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Electrostatic Shock Fronts in Two-Component Plasma And Its Evolution into Rogue Wave Type Solitary Structures

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Here, in this paper, the One Dimensional Quantum Hydrodynamic (QHD) model is used to investigate electrostatic-acoustic solitary wave structures in two-component plasma (ion and electron) at some finite temperature. We derived a linear dispersion relation by perturbation expansion technique & studied the dependency of both dispersion relation and damping factor (Which is Due to Viscous Coefficient) with the Viscosity coefficient (η). Moreover, by using the reductive perturbation technique, the KdV–Burger equation has been carried out analytically & from the solution, we obtained the solitary profiles and shock fronts we also studied the parametric dependence Quantum diffraction parameter (H). Hence the evolution of rogue waves has been studied by converting the KdV-Burger equation into an NLSE.

1. Introduction

In recent times, the Physics of Quantum Plasmas/Astrophysical Plasma became a rapidly growing subject of plasma physics. There has been a huge interest in studying the different aspects of wave propagation in quantum plasma such as Ion-acoustic [1], electron-acoustic [2], Dust acoustic [3] in a two or three-component Plasma. The study of the propagation of the wave in quantum plasmas has gain importance due to its vast application in understanding the particle or energy transport phenomena on short-scale lengths i.e., in micro and nanoscale electronic devices and dense compact stars [4-10] and other interstellar objects.

In ordinary Cases, we focused only on high temperature and low density where quantum effects have no impact. But in nature, the quantum effects in plasmas become important when the Fermi temperature, which is related to the density of plasma component (electron, ion, positron, etc.) becomes equal or greater than the system's spatial scales of thermal temperature or the inter-particle distance becomes smaller or of the same order of the particle's de Broglie thermal wavelength (λ_D). This phenomenon is well observed in some Compact astrophysical objects (e.g. white dwarfs, neutron stars, magnetars, etc.)

To study the dynamics of wave in quantum plasmas we will use the quantum hydrodynamic (QHD) model [4, 5, 9]. The quantum hydrodynamic (QHD) model is derived by taking velocity-space moments of the Wigner equations the same as the classical fluid model. it consists of a set of equations describing the transport of charge, momentum, and energy in a quantum charged particle system interacting through a self-consistent electrostatic potential. In this model, the quantum effects appear through the quantum statistical (Fermi) pressure [11] and the Bohm potential [12] (due to quantum diffraction or tunneling effects). There can be other pressure forms like relativistic pressure [13-14], even certain other effects due to thermal anisotropy may arise [14], as a result of such anisotropy violation of the incompressibility of fluid in phase space can be theorized [15]. The QHD is useful to study the collective effects on microscale lengths and has its limitation that is large compared to the Fermi Debye lengths of the species in the system. For example, it may lead to the generation of new wave modes in plasma [16]. For simplicity, straightforward approach, and numerical efficiency the QHD model has been widely used [17-24]. For the first time a detailed study of ion-acoustic waves was done by Haas et al. [4-5] Gardner and Ringhofer [17] has studied the electron-hole dynamics in semiconductors. Using the same model Shukla and Eliasson [18] have studied the dynamics and formation of dark solitons and vortices in quantum plasma. It has also been used to study the Korteweg deVries (KdV) solitary wave structure for ion-acoustic waves [19, 20], electron-acoustic waves [21], dust-acoustic waves, and dust ion-acoustic waves [22, 23].In recent days we have studied the effect of quantum diffraction on the electron plasma waves and it has been found that quantum effects can significantly modify the modulation instability conditions and the instability growth rates of finite-amplitude electron plasma waves [24].

There are also some works on Electrostatic shock fronts [25].The family of K-dV equations and the non-linear Schrödinger equation (NLSE) along with their variants used to interpret and explore a variety of non-linear phenomena observed in non-linear systems, such as the ocean, water tank, space, and astrophysical plasmas as well as in laboratory experiments [26]. The reductive perturbation technique has been used to derive the KdV family of equations, which describes the evolution of a non-modulated (non-envelope) waves. On the other side, the NLSE governs the dynamics of a modulated (envelope) wave packet [27] in a way that the non-linearities are in balance with the wave group dispersion relation resulting in the stationary solutions with an envelope-like structure.

