Solitons in ETG Driven Magneto-Plasma with Respect to Entropy

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Abstract- The finding of the connection of plasma density and temperature with entropy provides a way for researchers to investigate different plasma models with respect to entropy. After including the entropy drift in ETG mode, linear dispersion relation and KdV equation are derived. It is noticed that entropy affects the width and amplitude of rarefactive solitons in ETG mode. It is also noticed that entropy enhances the effects of $\tau = T_{eo}/T_{io}, \eta_e = L_n/L_T,$ magnetic field B_0 and inhomogeneity drift v_{Be} on the structure of solitons. Only rarefactive solitons are found in this case. This work is novel because the plasma old results can be changed by adding the entropy in system. Also, the present study will be helpful in analysis of solitary waves in magnetically confined plasmas with respect to entropy.

Keywords- Solitons; ETG; KdV; HPM.

I. INTODUCTION

Electron temperature gradient (ETG) modes, which are considered a source of anomalous transport in fusion plasma, have become a subject of great interest in the laboratory experiments. Their nonlinear behaviour provides a good understanding of temperature gradient driven turbulence in the electron (ion) channel. Many researchers have studied ETG/ITG modes for anomalous transport [1-2]. So, anomalous transport is considered a problem of interest for confinement of plasma. The drift instabilities have got significant importance in the theory of a magnetized plasma. Many years ago, it was showed that drift instabilities are responsible for formation of regular drift structures (a train of solitons). It is studied that non-perturbative entities such as solitons bounds on entropy when the theory saturates unitarity and entropy becomes equal to the area of the soliton [3]. It was found by many researchers that the presence of ETG is a necessary condition for the formation of such structures. The ion and electron heat transport is also a problem of interest in tokamak. Simulations and experiments have showed that ion heat transport is dominated by ITG instability. Electron heat transport is calculated by fluctuations (short scale) which do not influence ion heat transport. The theories (linear and nonlinear) of ETG mode are thus of interest in plasma field. Many researchers have studied different types of drift wave instabilities to settle the plasma confinement problem. An important dispersion relation is derived by Shukla for low frequency electrostatic waves in ETG mode [4.] In plasma, structures like solitons, vortices and shocks play significant role in heat, mass and momentum transport [5-6]. Solitons were proposed to be studied as solutions to non-linear equations of motion. In quantum magneto electron-positron and ion plasma, such nonlinear structures were discussed [7]. A nonlinear equation in ETG mode in-homogeneous plasmas was derived and they found the shock like structures [8]. The ETG gradients are found necessary for formation of drift solitons [9]. The formation of solitons and shocks in ITG mode was discovered [10]. Short-wavelength drift solitons with cold electrons were also investigated [11]. The formation of solitons in ITG mode, derivation of KdV equation and solution of KdV equation bu HPM technique were presented [12].

Due to gradients in entropy, entropy has significant importance in transport of mass, momentum and energy. In ETG mode, the entropy effect on anomalous transport was discovered [13]. Entropy was found experimentally in 1989 [14]. The dependence of shear viscosity on entropy density was found [15]. Different aspects of entropy are investigated by many authors [16-20]. Fluctuations and associated transport in non-equilibrium systems are problems of interest. The importance of entropy for nonlinear structures in η_i mood was investigated [21]. Entropy mode can support anomalous heat flux [22]. Traveling solitary waves, or solitons and other topological defects were already approached in the context of the configurational entropy [23-25]. The entropy production in plasma due to radio-frequency heating is evaluated in kinetic model [26]. The different terms of the entropy production are analyzed to reveal the rate of entropy change due to different process in plasma. Pressure and entropy changes in the flow-braking region during magnetic field depolarization was investigated [27]. Entropy, more than any other physical quantity, has led to various, and sometimes contradictory interpretations [28]. Entropy-related approaches to find long-time steady states of turbulent or chaotic plasma systems are also briefly reviewed [29]. Non-conservation of entropy can result from turbulent transport, magnetic reconfiguration, energizations and thermal energy transport in space plasmas. Due to robust variational principles for prediction of the behaviour of fusion plasmas, we expect entropy-based methods are important.

