CHAPTER 5

KINETIC ALFVÉN SOLITONS IN A WARM LOW-β PLASMA WITH ELECTRON DRIFT MOTION

5.1 Introduction

In a thermal equilibrium plasma, both the electrostatic and electromagnetic modes of waves of different frequencies exist. The magnetohydrodynamic (MHD) surface mode of waves are easily excited by an antenna, resulting in the mode conversion into the Shear Alfvén waves (SAWs) or Kinetic Alfvén waves (KAWs) at the spatial Alfvén resonance layer (Tataronis and Grossmann, 1973; Hasegawa and Chen, 1975). The validity limits of the classic MHD results of Sagdeev and Galeev (1969), are opposite in case of the nonlinear analysis of the KAW. A unique feature of the KAW is that it accompanies the electric field E_z in the direction of the ambient magnetic field B_z.

In case of low-β ($\beta \ll 1$) ideal MHD plasmas, the axisymmetric perturbations are noticed to produce decoupling of shear Alfvén and the compressional Alfvén wave (Hasegawa and Uberoi, 1982). These kinetic Alfvén waves are dispersive for oblique propagation and form solitary KAW having nonlinear effect from the compressive character. In the process, the charge fluctuation remains absent within the fluid model. Oblique propagation of solitary Alfvén waves in this respect are extensively studied during the last two decades. Considerable changes are found to take place for pressure variation because of the decoupling of the wave with the compressional mode.

Investigations of nonlinear Alfvén waves have been extended through kinetic effects in the works of Rogister (1971), Mjolhus and Wyller (1986, 1988) and Spangler (1989, 1990). Solitary wave solutions of the kinetic (or shear) Alfvén waves obtainable from the consideration of finite frequency effects (Kakutani, 1974) or the finite larmour -radius effects (Hasegawa and Mima 1976) are sequely treated under more and more general situations by different followers. In numerous plasma situations as resistive fluid model, the kinetic effects of parallel electron inertia have been incorporated to establish the emergence of significant results (Yu and Shukla, 1978; Kalita and Kalita, 1986; Kalita and Bhatta, 1997). Kalita and Bhatta (1997) have shown that the electron pressure gradient supresses the speed of the KAS.

Actually, the fast-shear mode conversion gives rise to the shear Alfvén modes (Hasegawa and Chen ,1976) . Due to the inclusion of either the electron inertia or the thermal velocity , they decay to different shear Alfvén modes giving rise to acoustic mode in excess with some limitation of the low -β to determine the parallel effects of the electron motion in a collisionless plasma. Moreover, for low values (<< 1) of the plasma- beta, the magnetic compression B_z is not so important. Also, the assumption of a very small component of the Larmor radius at right angles to B_z, justifies the intuitive study required to understand the evolution equation describing the solitary waves in a warm plasma.

In the low-β assumption , exact solitary wave solutions can be obtained through the Sagdeev potential when the phase velocity of the wave is greater than the sound speed. If the plasma is warm and is produced under dc discharges , particle drift becomes a common feature; ion drift being negligible relative to electron drift, provided that the degree of nonisothermality measured by the ratio T_i / T_e - is neither too low nor too high ($T_i < T_e$). So the highly conducting plasma medium with a low-β (<< 1), either cosmic or laboratory , is available as a fluid model for the description of kinetic Alfvén solitons. The use of heated filament in the thermoionic emission method results in supply of electrons at the source region in the laboratory.

In this chapter , we consider a warm low-β plasma with drifting effect of the electrons parallel to the ambient magnetic field B_z . The ion species with temperature T_i ($< T_e$) is taken without the polarization drift. This emerges from the neglect of the displacement current. In addition to the initial drift velocity of the electrons (discussed in the chapter 4), the role of temperature $\alpha (= T_i / T_e)$ is considered in the formation of KAS.

5.2 Basic equations for the dynamics of the motion

We consider a warm low-β plasma with ion and electron populations varying in the zx-plane. The behaviour of our fully ionized warm collisionless plasma, under the influence of highly magnetized drifting electrons in the direction of the ambient magnetic field $B\hat{\mathbf{z}}$ ($\hat{\mathbf{z}}$ is the unit vector along z-axis), is described by the following set of equations:

$$\frac{\partial n_e}{\partial t} + \frac{\partial}{\partial z}(n_e v_{ez}) = 0, \tag{5.1}$$

