plasma maser instability and had taken interaction between non-resonant O-mode radiation with resonant ion cyclotron wave. There are other reports on wave energy enhancement of high frequency waves like Berenstein mode [32], ion acoustic wave [33], electromagnetic O-mode [34] in presence of drift wave turbulence in inhomogeneous magnetically confined plasma through plasma maser effect. In 2018, Deka et al.[35] had investigated through this maser effect on amplification of ion acoustic wave in presence of drift wave turbulence in Tokamak plasma.

To explain different types of radiation emission phenomena and plasma waves instabilities which are observing at different altitudes in terrestrial ionospheric plasma , are attempting theoretically by both linear and nonlinear methods. In nonlinear theoretical model, nonlinear mode-mode couplings are dominating interactions in wave - energy exchange process for plasma waves instabilities. To investigate wave amplifications of plasma waves and its energy enhancement, plasma maser instability is one of the prominent nonlinear wave-particle interaction energy transfer modes in both astrophysical and tokamak plasma environment. In this study, we present a briefer review on probable growth rate of high frequency plasma waves at some regions of the Earth's ionosphere through plasma maser instability.

2 THEORETICAL ANALYSIS ON WAVE ENERGY UPCONVERSION IN IONOSPHERIC PLASMA

For theoretical investigation on plasma maser instability, governing equations are

$$\left[\frac{\partial}{\partial t} + \vec{v} \cdot \frac{\partial}{\partial \vec{r}} - \frac{e}{m} \left(\vec{E} + \frac{\vec{v} \times \vec{B}}{c} \right) \cdot \frac{\partial}{\partial \vec{v}} \right] f_j(\vec{r}, \vec{v}, t) = 0. \quad (1)$$

where f_j is particle distribution function for jth species particles in phase space. Equation (1) is Vlasov equation which was introduced by A.Vlasov in 1945 and L.D.Landau in 1946 to study collective behavior and instabilities of collisionless plasma.

$$\vec{\nabla} \cdot \vec{E} = -4\pi n_j e_j \int f_j(\vec{r}, \vec{v}, t) \cdot d\vec{v}. \quad (2)$$

Equation (2) is Poissons equation for electrostatic plasma waves to calculate mean self-consistent electric field by using charge density.

$$\vec{\nabla} \times \vec{E} = \frac{1}{c} \frac{\partial \vec{B}}{\partial t}. \quad (3)$$

$$\vec{\nabla} \times \vec{B} = \frac{1}{c} \frac{\partial \vec{E}}{\partial t} + \frac{4\pi}{c} \vec{J}. \quad (4)$$

Equations (3) – (4) are Maxwell's equations for electromagnetic plasma waves to calculate electromagnetic field by using current density.

To determine fluctuating parts of a distribution function in presence of modulating and modulated fields due to nonlinear modes-modes interactions, and to derive dispersion relation and growth rate, usually method of characteristics [36], Fourier transforms, complex residue integration, Bessels recursion relations, Dirac Delta functions, random phase approximations and causality principles are using. But the major disadvantage of these complicated and lengthy calculations is that exact solutions are not obtained due to nonlinearity and non-locality of the plasma medium.

Gogoi and Deka [37] had studied on probable amplification of electromagnetic O-mode in presence of low frequency ion sound wave turbulence by plasma maser effect in the ionosphere regime. For this problem, spatial inhomogeneity of density was taken in nonuniform Earth's ionosphere. After lengthy and complex calculations, the approximate expression of growth rate for electromagnetic O-mode was found as

$$\frac{\gamma_p}{\Omega} = \sqrt{\pi} \left(\frac{\omega_{pj}}{\Omega_j} \right) \left(\frac{e_j}{m_j} \right)^2 \frac{1}{v_j^2} \frac{k_{\parallel}^2}{K_{\perp}^2} \frac{1}{(\Omega_j - \Omega)^2} \exp \left(- \left(\frac{\omega}{k_{\parallel} v_j} \right)^2 \right). \quad (5)$$