Experimental observations of the modulational instability of the monochromatic ion-acoustic wave first time reported by Watanabe [28]. Now from the concept of NLSE, we studied the evolution of the Rouge wave in Dense Plasma. Rogue waves are unexpectedly high-amplitude single waves [29]. Rogue waves can appear both in the open ocean and in coastal areas [30]. The physical difference in the two cases is the depth of water. Deepwater waves are commonly described by NLSE [31]. Shallow water waves are described by the KdV equation [32, 32]. There are some other model equations for shallow water waves, such as the modified KdV (mKdV) [34] and Camassa–Holm [35] equations. The mKdV equation is also used in the analysis of optical soliton propagation [36]. Solutions of KdV and mKdV equations are related through the Miura transformation [37]. The first mathematical description of NLSE to rogue waves was given in [38]. It was suggested that rogue waves are the solutions of nonlinear evolution equations that are localized both in space and in time. As an example of such treatment, the two lowest order doubly localized solutions of the nonlinear Schrödinger equation (NLSE) were given in [38]. The lowest order solution is called "Peregrine" which is a rational solution and can be independently considered as a prototype of an oceanic rogue wave in [39].

There are lots of works on this topic[40-60] but it this paper using the one-dimensional quantum hydrodynamic (QHD) model for two-component electron-ion dense quantum plasma we have studied the linear and nonlinear properties of a plasma wave mode (Electrostatic Mode) as well as the evolution of rouge wave inside the dense quantum plasma. Here the paper is organized in the following pattern. In [Section-2] "Basic equation" section, we set our governing equations and with proper normalization & simplified them. In the next sections [Section-3], we obtain the "Linear Dispersion relations" [3.1], "KdV–Burger's equation and Shocks and solitary formation"[3.2], and " NLSE "[3.3]. In [Section-4] we analyze the results from them & discuss the result with associated figures.

2. Governing Equations

We consider a one-dimensional quantum hydrodynamic QHD model to describe the dynamics of electron plasma waves in a two-component homogeneous plasma consisting of electrons and ions. With a streaming motion along the x-axis experiencing viscous effects. We assume that the plasma particles behave as a one dimensional Fermi gas at zero temperature and therefore the pressure law [61] is

$$P_j = \frac{m_j V_{Fj}^{\;2}}{3 n_{j0}^{\;2}} n_j^{\;3} \tag{1}$$

Where j=e for electron and j=i for ions, m_j is the mass, $V_{Fj} = \sqrt{2K_B T_{Fj} / m_j}$ and $K_B$is the Boltzmann constant. n_j is the density with the equilibrium value n_{j0}. For Electrostatic mode QHD equations governing the dynamics of plasma waves in two-component (e-i) plasma are given by

$$\frac{\partial(n_e)}{\partial t} + \frac{\partial(n_e u_e)}{\partial x} = 0 \tag{2}$$

$$\frac{\partial(n_i)}{\partial t} + \frac{\partial(n_i u_i)}{\partial x} = 0 \tag{3}$$

$$\left(\frac{\partial}{\partial t} + u_i \frac{\partial}{\partial x}\right) u_i = \frac{1}{m_i}\left(Q_i \frac{\partial \varphi}{\partial x} + \eta_i \frac{\partial^2 u_i}{\partial x^2}\right) \tag{4}$$

$$0 = \frac{1}{m_e}\left(Q_e \frac{\partial \varphi}{\partial x} - \frac{1}{n_e}\frac{\partial P_e}{\partial x} + \frac{\hbar^2}{2m_e}\frac{\partial}{\partial x}\left[\frac{1}{\sqrt{n_e}}\frac{\partial^2 \sqrt{n_e}}{\partial x^2}\right]\right) \tag{5}$$

$$\frac{\partial^2 \phi}{\partial x^2} = 4\pi\left(Q_e n_e + Q_i n_i\right) \tag{6}$$

Where u_j, Q_j, and Pj are, respectively, the fluid velocity, charge, and pressure of the jth species, Qe=e, Qi=−Ze, Where e=-1.6×10^{-19}. $\hbar$ is Planck's constant divided by 2, η is the viscosity coefficient and ϕ is the electrostatic wave potential. We now introduce the following Normalisation

$$x \rightarrow x\omega_e / V_{Fe} \qquad u_j \rightarrow u_j / \mathrm{V}_{Fe} \qquad V_{Fe} \rightarrow \sqrt{2K_B T_{Fe}/m_e}$$

$$t \rightarrow t\omega_e$$

$$n_j \rightarrow n_j / n_{j0} \qquad \Phi \rightarrow e\Phi / 2K_B T_{Fe}$$

$$\eta_j \rightarrow \frac{\omega_e}{m_e V_{Fe}^{\,2}} \eta_j \qquad \omega_e \rightarrow \sqrt{4\pi n_{e0} e^2 / m_e}$$