$$\frac{\partial v_{ez}}{\partial t} + v_{ez}\frac{\partial v_{ez}}{\partial z} = \frac{\beta}{2Q}\left(\frac{\partial \psi}{\partial z} - \frac{1}{n_e}\frac{\partial n_e}{\partial z}\right), \tag{5.2}$$

for the electrons

$$\frac{\partial n_i}{\partial t} + \frac{\partial}{\partial x}(n_i v_{ix}) + \frac{\partial}{\partial z}(n_i v_{iz}) = 0, \tag{5.3}$$

$$\frac{\partial v_{ix}}{\partial t} + v_{ix}\frac{\partial v_{ix}}{\partial x} + v_{iz}\frac{\partial v_{ix}}{\partial z} = -\frac{\beta}{2}\left(\frac{\partial \phi}{\partial x} + \frac{\alpha}{n_i}\frac{\partial n_i}{\partial x}\right) + v_{iy}, \tag{5.4}$$

$$\frac{\partial v_{iy}}{\partial t} + v_{ix}\frac{\partial v_{iy}}{\partial x} + v_{iz}\frac{\partial v_{iy}}{\partial z} = -v_{ix}, \tag{5.5}$$

$$\frac{\partial v_{iz}}{\partial t} + v_{ix}\frac{\partial v_{iz}}{\partial x} + v_{iz}\frac{\partial v_{iz}}{\partial z} = -\frac{\beta}{2}\frac{\partial \psi}{\partial z} - \frac{\alpha\beta}{2n_i}\frac{\partial n_i}{\partial z}, \tag{5.6}$$

for the ions

$$\frac{\partial^4(\phi - \psi)}{\partial x^2 \partial z^2} = \frac{2}{\beta}\left[\frac{\partial^2}{\partial t \partial z}\left(n_i v_{iz}\right) + \frac{\partial^2 n_e}{\partial t^2}\right], \tag{5.7}$$

for the integrated Maxwell's equations (derived in chapter 4)

and $$\varepsilon\left(\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \psi}{\partial z^2}\right) = n_e - n_i, \tag{5.8}$$

from the Poisson equation, where $Q = m_e / m_i$ (electron to ion mass ratio), $\alpha = T_i / T_e$ (ion to electron temperature ratio) and $\varepsilon = c_s^2 / c^2$.

Here the low-β assumption ushers the two potentials ϕ and ψ to describe the electric field by

$$E_x = -\frac{\partial \phi}{\partial x} \text{ and } E_z = -\frac{\partial \psi}{\partial z} \quad \text{(Kadomtsev, 1965, p.82)}$$

The flow variables namely density, time, velocity, space and potential are normalized respectively by the equilibrium plasma density n_0, the inverse of the ion cyclotron frequency Ω^{-1}_{ci}, the Alfvén velocity v_A, c/ω_{pi} (the ratio between the velocity of light and the ion plasma frequency) and T_e/e.

The linear dispersion relation for the solitary kinetic Alfvén waves is obtained from the original set of equations of (5.1) - (5.8), as (derivation is given in the appendix II)

$$\text{or, } \left(1+\frac{v^2_A}{c^2}\right)\omega^4+\left[\left(1+\frac{v^2_A}{c^2}\right)\frac{\lambda^2c^2}{\omega^2_{pe}}k^2_x-k^2_z v^2_A\left\{\left(1-\frac{\alpha\beta}{2}\right)\left(1-\frac{\lambda^2}{\omega^2_{pe}}\right)\right.\right.$$

$$\left.\left.+\frac{\alpha\beta v^2_A}{2c^2}\right\}\omega^2+\frac{\alpha\beta}{2}k^2_z v^4_A\left(k^2_z-\frac{\lambda^2 k^2}{\omega^2_{pe}}\right)\right]=0. \qquad (5.9)$$

Where $\lambda^2=(\omega-v'_e k_z)^2-\frac{c_s^2 k^2_z}{Q}$, v'_e is the initial drift velocity of the electrons in the z- direction, $\beta=8\pi\, n_0 T/B^2_G$ and $\omega_{pe}=(4\pi n_0 e^2/m_e)^{1/2}$ is the electron plasma frequency. For the cold plasma ($\alpha=0$), this dispersion relation takes the form

$$k^2_z v^2_A-\omega^2\left(1+\frac{v^2_A}{c^2}\right)=\left(\frac{\lambda^2c^2}{\omega^2_{pe}}\right)\left[\left(\frac{k^2_z v^2_A}{c^2}\right)+k^2_x\left(1+\frac{v^2_A}{c^2}\right)\right]$$

(Kalita and Devi, 1996)

Interestingly, in the limiting transition $m_e\to 0$ (i.e. $Q\to 0$), the dispersion relation for $T_e\to 0$ (as evident from the value of λ^2) reduces to $\omega^2=k^2_z v^2_A(1+v^2_A/c^2)$. Further, for the simple Alfvén waves it transforms to $\omega^2=k^2_z v^2_A$ (when $v^2_A/c^2 \ll 1$). But in this general situation of warm low - β plasma, an unstable mode of kinetic Alfvén waves is generated by (5.9) without further approxima tion as included in chapter 6.