where ω_{pj} is charged particle plasma frequency, Ω_j is charged particle gyrofrequency, Ω is nonresonant electromagnetic O-mode frequency, k_{\parallel} and K_{\perp} are propagation vectors of low frequency resonant and high frequency nonresonant waves which are parallel and perpendicular directions of magnetic fields respectively. With the help of observational data on the plasma parameters, O-mode plasma wave characteristics in space, ion sound wave and ionospheric parameters from ROSE satellite observations and other sources [38, 39, 40, 41], the approximate growth rate for O-mode from equation (5) was found as $\frac{\gamma_p}{\Omega} = 10^{-5}$. In this investigation it had been established that high frequency O-mode was amplified in presence of ion sound wave in ionospheric plasma due to wave-particle interaction through plasma maser effect.

In another study [42] it was examined wave energy upconversion of electrostatic nonresonant lower hybrid wave through plasma maser instability in the mid-altitude Earth's ionosphere in where both gradients in density and magnetic field were taken in presence of drift wave turbulence. The dispersion relation of nonresonant lower hybrid wave in presence of drift wave was found as

$$\Omega^2 - \omega_{ce}\omega_{ci} = i \frac{F_{Nhz}}{m_j (\omega_{ce}^2 - \omega_{ci}^2)}. \quad (6)$$

where ω_{ce} and ω_{ci} are electron and ion cyclotron frequency respectively and F_{Nhz} is high frequency nonlinear effective force. Approximate growth rate expression of nonresonant lower hybrid wave was found as

$$\frac{\gamma}{\Omega} = e_j n_{j0} \left(\frac{e_j}{m_j} \right)^2 \left(\frac{m_j}{k_B T_j} \right) \frac{K_{\parallel} (K_{\parallel} - k_{\parallel})}{m_j (\omega_{ce}^2 - \omega_{ci}^2)} \frac{k_{\perp}}{k_{\parallel}^2} \frac{\omega_{pj}^2}{\Omega_j^3 (\Omega_j - \Omega)} E_{i\parallel}^2 \frac{\epsilon'}{\Omega_j} \exp \left(- \left(\frac{v_d}{v_j} \right)^2 \right). \quad (7)$$

Using observational data of lower hybrid waves, drift waves and plasma parameters in space [43, 44, 45, 46] and considering density gradient $\epsilon' = 0.1$ in equation (7), the probable growth rate of lower hybrid wave was found as $\frac{\gamma}{\Omega} = 10^{-5}$.

In another problem [47] probable amplification of electrostatic Langmuir wave was studied in presence of lower hybrid waves turbulence in polar ionospheric plasma, neglecting gradients parameters.

Observation of radiation emission phenomena responsible for nonlinear stimulating processes in this zone can lead to interesting theoretical investigations on different aspects. The approximate growth rate expression for Langmuir wave due to plasma maser effect was found as

$$\frac{\gamma}{\Omega} = \frac{\sqrt{\pi}}{2} E_{i\parallel} \frac{E_{i\parallel}}{4\pi n_j T_j} \left(\frac{e_j}{m_j} \right)^2 \frac{\omega_{pj}^4}{\Omega^2(\Omega^2 - \Omega_j^2)} \frac{k_e^2 K_{\parallel}}{k_{\parallel}^2(K_{\parallel} - k_{\parallel})} \left(\frac{v_{lh}}{v_e} \right) \exp \left(- \left(\frac{v_{lh}}{v_e} \right)^2 \right). \quad (8)$$

The term $\frac{E_{i\parallel}}{4\pi n_j T_j} \frac{k_e^2}{k_{\parallel}^2}$ represents low frequency turbulence wave energy and it indicates possibility of wave energy enhancement of Langmuir wave at the expense of low frequency lower hybrid wave turbulence energy. Using observational data from Freja satellite observations at topside polar ionospheric regions and from other sources at the Earth's near space region [48, 49, 50], the probable growth rate was found as 10^{-2} which indicates wave energy enhancement of Langmuir wave.