Where $\omega_e \rightarrow \sqrt{4\pi n_{e0} e^2 / m_e}$ is the electron plasma oscillation frequency, VFeis the Fermi thermal speed of electrons &η_j is the viscosity coefficient. Using all the above relation we normalized the above equation (2-6) and obtained the following equations

$$\frac{\partial (n_e)}{\partial t} + \frac{\partial (n_e u_e)}{\partial x} = 0 \tag{7}$$

$$\frac{\partial (n_i)}{\partial t} + \frac{\partial (n_i u_i)}{\partial x} = 0 \tag{8}$$

$$\left(\frac{\partial}{\partial t} + u_i \frac{\partial}{\partial x} \right) u_i = \left(-\mu \frac{\partial \varphi}{\partial x} + \eta_i \frac{\partial^2 u_i}{\partial x^2} \right) \tag{9}$$

$$\left(\frac{\partial \varphi}{\partial x} - n_e \frac{\partial n_e}{\partial x} + \frac{H^2}{2} \frac{\partial}{\partial x} \left[\frac{1}{\sqrt{n_e}} \frac{\partial^2 \sqrt{n_e}}{\partial x^2} \right] \right) = 0 \tag{10}$$

$$\frac{\partial^2 \phi}{\partial x^2} = \left(n_e - n_i \right) \tag{11}$$

Where H=$\hbar\omega_e / 2K_B T_{Fe}$ is a nondimensional quantum parameter proportional to the quantum diffraction, μ=(m_e/m_i) (Electron and Ion mass ratio) and The parameter H is proportional to the ratio between the plasma energy $\hbar\omega_e$ the energy of an elementary excitation associated with an electron plasma wave and the Fermi energy$K_B T_{Fe}$. The equations (7)-(11) constitute the basic set of quantum hydrodynamic equations to be used in the investigation of the propagation of plasma waves in quantum plasma. The second term on the L.H.S of Equations (9) includes quantum statistical effect through the Pressure term. (1). the second term on the R.H.S of equations (9) is due to the viscous effect. The third term in the L.H.S of Equations (10) arises due to quantum correction of density fluctuations and this type of quantum effect is called quantum diffraction or Bohm potential.

3. Analytical Study

3.1. Linear Dispersion Relation:

To find the Linear dispersion characteristic of plasma waves we make the following perturbation expansion for the field quantities u_e,u_i,φ ,n_i,$n_e$about their equilibrium values And from the normalized equation we get the linear dispersion relation.

$$\begin{bmatrix} n_e \\ n_i \\ u_e \\ u_i \\ \phi \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ u_0 \\ u_0 \\ \phi_0 \end{bmatrix} + \varepsilon \begin{bmatrix} n_e^{(1)} \\ n_i^{(1)} \\ u_e^{(1)} \\ u_i^{(1)} \\ \phi^{(1)} \end{bmatrix} + \varepsilon^2 \begin{bmatrix} n_e^{(2)} \\ n_i^{(2)} \\ u_e^{(2)} \\ u_i^{(2)} \\ \phi^{(2)} \end{bmatrix} + \ldots\ldots\ldots \tag{12}$$

(8) ((

Assuming that all the field quantities are varying a $e^{i(kx-\omega t)}$, we get for normalized wave frequency ω and wavenumber *k*, the following dispersion relation of electrostatic plasma waves which includes quantum effects for electrons. After expanding all the substituting them in the normalized equation we get the following dispersion relation

$$\omega = ku_0 + \frac{-\eta i k^2 \pm k}{2} \sqrt{-\eta^2 k^2 + \frac{4\mu \left(\frac{H^2 k^2}{4} + 1 \right)}{1 + \frac{H^2 k^4}{4} + k^2}} \tag{13}$$

After substituting and eliminating we get a quadratic equation of ω hence from solving the equation we get the above dispersion relation. Here, the viscous term plays a very vital role. The dispersion relation has a decaying complex part in addition to the real dispersion relation. In this case, if we substitute the wave number with real plus imaginary parts given by k = k_r+ik_i , we obtain the two dispersion relations which are given by

$$\omega_r = k_r u_0 \pm \frac{k_r}{2} \sqrt{ \begin{array}{l} -\eta^2 \left(k_r^{\,2} - k_i^{\,2} \right) + \\ \dfrac{4\mu \left(H^2 \left(k_r^{\,2} - k_i^{\,2} \right) + 4 \right)}{4 + H^2 \left(k_r^{\,4} + k_i^{\,4} - 6 k_r k_i \right) + 4 \left(k_r^{\,2} - k_i^{\,2} \right)} \end{array} }$$