5.3 Sagdeev Potential for the solitary kinetic Alfvén waves

The stationary character of the KAW propagation is chosen to be described by the independent variable ξ, where $\xi=xk_x+zk_z-Mt$ with $k^2_x+k^2_z=1$ and the pluse speed M is normalized to the Alfvén speed v_A.

Using the above set up for the stationary Alfvén waves, equations (5.1) - (5.8) can be tarnsformed to the moving co-ordinate ξ as

$$n_e = e^{\psi}\left[exp\left\{A(1 - \frac{1}{n_e^2})\right\}\right], \tag{5.10}$$

$$k_x v_{ix} + k_z v_{iz} = M\left(1 - \frac{1}{n_i}\right), \tag{5.11}$$

$$\frac{M}{n_i}\frac{\partial v_{ix}}{\partial \xi} = \frac{\beta}{2}k_x\frac{\partial \phi}{\partial \xi} - v_{iy} + \frac{\alpha\beta}{2n_i}k_x\frac{\partial n_i}{\partial \xi}, \tag{5.12}$$

$$\frac{M}{n_i}\frac{\partial v_{iy}}{\partial \xi} = v_{ix}, \tag{5.13}$$

$$\frac{M}{n_i}\frac{\partial v_{iz}}{\partial \xi} = \frac{\beta}{2}k_z\frac{\partial \psi}{\partial \xi} + \frac{\alpha\beta}{2n_i}k_z\frac{\partial n_i}{\partial \xi}, \tag{5.14}$$

$$k_x^2 k_z^2\frac{\partial^2}{\partial \xi^2}(\phi - \psi) = \frac{2}{\beta}\left[M^2 n_i - Mk_z(n_i v_{iz})\right]. \tag{5.15}$$

The boundary conditions $v_{ez} = v'_e$ at $n_e = 1$ and $v_{ix} = v_{iz} = 0$ at $n_e = n_i = 1$ as $|\xi| \to \infty$ have been used in the derivation. The parameter A, used in the equation (5.10) is given by

$$A = \frac{Q}{\beta}(v'_e - M/k_z)^2 .$$

When the electron inertia is neglected, A becomes zero to give rise to the electrons' Boltzmann distribution (Kalita *et al.,* 1986).

Combining the results of (5.11) and (5.13) we get

$$\frac{M}{n_i}\frac{\partial v_{iy}}{\partial \xi} = \frac{1}{k_x}\left(M - \frac{M}{n_i} - k_z v_{iz}\right). \tag{5.16a}$$

Differentiating (5.10) with respect to ξ,

$$\frac{\partial \psi}{\partial \xi} = \left(\frac{1}{n_e} - \frac{2A}{n_e^3}\right)\frac{\partial n_e}{\partial \xi} .$$

Using this result in (5.14) , we obtain

$$\frac{M}{n_i}\frac{\partial v_{iz}}{\partial \xi} = \frac{\beta k_z}{2}\left(\frac{1}{n_e} - \frac{2A}{n_e^3}\right)\frac{\partial n_e}{\partial \xi} + \frac{\alpha\beta}{2n_i}k_z\frac{\partial n_i}{\partial \xi}\ .$$

Putting $n_i = n_e = n$ and integrating the resulting equation under the boundary conditions $n = 1, v_{iz} = 0$ at $|\ \xi\ | = \infty$, equation obtained is

$$v_{iz} = \frac{\beta k_z}{2M}\left[(n-1)(\alpha+1) + 2A\left(\frac{1}{n} - 1\right)\right]. \tag{5.16b}$$