3 DISCUSSION

Information on nonlinear phenomena in ionospheric plasma are evident from spectra of reflected waves in experimental observations and it appears that mode conversion and wave energy upconversion are possible mechanisms for these responses [1, 51, 52, 53, 54, 55].

After investigation on amplified radiations in top ionospheric regions of Earth, Mellot et al.[22] had proclaimed that auroral kilometric radiation was composed of electromagnetic plasma radiations. Generation of high frequency electromagnetic O-mode wave and low frequency ion sound wave in the upper ionosphere region were mentioned in several studies [16, 22, 23]. Interaction between plasma particles and ion sound plasma waves in the ionospheric zone was discussed by Kantor et al.[15].

In the mid-altitude ionospheric plasma, gradient drift instability and temperature drift instability had observed from satellite observation during turbulent geomagnetic field conditions [56]. Kelly had observed that at the mid altitude inhomogeneous ionospheric region, different entities like gravity waves, shear effects, drift waves and lower hybrid waves were contributed in turbulence processes [1].

In the polar ionosphere region presence of Langmuir turbulence was pointed out in several studies [17, 18, 19, 20]. Utlaut had studied on enhancement of Langmuir waves in the ionospheric F-layer in 1970 and its discussion was important for future perspective in the collisionless magnetospheric plasma to describe non-linearities of turbulent plasma [57, 58]. In

the auroral ionosphere, the generation of electric field amplitude modulations of Langmuir wave was observed by Ergun et al.[59]. In the topside polar ionosphere, Langmuir emission was observed by Swedish satellite Freja and had found Langmuir mode was appeared as a chain of strongly modulated wave packets[60]. Lizunov et al.[61] had discussed on wave-wave interaction between Langmuir wave and lower hybrid wave to explain Freja satellite observational data in the polar ionosphere and had found from frequency spectra-both secondary Langmuir wave and lower hybrid wave were parametrically connected.

In open nonlinear plasma, various forms of radiation mechanisms are analyzed and characterized by nonlinear theoretical models, weak turbulence theory is one of these. On the basis of quasilinear theory, nonlinear energy exchange between resonant and nonresonant modes can explain effectively through plasma maser effect in an open system where free energy sources like energetic electron flux or magnetic flux are available.

In brief the major findings in this study are plasma maser effect has demonstrated a decisive role in amplification or wave energy up conversion of nonresonant electromagnetic and electrostatic waves in presence of resonant waves in collisionless ionospheric plasma. It has been found that electromagnetic O-mode is amplified in presence of low frequency ion sound wave where the external magnetic field acts as momentum source. At mid-altitude ionosphere region, electrons which are accelerated by resonant mode drift wave turbulent field transfer

its energy to high frequency lower hybrid wave through a modulated field nonlinearly. Also due to wave-particle interaction a high frequency dissipative nonlinear force is developed which acts as driving force for the growth of nonresonant mode. At polar ionosphere, it has been found the possibility of wave energy enhancement of Langmuir wave at the expense of low frequency lower hybrid wave turbulence energy under considering only such parameters which influence may be significant to the result of the estimate of growth rate. There is other subdominant processes exist in such situations but these effects are not included in this study.

4 CONCLUSION

Earth's ionosphere is an open system in where exotic modes-modes mechanisms are registered due to entry of input energy and momenta through primary solar radiation and other external agents. From study on these nonlinear phenomena, useful information can be assembled and prove helpful for further improvement on knowledge of near-Earth space environment. On the basis plasma maser effect, such issues can be studied thoroughly in the magnetosphere and in Earth's ionospheric plasma processes and satisfactorily may give interpretation of many radiation phenomena.

Future possible extension works are, plasma maser effect may consider as one of the factors for secondary electromagnetic radiation phenomenon in top ionospheric and magnetospheric region. Temperature gradient and pressure gradient may include in the particle distribution function to get further information through plasma maser instability in enhancing the instability of plasma waves in ionospheric plasma. Also, conservative chaotic behaviours of nonlinear mode-mode interaction through plasma maser effect may be extended to inhomogeneous ionospheric plasma.

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COMPETING INTERESTS

Author has declared that no competing interests exist.

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