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Energy Loss of Correlated Ions in Dense Plasma

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The interaction between proton clusters and plasma gas is studied using the dielectric function by fried-conte formalism. The theoretical formula of the potential basis equation derived and the energy loss of incident proton (point-like, correlate and dicluster) with different parameters (velocity, distance, densities and temperatures) is calculated numerically. Two different equations were used to enhance the correlation stopping (ECS), it is clear that the present results are consistent with the dielectric calculation of energy loss at parameters $ne = 10^{17} cm^{-3}$ and $T = (2 - 10)$ eV. The result showed a good correlation with the previous work.

Keywords: plasma gas, energy loss, dicluster ions, enhanced correaltion, dielectric dispersion function

1. INTRODUCTION

Plasma represents the forth state of matter, must recall to the properties of a neutral gas to understand the plasma. A gas is described by the number of particles per unit volume (n) in m−3. The motion of the particle in thermodynamic equilibrium is determined by the temperature (T) of the gas. The result of number density and temperature gives the pressure ($p = nk_BT$), in which k_B is Boltzmann's constant.[1]

Langmuir is the first one who introduced the word "plasma" in 1928. Which is described in terms of the ionization degree. They considered state of a balanced gas because it does contains most ions of the matter around consists of neutral atoms and equal number of electrons (−) and protons (+).

The main difference between a neutral gas and a plasma is mechanism of collision. At which Coulomb force dominated the electrostatic interaction in plasma while in the gas the Vander-Vaals collisions governed.[2]

Energy loss is the most important phenomenon accompanied the interaction of charge particles with dense and hot target plasma**.** The aim of this work is to study the energy loss of proton in two cases of interaction, point-like and correlate protons in the dense classical plasma for different temperatures and densities, many equations were used to enhance the stopping power of proton ions in plasma.[3,4]

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In order to calculate the stopping power the present work depended on several parameters (i) Correlation effects of Proton in plasma gas (ii) The constant of ions colliding distance (iii) Range of distances between incident proton with target in different temperature and densities.[4,5]

In classical plasma the motion of ion in general is specific by the collision and degenerate electrons surrounding it, where the distance of this ion is often reduced by collisions with ions and electrons and because coulomb effect all would help to stop the ions in plasma and loss the energy.[6] The present work shows the energy loss of the cluster important differences, called vicinage effects.[7,8] Originally vicinage effect lies in the interference produced by the electronic excitations of the target due to the correlated motion of the particles that form the cluster.

A Frotran-90, program has been written to analysis data and developed to treat the processes to involve the interaction of hydrogen clusters in plasma.[9]

2. THEORETICAL BACK GROUND

2.1 Energy loss of proton in plasma jellium

A plasma is a neutral ionized gas (through heating or photoionization), consists of electrons and ions, it has a low sufficient density to behave classically, moving the proton in the plasma makes the cloud of oppositely charge around it, this cloud of electrons has been represented Debye length.[10,11]

Briefly formulation for di-cluster stopping in a dense and hot classical plasma is shown in for a cylindrical geometry[12,13] defined by drift velocity **V** and interparticle distance r_{12} as shown in Fig. 1, any velocity between the two charges z_1 and z_2 are neglected.[14]

To calculatethe dicluster stopping power in Fig. 1 the electrostatic potential a basic system where the two ions are at rest.[6]

$$\varnothing_1(r) = \frac{1}{(2\pi)^3}\int d^3k \frac{e^{ik,r}}{k^2\varepsilon(k,k,v)}(Z_1 + Z_2 e^{-ik,r_{12}}) \tag{1}$$

Where $\varnothing_1(\mathbf{r})$ represent the potential at postion (r_{12}), z_1 and z_2 represent the incident and target ions respectively, $\varepsilon(k,k,v)$ is the dielectric function for a Maxwelian classical electron in plasma.

In this work we used a rather moderate temperature T approximately equal to a few eV at range (2−10) eV and density 10^{17} cm^{-3}. Depending on the dielectric theory by Maxwell and classical electron plasma many expression equations have been solved. Fried-Conte equations are solved analytically and numerically for stopping single proton (point like S_{point}), pair proton (correlated $S_{correlated}$), to obtain the best (ECS) in plasma of proton.

To get rid of problems physically of the heavily dynamic scaling variables called plasma units with dimensionless variables.[15,16]

$$r \to \frac{r}{\lambda_D}, t \to \omega_p t, V \to \frac{v}{v_{th}}, \varnothing \to \frac{e}{K_B T}\varnothing \tag{2}$$

Any charged particle inside the plasma attracts other particles with an opposite charge and repels those with the similar charge, so that form a net cloud of opposite charges around itself called Debye length.[17] This cloud screen helps to stop a large number of ions. This shielding represent a measure the sphere due to the influence of a test charge in a plasma. Debye length depends on the energy of incident ion and the density of target shown below.[18]

$$\lambda_D = 7.43 \times 10^2 \frac{[T(\text{eV})]^{1/2}}{[n_e(\text{cm}^{-3})]^{1/2}} \tag{3}$$

Where λ_D is the Debye length in atomic unit (a.u), n is the density of electrons (or ions) cm^{-3} and T is the temperature in the (eV), the numbers of electrons in a Debye sphere N_D in cm^{-3}, and ω_p is the electron plasma frequency, as shown.