Using euqations (5.11) and (5.16a) in the result obtained by adding euqations (5.12) and (5.14) after multiplying both sides of them by k_x and k_z respectively, we get

$$\frac{\partial}{\partial \xi}\left(\frac{M^2}{n^3}\frac{\partial n}{\partial \xi}\right) = \frac{\beta}{2}\left(k^2_x\frac{\partial^2 \phi}{\partial \xi^2} + k^2_z\frac{\partial^2 \psi}{\partial \xi^2}\right) + \frac{\partial}{\partial \xi}\left(\frac{\alpha\beta}{2n}\frac{\partial n}{\partial \xi}\right) \tag{5.17}$$

$$- \frac{n}{M}\left(M - \frac{M}{n} - k_z v_{iz}\right).$$

Equations (5.16b) and (5.17) can be transformed to

$$\frac{\beta}{2}\frac{\partial^2}{\partial \xi^2}(k^2_x\phi + k^2_z\psi) = \frac{\partial}{\partial \xi}\left(\frac{M^2}{n^3}\frac{\partial n}{\partial \xi} - \frac{\alpha\beta}{2n}\frac{\partial n}{\partial \xi}\right) + \left[(n-1) - \frac{\beta k^2_z}{2M^2}\right.$$

$$\left. n\left\{(n-1)(\alpha+1) + 2A\left(\frac{1}{n} - 1\right)\right\}\right]. \tag{5.18}$$

Now, euqations (5.15) and (5.16b) can be combined with (5.18) to give

$$\frac{\partial}{\partial \xi}\left[\left\{\frac{2k^2_z}{\beta}\left(\frac{M^2}{n^3} - \frac{\alpha\beta}{2n}\right) - k^2_z\left(\frac{1}{n} - \frac{2A}{n^3}\right)\right\}\frac{\partial n}{\partial \xi}\right] = \frac{2}{\beta}(M^2 - k^2_z)(n-1)$$

$$+ k^2_z n\left(\frac{k^2_z}{M^2} - 1\right)\left\{n - 1)(\alpha+1) + 2A\left(\frac{1}{n} - 1\right)\right\}.$$

Multiplying both sides of it by the expression in the parantheses of the left hand side and integrating, we get

$$\frac{1}{2}\left(\frac{\partial n}{\partial \xi}\right)^2 + K(n, \beta, M, k_z, \alpha) = 0, \tag{5.19}$$

where

$$K(n, \beta, M, k_z, \alpha) = \frac{(k_z^2/M^2 - 1)P}{k_z^2\left\{(2M^2/\beta - \alpha n^2) - (n^2 - 2A)\right\}^2},$$

is the Sagdeev potential with

$$P = (k_z^2/2)(\alpha+1)^2 n^4 - \{2M^2/\beta + (1+2A+\alpha)\}k_z^2(\alpha+1)\, n^3$$

$$+ (2M^2/\beta)(1-k_z^2)(\alpha+1)n^2 \,Log(n) + \Big[(2M^2/\beta)\{(A+1+\alpha)(k_z^2+1)$$

$$+ (M^2/\beta)\} + \{(1+2A+\alpha)^2 + 4A(\alpha+1)\}k_z^2/2\Big]\, n^2$$

$$- \Big[(2M^2/\beta)\{(2M^2/\beta+2A) + (1+2A+\alpha)k_z^2\} + 2(1+2A+\alpha)Ak_z^2\Big]n$$

$$+ (2M^2/\beta)\{A(k_z^2+1) + (M^2/\beta)\} + 2k_z^2A^2$$

In deriving the equation (5.19), the boundary condition $\frac{\partial n}{\partial \xi} = 0$ at $n = 1$ has been used.

The maximum variation N of n is the exact Alfvén wave amplitude given by the nonlinear dispersion relation.

$$(k_z^2/2)(\alpha+1)^2N^4 - \{2M^2/\beta + (1+2A+\alpha)\}k_z^2(\alpha+1)N^3 + (2M^2/\beta)(1-k_z^2)(\alpha+1)N^2\,Log(N)$$

$$+ \Big[(2M^2/\beta)\{(1+A+\alpha)(k_z^2+1) + M^2/\beta\} + \{(1+2A+\alpha)^2 + 4A(\alpha+1)k_z^2\Big]N^2$$

$$- \Big[(2M^2/\beta)\{(2M^2/\beta+2A) + (1+2A+\alpha)k_z^2\} + 2(1+2A+\alpha)Ak_z^2\Big]N$$

$$+ (2M^2/\beta)\{A(k_z^2+1) + M^2/\beta\} + 2k_z^2A^2 = 0, \tag{5.20}$$

for different values of the parameters $\beta, M, k_z, \alpha,$ and A .