(14)

$$\omega_i = k_i u_0 - \frac{\eta}{2}\left(k_r^{\ 2} - k_i^{\ 2}\right) \quad (15)$$

Thus in the presence of streaming motion, we have two distinct modes of an electrostatic plasma wave On the other hand, the imaginary part gives us the damping curve which has only one mode. There is another thing to notice For a given *k*, the frequency of oscillation of the fast mode increases with *H* and u_0Thus, it is important to study the effects of streaming motion on quantum electron plasma waves. In the absence of streaming motion (u_0=0), the slow mode does not exist at all.

3.2. Kdv-Burgers Equation:

To derive the desired KdV-Burger equation describing the non-linear behavior of electrostatic Plasma waves in a two-component plasma (electron and ion) .here we use the standard reductive perturbation technique. At first, we introduce the usual stretching of space and time variables

$$\tau = \varepsilon^{3/2} t;\ \xi = \varepsilon^{1/2}\left(x - Mt\right);\ \eta = \varepsilon^{1/2}\eta_0 \quad (16)$$

Where ε is a small parameter that characte strength of nonlinearity, and M is the phase ...... of the wave. The stretching in η is due to the small variations in perpendicular directions Equations are written in terms of the stretched coordinates ξ and τ then the perturbation expansions of $u_e^{(1)}, u_i^{(1)}, n_e^{(1)}, n_i^{(1)}$ $\varphi^{(1)} \to$ being substituted. Solving the lowest order equations of ε with the boundary conditions 0 and $|\xi| \to \infty$ we get

$$u_e = \left(M - u_0\right)\varphi^{(1)} \qquad u_i^{(1)} = \frac{\varphi^{(1)}\mu}{\left(M - u_0\right)}$$

$$n_e = \varphi^{(1)} \qquad n_i^{(1)} = \frac{\varphi^{(1)}\mu}{\left(M - u_0\right)^2}$$

Going for the next higher-order terms in ε ($\varepsilon^{5/2}$) and the following the usual method (substituting all the above relations and eliminating all the higher-order term) we obtain the desired Korteweg-de Vries-burger (KdV-Burger) equation

$$\frac{\partial\varphi}{\partial\tau} + A\varphi\frac{\partial\varphi}{\partial\xi} + B\frac{\partial^3\varphi}{\partial\xi^3} - C\frac{\partial^2\varphi}{\partial\xi^2} = 0 \quad (17)$$

Where,

(18)

$$A = \frac{3\mu^2 + R^4}{2R\mu}$$

(19)

(20)

in a two-component plasma (electron and ion). The real part gives us the linear dispersion characteristic curve for two-mode (fast mode and slow mode) first mode has a phase velocity greater than the later mode. So they may be called ‘fast mode’ and ‘slow mode’, respectively

$$B = \frac{R^3}{2\mu}\left(1 - \frac{H^2}{4}\right)$$

$$C = -\frac{\eta_0}{2}$$

$$R = \left(M - u_0\right)$$

Where A is the nonlinear term, B is the dispersive term and C is the viscosity term from the equation we can see that if the viscous coefficient η_0= 0, then (17) reduces to the KdV equation with C=0. The dissipation is taken into account due to the viscous coefficient C. Now to obtain the nonlinear Characteristics of electrostatic plasma wave and evolution of solitary structure and its transformation into shocks under limiting situations we have to solve the equation. To solve the equation we use the standard method of hyperbolic tangent method. At first, we transform the independent variables ξ and τ into one variable χ as followsχ= ξ−Mτ Where M is the normalized constant speed of the wave frame and the boundary condition as ξ →∞ then $\phi \to 0; \frac{\partial^2\phi}{\partial\xi^2} \to 0$, then the KdV–B equation can be written as

$$\varphi = \frac{12B}{A}\left[1 - \tanh^2\left(\xi\right)\right] - \frac{36C}{15A}\tanh\left(\xi\right) \quad (21)$$

Now using the equation as a solution and substituting the value of A, B and C we can study the parametric dependence of the electrostatic shock waves and the solitary formation and discuss the results with special reference to space and astronomical plasma phenomena.