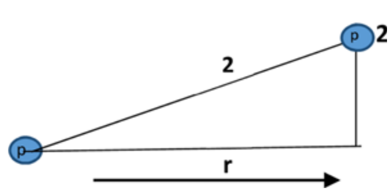

Fig. 1. Cylindrical coordinates along Projectile velocity (V) for dicluster stopping with intercharges distance r_{12}. (r_1 and r_2) denote projections perpendicular and parallel, respectively to **V**.

$$N_D = n_e\lambda_D^3 = \frac{3}{4\pi} \times 1.72 \times 10^9 \frac{[T(\text{eV})]^{1/2}}{[n_e(\text{cm}^{-3})]^{1/2}}$$

$$\omega_D = 5.69 \times 10^4 [n_e(\text{cm}^{-3})]^{1/2} \frac{\text{rad}}{\text{sec}}$$

Finally the thermal velocity, $V_{\text{th}} = \sqrt{K_B T/m_e}$ and $K_B = 1.38 \times 10^{-23}$ is the Boltzman constant.

In the classical dense plasma, dielectric formalism describe the stopping power and $W(\zeta)$ in dielectric function represents the plasma dispersion function,[19,20] where,

$$\zeta = \frac{(\omega + i\gamma)/\omega_p}{k/k_D} \tag{4}$$

with damping $\gamma \to 0$ for collisionless plasma, take

$$\zeta = \frac{\omega/\omega_p}{k/k_D}$$

Plasma dispersion function $w(\zeta)$ has been derivation from of the longitudinal electron capability for a nonrelativistic thermal electron gas. In this paper, using formula to study the propagation of waves in a hot plasma when the particle move behind it conical wave.[21]

This form of dielectric function is useful to study movement of ions in the target of plasma gas and give information about the energy loss of ions and correlated with others in case of fast ions moving with velocities perpendicular with other ion.[22]

The dielectric function of fried-Conte expression is explained below.[23]

$$\varepsilon(k,\omega) = 1 + w\left[\frac{\omega}{k}\right]\frac{1}{k^2} \tag{5}$$

While the fried-conte expression is described in eq.,

$$w(\zeta) \equiv X(\zeta) + iY(\zeta) \tag{6}$$

$$X(\zeta) = 1 - \zeta\exp\left(\frac{-\zeta^2}{2}\right)\int_0^\zeta dx\exp\left(\frac{x^2}{2}\right) \tag{7}$$

$$Y(\zeta) = \left(\frac{\pi}{2}\right)^{1/2}\zeta\exp\left(\frac{-\zeta^2}{2}\right) \tag{8}$$

$$= i\left[\frac{\pi}{2}\right]^{1/2}\zeta e^{-\zeta^2/2} + 1 - \zeta e^{-\zeta^2/2}\int_0^\zeta dy e^{y^2/2} \tag{9}$$

When $\zeta \ll 1$ the form of equation become,

$$= i\left[\frac{\pi}{2}\right]^{1/2}\zeta e^{-\zeta^2/2} + 1 - \zeta e^{-\zeta^2/2} + \frac{\zeta^4}{3} + \ldots$$

$$+ \ldots(-)^{n+1}\frac{\zeta^{2n+1}}{(2n+1)} + \ldots$$

Therefor the dicluster stopping become,

$$-\left(\frac{dE}{dx}\right) = Z_1 N_D \frac{\delta Ø_{ind}}{\delta r}\bigg|_{r=r_1(t)} + Z_2 N_D \frac{\delta Ø_{ind}}{\delta r}\bigg|_{r=r_2(t)} \quad (10)$$

Assume $\mu = \frac{\vec{k}v}{kv}$, therefor Eq. (5) become,

$$\in(k,\omega) = 1 + w(\mu v)\frac{1}{k^2}$$

$$\frac{1}{\in(k,\omega)} = \frac{1}{1+(X(\mu v)+iY(\mu v))\frac{1}{k^2}}$$

$$= \frac{k^2}{k^2 + X(\mu v) + iY(\mu v)} \quad (11)$$

Therefore,

$$\mathrm{Im}\left[\frac{-1}{\in}\right] = k^2 Y/[k^2 + X^2(\mu v) + iY^2(\mu v)] \quad (12)$$

$$\mathrm{Re}\left[\frac{1}{\in}\right] = k^2(k^2 + X^2(\mu v))/[k^2 + X^2(\mu v) + iY^2(\mu v)] \quad (13)$$