5.4 Conditions for the existence of Solitary Alfvén waves

For the existence of stationary soliton solution of the equation (5.19), we analyse the potential $K(n)$ to admit the conditions.

$$K(1)=K(N)=K'(1)=0, \text{ where } K'(1) = dK/dn\Big|_{n=1},$$

and

$K(n) < 0$ between the values $n = 1$ and $n = N$. These conditions are found to fulfil respectively due to the results $P = 0$ for $n = 1$, $\frac{dP}{dn} = 0$ for $n = 1$ and $P = 0$ for $n = N$ (as given by the nonlinear dispersion relation (5.20)) Also from computation in the range $n = 1$ to $n = N$, the negativity of K (n) can be ascertained for sets of assigned values of the parameters k_z, α, β, M and A.

For this, we expand $K(n)$ near $n = 1$ by Taylor's series , to get

$$K(n \approx 1) = \frac{(n-1)^2(1 - M^2/k_z^2)}{\beta\left\{\left(\frac{2M^2}{\beta} - \alpha\right) - (1 - 2A)\right\}^2} \left\{\frac{2}{\beta}(M^2 + A\beta) - (1+\alpha)\right\} \times \left\{1 - \frac{k_z^2\beta}{2M^2}(1 + \alpha - 2A)\right\}.$$

Similary the Taylor's expansion of $K(n)$ near $n = N$ gives

$$K(n \approx N) = -\frac{(n-N)(N-1)N^3(1-k_z^2/M^2)}{k_z^2\left\{\left(\frac{2M^2}{\beta} - \alpha N^2\right) - (N^2 - 2A)\right\}^2} \left[\frac{2M^2}{\beta} - k_z^2\{(1+\alpha)N - 2A\}\right] \times \left\{\frac{2}{\beta}(M^2 + A\beta) - (\alpha+1)N^2\right\}.$$

Analysis of the behaviour of the potential $K(n)$ from its Taylor's series expansion near $n = 1$ gives

$$(1 - 2A + \alpha) > 2M^2/\beta > k_z^2(1 - 2A + \alpha), \qquad (5.21)$$

and , near $n = N$

$$N > (2M^2/\beta k_z^2 + 2A)/(1+\alpha) > \left[(2M^2/\beta + 2A)/(1+\alpha)\right]^{1/2}, \qquad (5.22)$$

for a density hump ($N > 1$)

or,

$$N < \left[(2M^2/\beta + 2A)/(1+\alpha)\right]^{1/2} < (2M^2/\beta k_z^2 + 2A)/(1+\alpha), \qquad (5.23)$$

for a density dip ($N < 1$) when $M < k_z$.

Also

$$k_z^2(1+\alpha - 2A) < (1-2A+\alpha) < 2M^2/\beta \quad , \qquad (5.24)$$

and

$$\left[(2M^2/\beta+2A)/(1+\alpha)\right]^{1/2} < N < (2M^2/\beta k_z^2+2A)/(1+\alpha), \qquad (5.25)$$

for a density hump ($N>1$), when $M > k_z$

Subject to these conditions (5.21) – (5.25), the amplitudes (N) of the kinetic Alfvén solitons are determined for different sets of assigned parameters α, β, k_z, M, and A. The width Δ corresponding to each soliton of amplitude N is then determined from

$\Delta = N/\sqrt{d}$, d being the maximum depth of the Sagdeev potential $K(n, \alpha, \beta, k_z, M, A)$.

5.5 Discussion

In this warm magnetized plasma, both compressive and rarefactive Kinetic Alfvén solitons (KAS) are found to exist when the highly magnetized electrons undergo initial drift motion in the direction of the magnetic field. Characteristic changes are noticed in the Alfvén solitons for the consideration of ion temperature. The ion temperature α in the plasma, further causes deviation of the propagation direction of the KAS from the direction of the magnetic field that narrows down its existence region compared to that of cold plasma (Chapter 4) in presence of the electrons' drift motion. Unlike previous works, the amplitudes of the rarefactive Alfvén solitons (RAS) are noticeably limited due to the consideration of the ion temperature.

The amplitude of the compressive Alfvén soliton (CAS) slowly diminishes and the corresponding width slowly increases with temperature α [Figs. 1(a) and 1(b)]. On the other hand, the amplitude of the RAS linearly decreases with α in the region away from the magnetic field. Interestingly, high amplitude RAS exists near the magnetic field for low temperature [Fig. 2(a)] but the corresponding width [Fig. 2(b)] decreases for small α remaining almost constant and negligible in an intermediate range to reflect its uniform increase thereafter. Again for the fixed value of α, the amplitude of the CAS are noticed to decrease uniformly attaining higher values for smaller α [Fig. 3(a)] as k_z increases. Also it tends to zero in the upper existence region of k_z (= 0.5) but the corresponding changes in widths [Fig. 3(b)] with k_z appear to be of opposite character. Contrary to this, the amplitude (width) of the

RAS slowly increases [Figs. 4(a) and 4(b)] with k_z for fixed values of α. But the amplitudes (widths) of the CAS exhibit their uniform increase (decrease) with the drift velocity v'_e [Figs. 5(a) and 5(b)] for all α . The width becomes constant in the higher existence region of v'_e. But their counterparts for RAS decrease slowly [Figs. 6(a) and 6(b)] with v'_e for all values of α.