Recently, the study about soliton formation in ETG mode was published [30]. Also, the entropy effect on nonlinear structures (solitons and shocks) was investigated [31-32]. Since entropy relation $S(n,T)=c_v\, log(P/\rho)$ shows that entropy has relation with plasma temperature T, density n and pressure P [31-32]. Therefore, variation in values of T and n would change the entropy. If we take temperature only from entropy then it means we are ignoring some effects of n and P. Motivated by aforesaid theory, it is better to study the entropy effect on solitary waves in ETG mode. Section II contains basic equations and linear dispersion relation is derived here. The nonlinear analysis (derivation of KdV and its solution by HPM) is also in this section. The effects of plasma parameters on drift solitons are discussed in section III, while section IV is for conclusion.

II. Basic Model Equations

We assume an electron-ion plasma embedded in a uniform external magnetic field $B_0=B_0\hat{z}$. The gradients of unperturbed electron temperature $T_{e0}(x)$, electron number density $n_0(x)$ and a magnetic field $B_0(x)$ are taken to be along x-axis. We consider electrostatic fluctuations for which $E=-\nabla\phi$. The frequency of ETG mode is considered much smaller than electron gyro-frequency.

The ion number density is

$$n_i=n_{i0}\exp\left(-\frac{e\phi}{T_i}\right) \quad (1)$$

Under low frequency limit (compared with $\omega_{ce}=eB_0/m_e c$), the drift approximation is

$$v_e=v_E+v_p+v_s+v_D+v_{ez}\hat{z}$$

where $v_E=\frac{c}{B_0}\hat{z}\times\nabla\phi$ is $E\times B$ drift, $v_D=(1+\eta_e)v_{ne}$, v_{ez} is z-component of electron fluid velocity,

$v_s=\frac{cm_eT_e}{eB}\,\hat{z}\times\nabla S$ and $v_p=-(c/\omega_{ce}B_0)[\partial_t+v_e.\nabla]\hat{z}\times v$ is polarization drift.

The equation of continuity representing electrons is

$$\frac{\partial n_e}{\partial t}+\nabla.(n_e v_e)=0 \quad (2)$$

The equation of momentum is

$$(\partial_t+v_e.\nabla)v_e=-\frac{e}{m_e}\left(-\nabla\phi+\frac{v_e\times B_o}{c}\right)-\frac{1}{m_e n_e}\nabla(n_eT_e)-\frac{T_e}{m_e}\nabla S \quad (3)$$

The energy equation is

$$\frac{3}{2}(\partial_t+v_e.\nabla)T_e-\frac{T_e}{n_e}(\partial_t+v_e.\nabla)n_\mathrm{e}=\frac{1}{\mathrm{n_e}}\nabla.q^* \quad (4)$$

where $q^*=\frac{5}{2}\frac{n_ecT_e}{eB_0}(\hat{z}\times\nabla T_e)$.

To close our system we use quasi-neutrality approximation $n_{i1}\approx n_{e1}$

In inhomogeneous magnetized plasma, equations (2)-(4) represent the nonlinear relation of electrostatic waves in ETG mode.

Linear Dispersion Relation

Equation (2), after using drift approximation, gives

$$(\partial_t+v_E.\nabla+v_{Be}.\nabla)N-\tau^{-1}(v_{ne}-v_{Be}).\nabla\boldsymbol{\phi}+v_{Be}.\nabla T+\partial_z v_{ez}-\rho^2\frac{\partial}{\partial t}\nabla^2\boldsymbol{\phi}-\rho^2\tau\frac{\partial}{\partial t}[\nabla^2N+\nabla^2T]+\sigma[(1+\eta_e)v_{ne}-v_{Be}].\nabla S=0 \quad (5)$$

where $\boldsymbol{\phi}=-\frac{e\phi}{T_{i0}}$, $\tau=\frac{T_{e0}}{T_{i0}}$, $N=\frac{n_{e1}}{n_{e0}}$, $\sigma=m_iS_0$ and $v_{ne}=-\frac{cT_e}{eB_0}(\nabla\ln n_{i0})$