3. 3. NLSE & Evolution of Rogue Wave:

To study the conditions of formation and properties of envelope soliton we transform our KdV equation into an NLSE by expanding Eq. (17) into a Fourier series and thereafter following using perturbation expansion and using the stretched variables as follows. Expanding φ as a Fourier series we get

$$\varphi = \varepsilon^2\varphi_0 + \varepsilon\varphi_1 e^{i\psi} + \varepsilon\varphi_1^* e^{-i\psi} + \varepsilon^2\varphi_2 e^{2i\psi} + \varepsilon^2\varphi_2^* e^{-2i\psi}$$

Again we have to use the stretched variables as

$\theta = \varepsilon^2\tau \qquad \rho = \varepsilon[\xi - c\tau]$

Now, The complex Nonlinear Schrodinger equation of the First type

$$\left(i\frac{\partial\varphi}{\partial\theta}\right) + P\left(\frac{\partial^2\varphi}{\partial\rho^2}\right) = -Q\left(\varphi^*\varphi\right)\varphi \tag{22}$$

$$P = \left(iR - 3Bk\right) \tag{23}$$

$$Q = \left[A^2K\left(\frac{1}{3BK^2} - \frac{1}{\left(6BK^2 + i4KR\right)}\right)\right] \tag{24}$$

Now solving The NLSE we get

$$\varphi(\rho,\theta) = \sqrt{\frac{2P}{Q}}\left[\frac{4(1+4Pi\theta)}{1+16P^2\theta^2+4\rho^2} - 1\right]\exp(2iP\theta) \tag{25}$$

Now to get the spatial and temporal evolution we have to rationalize the above term. Suppose the above term can be written as

$$\begin{aligned}\varphi(\rho,\theta) &= \sqrt{\left|\frac{2P}{Q}\right|}(C+iD)\exp(2iP\theta)\\ &= Fe^{i\alpha}e^{(2i(P_1+iP_2)\theta)}\\ &= Fe^{i(2P_1\theta+\alpha)}e^{-2P_2\theta}\end{aligned} \tag{26}$$

Where F is the magnitude part $e^{i(2P_1\theta+\alpha)}$ is the phase part and $e^{-2P_2\theta}$ is the damping part now To obtain spatial and temporal evolution we have to plot F vs. ρ or θ with a dependent Parameter (i.e. H) respectively. We can also study the stability factor by the term (PQ).

4. Result and Discussions:

The parametric variations (viscosity coefficient (η) of linear dispersion expressions for this problem have been carried out graphically by keeping all the parameters fixed in a certain range. We found that the dispersion relation (13) consists of real and imaginary segments. The real dispersion relation (14) gives us the linear characteristic curve whereas the imaginary part (15) gives us the damping effect.

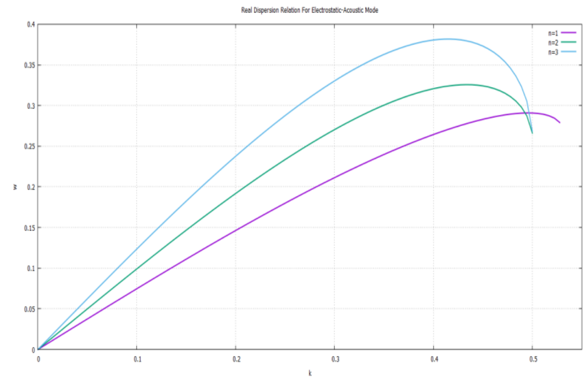

Fig 1. Real Dispersion Relation for different viscosity coefficient with(η) U_0 =0.5, $\mu = 1/1000$, H=2, K_i =0.5

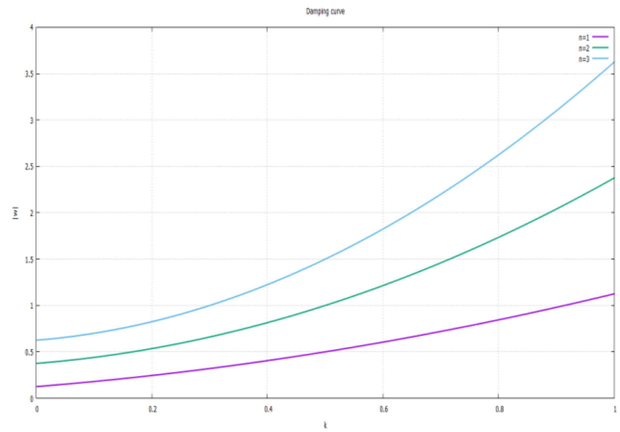

Fig-2.Imaginary part damping curve for different viscosity coefficient (η) with Uo=0.5,Kr=0.5