Compressive KAS are found to exist even for higher values of A and that too near the magnetic field. But in this region for the same value of A, rarefactive Alfvén soliton does not exist. There are propagation regions with much deviated directions where only rarefactive solitons exist with the introduction of the ion temperature, even if the value of β remains comparatively smaller. Both CAS and RAS are observed when the deviation approach to the magnetic field. In such cases, the wave mach number M remains small which increases with β.

In the case of RAS of warm plasma, the upper limits of slowly growing amplitudes are considerably reduced [Fig. 4(a)] in comparison to the sharply but linearly increasing [Fig. 6, Kalita and Devi (1996)] amplitudes for cold plasma ($\alpha = 0$) at fixed values of $A = 0.15$. Further, the corresponding width which are negligibly small for $\alpha = 0$, are noticebly high [Fig.4 (b)] for $\alpha \neq 0$. Compressive Alfvén solitons with magnified amplitudes but neglible widths are found to exist in case of $M > k_z$.

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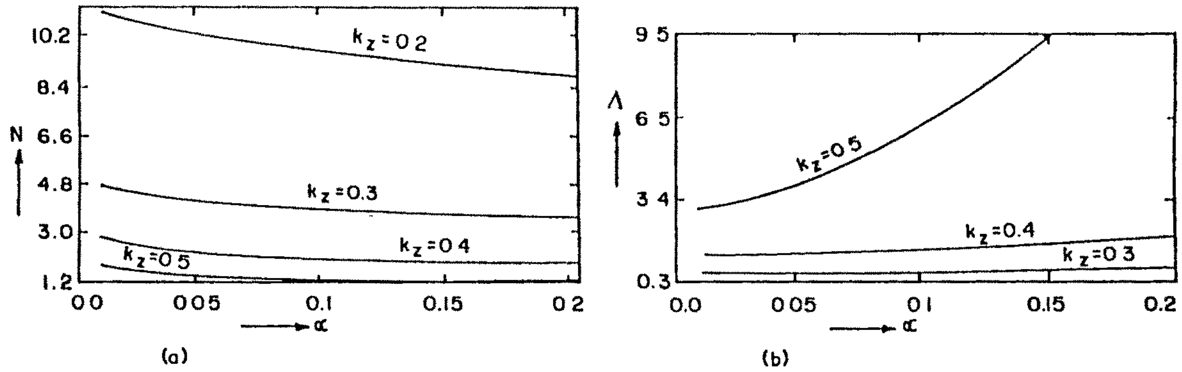

Fig 1 Amplitude N (a) and width Δ (b) of the compressive Alfvén soliton versus temperature ratio α at $\beta = 0.08$, $A = 0.15$, $M = 0.1$ for different values of k_z shown against the curves.

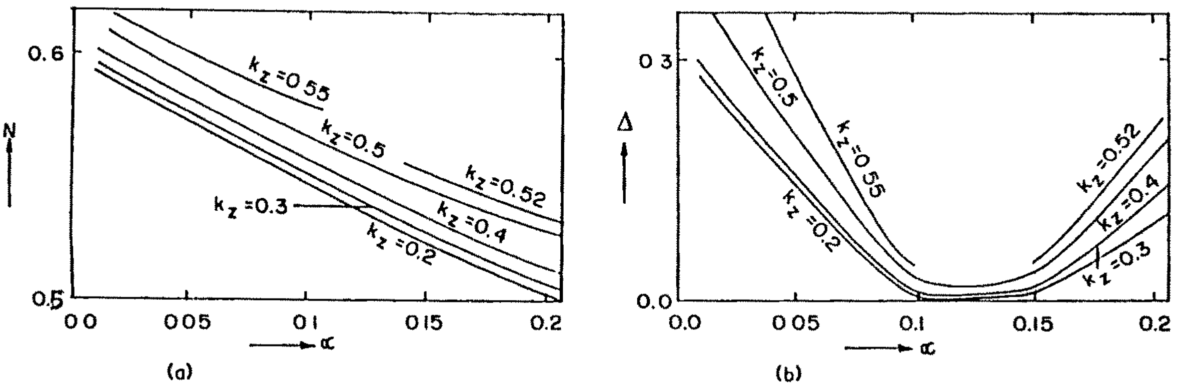

Fig 2 Amplitude N (a) and width Δ (b) of the rarefactive Alfvén soliton versus temperature ratio α at $\beta = 0.08$, $A = 0.15$, $M = 0.1$ for different values of k_z shown against the curves