We define entropy as [31]

$$S\propto\boldsymbol{\phi}\Rightarrow\ S=S_0\exp(\boldsymbol{\phi})\Rightarrow S=\boldsymbol{\phi} \quad (6)$$

Equation (3) yields

$$(\partial_t+v_E.\nabla+v_{ez}\partial_z)v_{ez}=-C_s^2\partial_z[(1-\tau)\boldsymbol{\phi}] \quad (7)$$

Similarly, equation (4) gives

$$(\partial_t+v_E.\nabla+v_{ez}\partial_z)T-\tau^{-1}\left(\eta_e-\frac{2}{3}\right)v_{ne}.\nabla\boldsymbol{\phi}-\frac{2}{3}(\partial_t+v_E.\nabla+v_{ez}\partial_z)N=0 \quad (8)$$

For derivation of dispersion relation, we use Fourier analysis $(\partial_t\to-i\omega,\nabla\to ik)$. Fourier transformations of (5)-(8) yield

$$(\omega-\omega_D)N+\tau^{-1}(\omega_n-\omega_D)\boldsymbol{\phi}-\omega_DT-kv_{ez}+\omega k^2\rho^2\boldsymbol{\phi}+\omega k^2\rho^2\tau(N+T)-\sigma\big((1+\eta_e)\omega_n-\omega_D\big)S=0 \quad (9)$$

$$v_{ez}=\frac{C_s^2k}{\omega}[(1-\tau)\boldsymbol{\phi}] \quad (10)$$

$$T=\frac{\tau^{-1}\omega_n}{\omega}\left(\eta_e-\frac{2}{3}\right)\boldsymbol{\phi}+\frac{2}{3}N \quad (11)$$

where $\omega_n=k.v_{ne}$ and $\omega_D=k.v_{Be}$

Combining (9)-(11), we find the dispersion relation

$$\left(1+k^2\rho^2\left(1+\frac{5}{3}\tau\right)\right)\omega^2-\left(\omega_nk^2\rho^2\left(\eta_e-\frac{2}{3}\right)-\tau^{-1}\omega_n-\left(\frac{5}{3}-\tau^{-1}-\sigma\right)\omega_D+\sigma(1+\eta_e)\omega_n\right)\omega-C_s^2k^2(1-\tau)+\tau^{-1}\omega_D\omega_n\left(\eta_e-\frac{2}{3}\right)=0 \quad (12)$$

Equation (12) is 2nd order required dispersion relation for ETG mode having entropy drift. If we consider the temperature fluctuation due to $E\times B$ only, then above relation becomes

$$(1+k^2\rho^2)\omega^2+(\tau^{-1}-\sigma(1+\eta_e))\omega_n\omega-k^2C_s^2=0 \quad (13)$$

Equation (13) is of the form $px^2+qx+c=0$. For $q^2<4pc$, entropy instability exists which can play important role in destabilizing plasma.

Derivation of Kdv Equation

We introduce transformation $\xi = y - \alpha z - ut$ for derivation of KdV equation for ETG mode with respect to entropy. Introducing new frame in equations (2), (7) and (8), we obtain [33]

$$(\partial_t + v_{Be}.\nabla + v_{ez}\partial_z)N - \tau^{-1}(v_{ne} - v_{Be}).\nabla\boldsymbol{\phi} + v_{Be}.\nabla T + \partial_z v_{ez} - \rho^2\frac{\partial}{\partial t}\nabla^2\boldsymbol{\phi} - \rho^2\tau\frac{\partial}{\partial t}[\nabla^2 N + \nabla^2 T] + \sigma[(1+\eta_e)v_{ne} - v_{Be}].\nabla S = 0 \quad (14)$$

$$v_{ez} = \frac{\alpha C_s^2}{u}(1-\tau)\boldsymbol{\phi};\ C_s^2 = \frac{T_i}{m_e} \quad (15)$$

$$T = -\frac{\delta e\phi}{T_i} = \delta\boldsymbol{\phi}\ ;\ \delta = \frac{2}{3}\left[1 + \frac{v_{ne}}{\tau u}\left(1 - \frac{3}{2}\eta_e\right)\right]/(1 - \frac{5v_{Be}}{3u}) \quad (16)$$