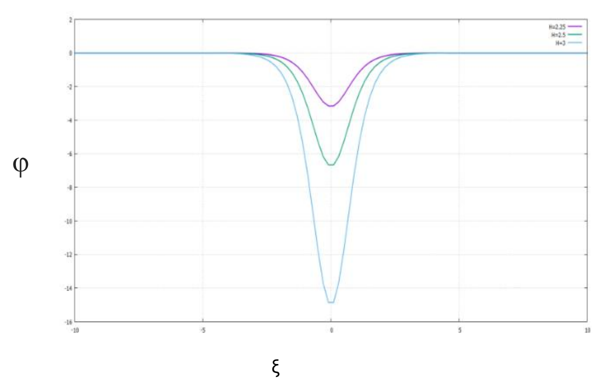

Fig-3. Solitary profile for different quantum diffraction parameter (H) Uo=0.3,ηo=1,M=1.4μ=1/1000, (H>2)

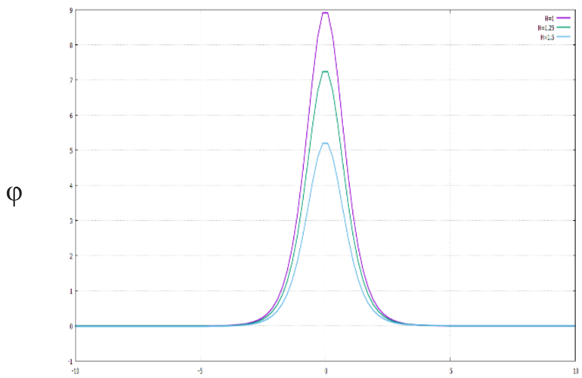

Fig-4. Solitary profile for diffe ξ ntum diffraction parameter (H) $U_o=0.3, \eta_o=1, M=1.4 \mu=1/1000$ H<2

For viscosity (Fig-1) we get a dispersion curve which shows gradually increasing nature in the high viscous range. For the imaginary part(Fig -2) we plot only the magnitude of (15) and the damping effect is shown for different viscosity coefficients (η) here increasing viscosity coefficient (η) damping rate increases as we know viscous damping cases for fluid mechanics. In the previous section, we did our discussions on the linear dispersion curve. Now we are going to study nonlinear characteristics and shock fronts .we already derived the kdv-burger equation in section 3.2 (17). Here, we have studied the parametric dependence and provide figures corresponding to expressions for shock wave formation as well as solitary structures. For changing the values of H the change is quite prominent. It is noted that for physically acceptable situations with $M > 0$ and $H < 2$ only a compressive solitary wave profile is obtained & its amplitude and width decrease significantly with the increase of H (Fig.4). Now from eq. (19) It is noted that the dispersion coefficient B vanishes at H=2 (say Hc). This critical value of H destroys the KdV-Burger equation and no solitary wave excitation can occur for this critical case. Now for M>0 and H>Hc, we obtain rarefactive solitons (Fig-3) it is clear that the amplitude and width increase with increasing H unlike H<Hc.

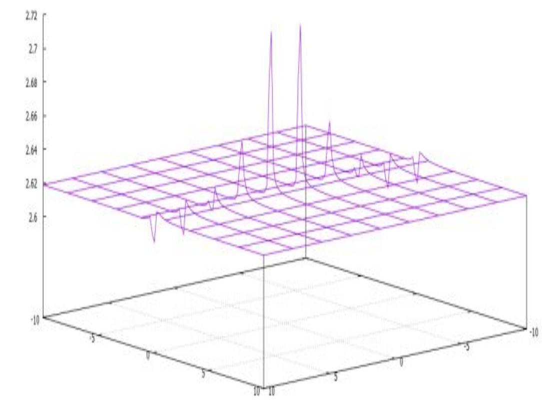

Fig-5.Spatio-temporal evolution of rogue wave in quantum plasma

Here in (Fig-5), we have shown the evolution of the rogue wave in space-time. It is noted that normally we found one peak at a time but this is something different which can be explained as below. As we know we have plotted potential in the z-axis and potential is proportional to particle density, now for highly dense particle potential is also high and due to this the quantum effect became very prominent and the amplitude level is split up in a combination of rarefactive and compressive and became symmetric.

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