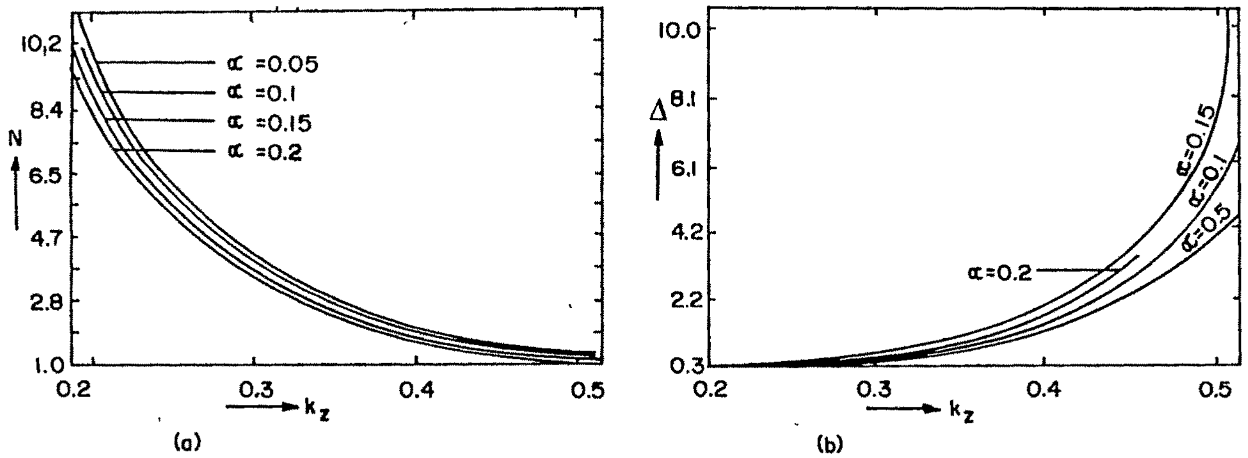

Fig.3. Amplitude N (a) and width Δ (b) of the compressive Alfvén soliton versus k_z for different values of α shown against the curves at $\beta = 0.08,\ A = 0.15, M = 0.1$.

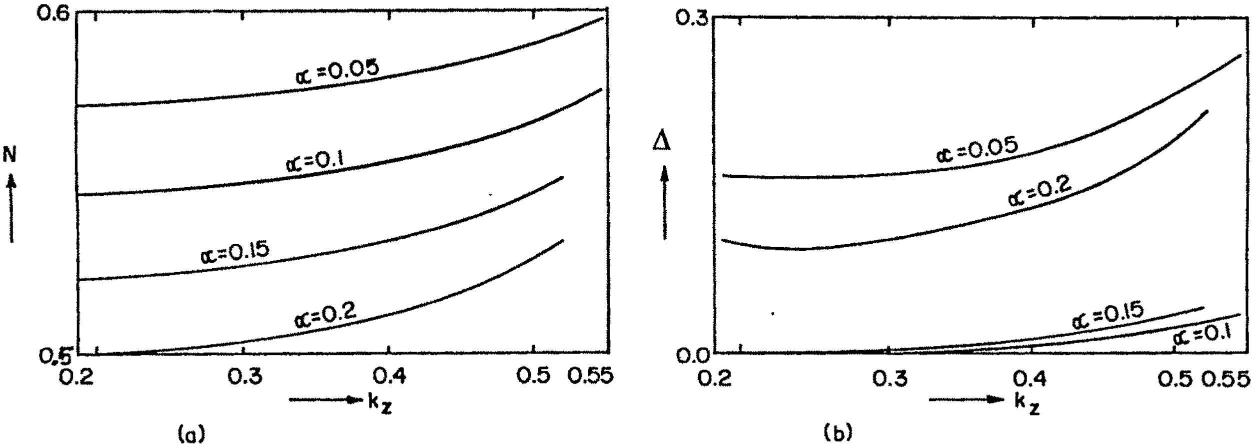

Fig.4. Amplitude N (a) and width Δ (b) of the rarefactive Alfvén soliton versus k_z for different values of α shown against the curves at $\beta = 0.08,\ A = 0.15, M = 0.1$.