Using (15)-(16) in (14), we get

$$-uA_1\partial_\xi\boldsymbol{\phi} - A_2\boldsymbol{\phi}\partial_\xi\boldsymbol{\phi} + A_3\partial_\xi^3\boldsymbol{\phi} = 0 \quad (17)$$

where $A_1 = 1 - C_s^2\alpha^2u^{-2}(1-\tau) - \sigma u^{-1}[(1+\eta_e)v_{ne} - v_{Be}] + (u\tau)^{-1}(v_{ne} - v_{Be})$

$A_2 = C_s^2\,\alpha^2u^{-1}(1-\tau)$ and $A_3 = u\rho^2(1+\tau+\delta\tau)$

Equation (17) is KdV equation in presence of entropy drift and is same as in ref.30. To find solution of equation (17), we consider GKdV equation

$$\phi_t + \epsilon\phi\phi_\xi + \mu\phi_{\xi\xi\xi} = 0 \quad (18)$$

Note that $\epsilon\phi\phi_\xi$ is similar to wave equation term cU_x.

Consider a homotopy

$H(p,q) = (1-q)[L(p) - L(\phi_0)] + q[w(p) - f(t)] = 0$

where $q \in [0,1]$, ϕ_0 is an initial approximation and

$p = p_0 + qp_1 + q^2p_2 + q^3p_3 + \cdots$

Now, $H(p,q)$ gives $H(p,0) = L(p) - L(\phi_0) = 0$ and $H(p,1) = W(p) - f(t) = 0$

Setting q=1, we can write $\phi = p_0 + p_1 + p_2 + p_3 + \cdots$

In equation (18) $L(\phi) = \phi_t$ and $N(p) = \epsilon\phi\phi_\xi + \mu\phi_{\xi\xi\xi}$, so

$H(p,q) = (1-q)[p_t - \phi_{0_t}] + q[p_t + \epsilon pp_\xi + \mu p_{\xi\xi\xi}] = 0$ gives

p^0: $p_{0_t} - \phi_{0_t} = 0$,

$p_0(\xi,0) = \phi_0$

p^1: $p_{1_t} + \phi_{0_t} + \epsilon p_0 p_{0_\xi} + \mu p_{0_{\xi\xi\xi}} = 0$,

$p_1(\xi,0) = 0$

… …

As $\phi = h\,\mathrm{sech}^2\left(\frac{h}{2}\right)^{\frac{1}{2}}(\xi - 2ht)$ is the particular solution of soliton [34], so we can take the initial approximation $\phi_0 = A\,\mathrm{sech}^2\left(\frac{\xi}{B}\right)$ to proceed in HPM, where $A = \frac{3c}{\epsilon}$ and $B = 2\sqrt{\frac{\mu}{c}}$ with $c = \epsilon\phi$

Now, from the initial approximation $\phi_0 = A\,\mathrm{sech}^2\left(\frac{\xi}{B}\right)$, we can calculate:

$p_0(\xi,t) = A\,\mathrm{sech}^2\left(\frac{\xi}{B}\right)$

$p_1(\xi,t) = t\left[8AB^{-3}\mu\,\mathrm{sech}^2\left(\frac{\xi}{B}\right)tanh\left(\frac{\xi}{B}\right) + 2AB^{-3}(AB^2\epsilon - 12\mu)\,\mathrm{sech}^4\left(\frac{\xi}{B}\right)tanh\left(\frac{\xi}{B}\right)\right]$

…. …. …. …

By HPM

$$\phi(\xi,t) = p_0 + p_1 + \cdots = A\,\mathrm{sech}^2\left(\frac{\xi}{B}\right) + t\left[8AB^{-3}\mu\,\mathrm{sech}^2\left(\frac{\xi}{B}\right)tanh\left(\frac{\xi}{B}\right) + 2AB^{-3}(AB^2\epsilon - 12\mu)\,\mathrm{sech}^4\left(\frac{\xi}{B}\right)tanh\left(\frac{\xi}{B}\right)\right] \quad (19)$$