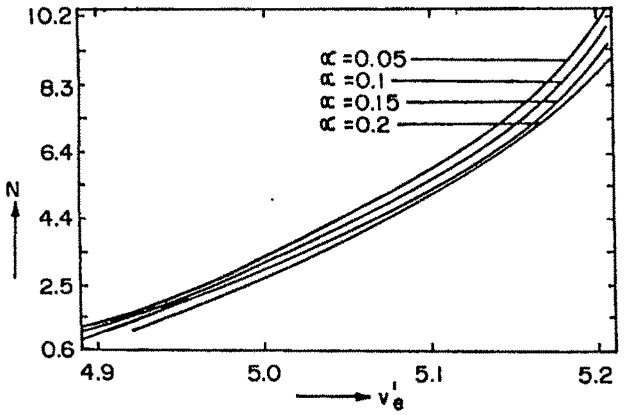

FIG. 5 (a)

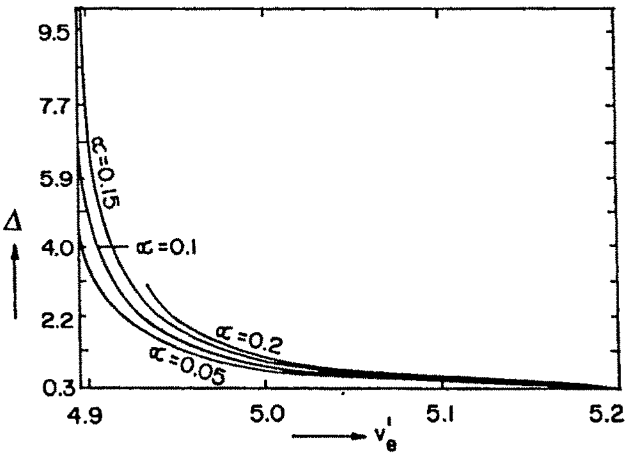

FIG. 5 (b)

Fig.5. Amplitude N (a) and width Δ (b) of the compressive Alfvén soliton versus drifting velocity v_e' of electron for different values of α shown against the curves at $\beta = 0.08$, $A = 0.15, M = 0.1$.

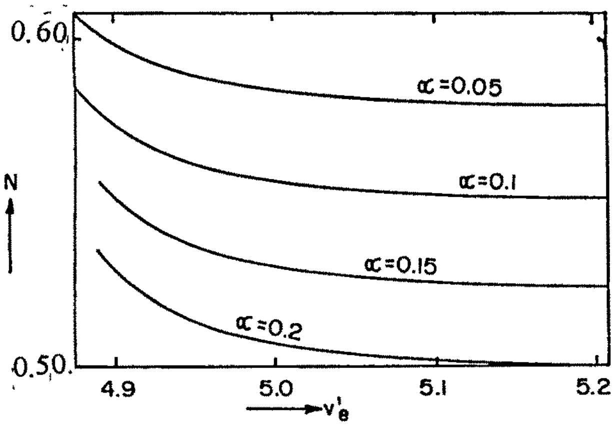

FIG. 6 (a)

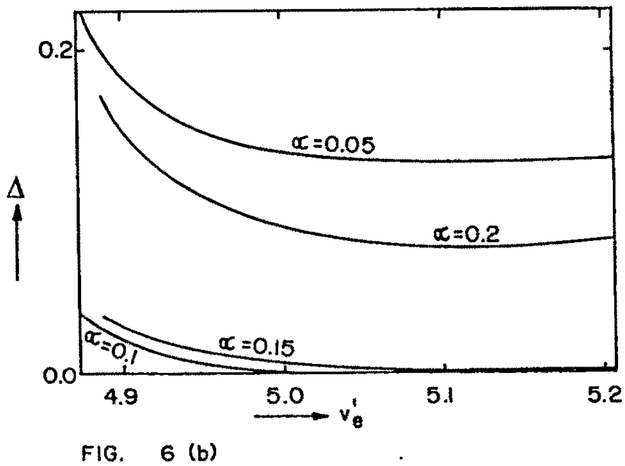

FIG. 6 (b)

Fig 6 Amplitude N (a) and width Δ (b) of the rarefactive Alfvén soliton versus drifting velocity v_e' of electron for different values of α shown against the curves at $\beta = 0.08$, $A = 0.15, M = 0.1$.