Now, we write equation (17) as

$$-u\partial_\xi\boldsymbol{\phi} + D\boldsymbol{\phi}\partial_\xi\boldsymbol{\phi} + E\partial_\xi^3\boldsymbol{\phi} = 0$$

with $D = -\frac{A_2}{A_1}, E = \frac{A_3}{A_1}$ (20)

As $\xi = y - \alpha z - ut = s - ut$, so equation (20) can be written as

$$\partial_t\boldsymbol{\phi} + D\boldsymbol{\phi}\partial_s\boldsymbol{\phi} + E\partial_s^3\boldsymbol{\phi} = 0 \quad (21)$$

Finally, after comparing equations (21) and (18), we get

$$\boldsymbol{\phi}(s,t) = A\,\mathrm{sech}^2\left(\frac{s}{B}\right) + t\left[8AB^{-3}E\,\mathrm{sech}^2\left(\frac{s}{B}\right)tanh\left(\frac{s}{B}\right) + 2AB^{-3}(AB^2D - 12E)\,\mathrm{sech}^4\left(\frac{s}{B}\right)tanh\left(\frac{s}{B}\right)\right] \quad (22)$$

Equation (22) represents HPM solution of derived KdV. Here $A = \frac{3u}{D}$ and $B = \sqrt{\frac{4E}{u}}$.

III. Results and Discussion

Equation (22) provides a good understanding of the solitary waves in ETG mode with respect to entropy in considered plasma model. The numerical analysis of $\boldsymbol{\phi}$ can be used to investigate the entropy effect on solitary structures in ETG mode. For weakly nonlinear analysis we choose parameters such that the range of potential $\boldsymbol{\phi}$ is 0 to -1. We normalized numerically equation (22) and draw different figures. From these figures we noticed only rarefactive solitons. In Fig.1, effect of electron temperature on soliton profile without entropy drift is shown. We found the amplitude of soliton decreases and the width of soliton increases by increasing the electron temperature. In Fig.2, we found that in the presence of entropy the soliton amplitude and width are sensitive to $\tau = T_{e0}/T_{i0}$ (the ratio of electron to ion temperature). By increasing electron temperature the soliton amplitude decreases and soliton width increases. If we compare Fig.1 with Fig.2 then we found that the soliton amplitude and width are enhanced due to entropy. We know that soliton amplitude and width are directly proportional to coefficients $A = 3u/D$ and $B = 2\sqrt{E/u}$ respectively. It means that the soliton profile will enhance if coefficients A and B increases. After comparing the coefficients of KdV equation without entropy drift with KdV equation having entropy drift, we notice that the coefficients A and B are increased due to entropy. It leads us to the result that the soliton amplitude and width in this case will be enhanced due to entropy. This result satisfies the entropy theory which states that entropy of system increases when energy is added to system, which results the enhancement of the mode. It means that soliton width and amplitude will increase due to entropy. In Fig.3, effect of η_e on amplitude and width of soliton without entropy drift is shown. We observed that increasing η_e does not contribute in non-linearities effects but contributes in dispersive effects of the system, i.e., increase in η_e makes the width of the non-linear solitary structure to increase only. In Fig.4, we observed that in presence of entropy the parameter $\eta_e = L_n/L_T$ ($L_n = 1/d_x ln n_{eo}$, $L_T = 1/d_x ln T_{eo}$) contributes in both non-linearities and dispersive effects. If we compare Fig.3 and Fig.4 we also observed due to entropy width of soliton is enhanced. In Fig.5 and Fig.6, we found magnetic field magnetic field B_0 affect soliton profile. By increasing B_0 the soliton width increases but soliton amplitude decreases. If we compare both figures then we found that entropy has enhanced the soliton amplitude and width. Fig.7 demonstrated the effect of inhomogeneity v_{Be} on soliton profile in presence of entropy. It is noticed that increasing v_{Be} enhances the width of soliton and decreases the amplitude. From these observations we can say that in presence of entropy the effect of $\tau = T_{e0}/T_{i0}$, $\eta_e = L_n/L_T$, B_0, and v_{Be} contribute to both the non-linearities and the dispersive effects in the medium. This result is congruent with the soliton propagation definition which states that for the propagation of a soliton, energy within the wave must be conserved. Using this condition we can say that the soliton width is inversely proportional to amplitude. The present work plays the aforesaid nature. It means our results also follow the soliton propagation theory. The values of typical parameters of tokamak plasma are taken from ref.30 : $n = 10^{14} cm^{-3}$, $C_s = 0.55 \times 10^8 cm/s$, $B_0 = 3 \times 10^4 G$, $T_{i0} = 0.1T_{e0}$, $T_{e0} = 8.6keV$ and ξ is normalized with ρ which is of order $0.01cm$.

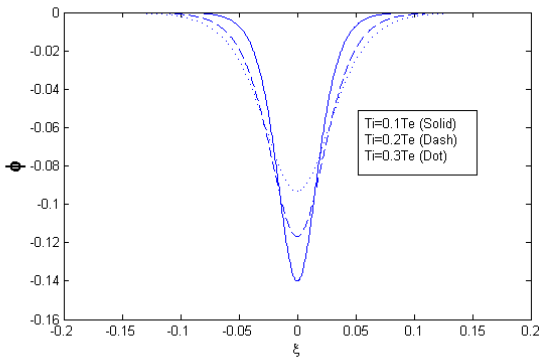

Fig.1: Effect of electron temperature on soliton profile $T_i = 0.1T_e$ (Solid line), $T_i = 0.2T_e$ (Dash line), $T_i = 0.3T_e$ (Dot line).
The amplitude of soliton decreases and the width of soliton increases by increasing the electron temperature

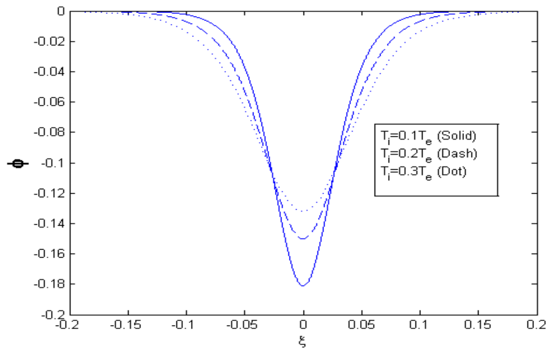

Fig.2: variation in soliton profile with respect to entropy for $T_i = 0.3T_e$ (Dot), $T_i = 0.2T_e$ (Dash) and $T_i = 0.1T_e$ (Solid).
The soliton amplitude decreases and soliton width increases if we increase electron temperature.

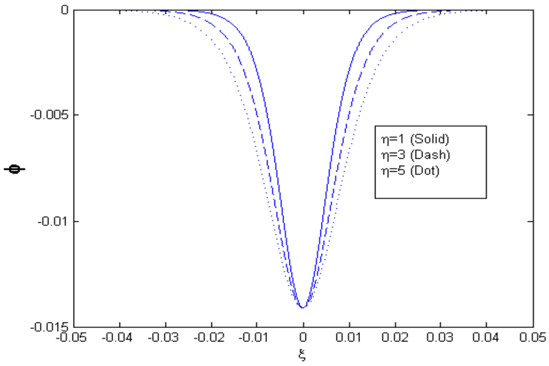

Fig.3: Effect of η_e on soliton profile, $\eta_e = 1$ (Solid line), $\eta_e = 3$ (Dash line), and $\eta_e = 5$ (Dot line).
increase in η_e makes the width of the non-linear solitary structure to increase only

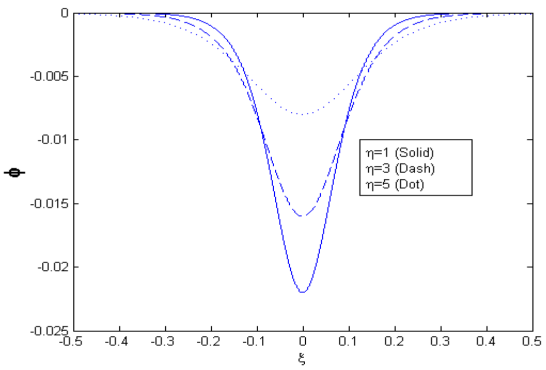

Fig.4: variation in soliton profile with respect to entropy for $\eta_e = 5$ (Dot line), $\eta_e = 3$ (Dash line) and $\eta_e = 1$ (Solid line).
due to entropy width of soliton increases

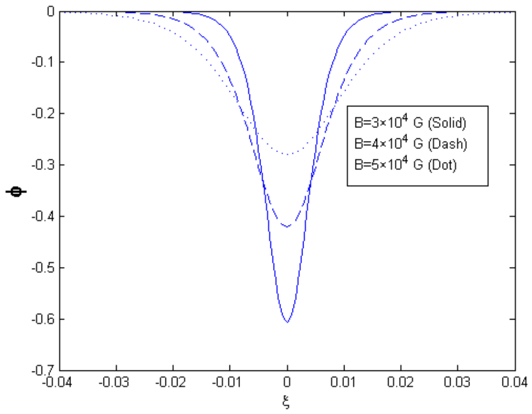

Fig.5: Effect of magnetic field on soliton profile, $B_0 = 3 \times 10^4 G$ (Solid line), $B_0 = 4 \times 10^4 G$ (Dash line), and $B_0 = 5 \times 10^4 G$ (Dot line)
Soliton width increases but soliton amplitude decreases due to magnetic field.

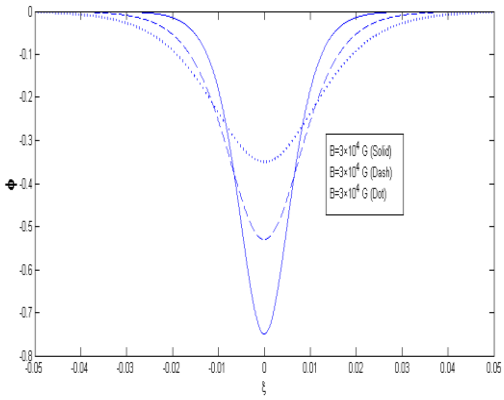

Fig.6: variation in soliton profile with respect to entropy for $B_0 = 5 \times 10^4 G$ (Dot line), $B_0 = 4 \times 10^4 G$ (Dash line) and $B_0 = 3 \times 10^4 G$ (Solid line)
Soliton width increases but soliton amplitude decreases due to entropy.

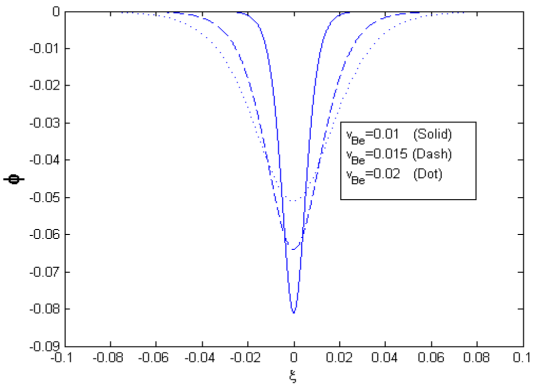

Fig.7: variation in soliton profile with respect to entropy for $v_{Be} = 0.01$ (Solid line), $v_{Be} = 0.015$ (Dash line) and $v_{Be} = 0.02$ (Dot line).
v_{Be} enhances the width of soliton and decreases the amplitude due to entropy.

IV. CONCLUSION

In the present work, we have shown the entropy effect on solitary structures in ETG mode in magnetized inhomogeneous plasma. In ETG mode with respect to entropy, after the derivation of dispersion relation, KdV equation is derived in this mode which allows pulse type solution. HPM technique is used to solve KdV equation. It is noticed that the solitary waves appear in such plasmas and entropy modifies the structures of the solitary waves. Also, entropy enhances the soliton amplitude and width, i.e., due to entropy the effects of $\tau = T_{eo}/T_{io}, \eta_e = L_n/\,L_T, B_0$ and v_{Be} on soliton profile are enhanced. It is found that the solitons are rarefactive in this mode. Our produced results follow the soliton propagation theory as well as entropy theory. Since drift waves produce the dominant mechanism for anomalous transport in magnetized plasmas. Therefore, we claim that our work is novel because the plasma old results can be changed by adding the entropy in system. Also, the present study will be helpful in analysis of solitary waves in magnetically confined plasmas with respect to entropy.

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