The general equation for point-like and correlated ions,

$$\left(\frac{dE}{dx}\right) = \frac{z^2 N_D}{\pi^2}\int_0^{k_{\max}} dk k^3 \int_0^1 \frac{d\mu Y(\mu V)}{[k^2 + X(\mu V)]^2 + Y^2(\mu V)}[1 +$$

$$\cos(k\mu r_1) J_0(k\sqrt{1-\mu^2} r_2) \quad (14)$$

The first term represents the energy loss of an ion impact on the electron target plasma. S_{point} is determined by the interaction of the ion with the target electrons,

$$-\left(\frac{dE}{dx}\right)_{point} = \frac{z^2 N_D}{\pi^2}\int_0^{k_{\max}} dk k^3 \int_0^1 \frac{d\mu Y(\mu V)}{[k^2 + X(\mu V)]^2 + Y^2(\mu V)} \quad (15)$$

$k_{\max} = (V^2 + 2)N_D/Z$, where V is velocity transvers (projectile velocity).

and the second term represent by pair ions correlations with the target

$$\left(\frac{dE}{dx}\right)_{corr.} =$$

$$\frac{z^2 N_D}{\pi^2}\int_0^{k_{\max}} dk k^3 \int_0^1 \frac{d\mu Y(\mu V)}{[k^2 + X(\mu V)]^2 + Y^2(\mu V)}$$

$$[\cos(k\mu r_1) J_0(k\sqrt{1-\mu^2} r_2)] \quad (16)$$

$$w(\zeta) = \frac{1}{\sqrt{2\pi}}\lim_{v\to 0} + \int_{-\infty}^{\infty} \frac{dx x e^{-x^2/2}}{x - \zeta - iv}$$

The expression of a normal Bessel functionis $J_0(x)$, $r_1(t) = Vt$ and $r_2(t) = Vt + r_{12}$, respectively where $Ø_{ind}$ denotes the electrostatic potential of one unit charge. r_1 and r_2 are the longitudinal and transversal projection of r_{12} and v. This equation usedin order to describe the response of the medium.[24]

The correlation effects of charged particles are highly important to study the stopping power in dense classical plasma.

2.1.1 Interaction of Point like projectile (un-correlation)

The stopping power formula of point-like projectile distribution in classical plasma is evaluated by using fried-Conte expression given, by Eq. (15)

$$\mu = \frac{\vec{k}v}{kv} \to \mu v = \frac{\vec{k}v}{k} = \frac{\omega}{k} \quad (17)$$

$$\left(\mu \frac{v}{v_{th}}\right) = \frac{(\omega/\omega_p)}{(k/\lambda_D)} \quad (18)$$

Where, $\lambda_D = k_D^{-1} = \frac{v_{th}}{\omega_p} \to v_{th} = \frac{\omega_p}{k_D}$

2.1.2 Interaction of pair proton (Correlation)

The correlation effects of charged particles are important to study the stopping in the dense classical plasma. The stopping power formula of fast proton with pair of projectile distribution in the classical plasma that includes the stopping of point-like and stopping pair ion (correlated) is shown in Eq. (16);[13]

2.2 Enhanced correlation stopping (ECS)

There are many methods to enhance the stopping power of the ions in the plasma, such as stopped dicluster in the target of Hydrogen. When impact of the diclusters of the ions (protons) with electrons of target generated a huge assortment of charge configurations leading to ECS.[6]

To study the ECS we adopted two equations, the first one is:

$$R_1 = \frac{S_{corr.}}{S_{stop}} = \frac{S_{corr.}}{S_{corr.} + S_{spoint}} = \frac{1}{1+\left(\frac{S_{spoint}}{S_{corr.}}\right)} \le 1 - \frac{\sum_{i=1}^{N} z_i^2}{(\sum_i z_i)^2} \quad (19)$$

Where the S_{stop}. represente the total stopping ($S_{point} + S_{corr.}$) that are defined previously. and second equation obviously related quantity of great interest is

$$R_2 = \frac{S_{corr.}}{S_{point}} = \frac{R_1}{1-R_1} \le \frac{[\sum_i z_i]^2}{\sum_i z_i^2} - 1 \quad (20)$$

Obviously the ratio of correlated to uncorrelated stopping can be seen the ratios are independent of target coupling.

3. DISCUSSION AND CONCLUSION

In this work (Eq. (10)) has been used as the key equation for stopping power calculations. Additionally Fortran program has been written for our data analysis.

As well (Eq. (10)) has been applied to evaluate the general equation stopping power of proton which contains groups of terms like K_{max}, Deby length, Deby density and Bessel function….all these parameters are helped to evaluate the energy loss as function of velocity of incident proton in plasma gas. moreover the used ratios in equations (13), (14) to enhance the stopping of (point-like, correlated and general equation of stopped) with dimensionless accuracy of velocity (v/vth) range (0 to 90) and the densities (2×10^{17}cm^{-3}) for different value of temperatures (2, 6, 10 eV).

Figure 2 and 3 demonstrate two targets plasma, dropped

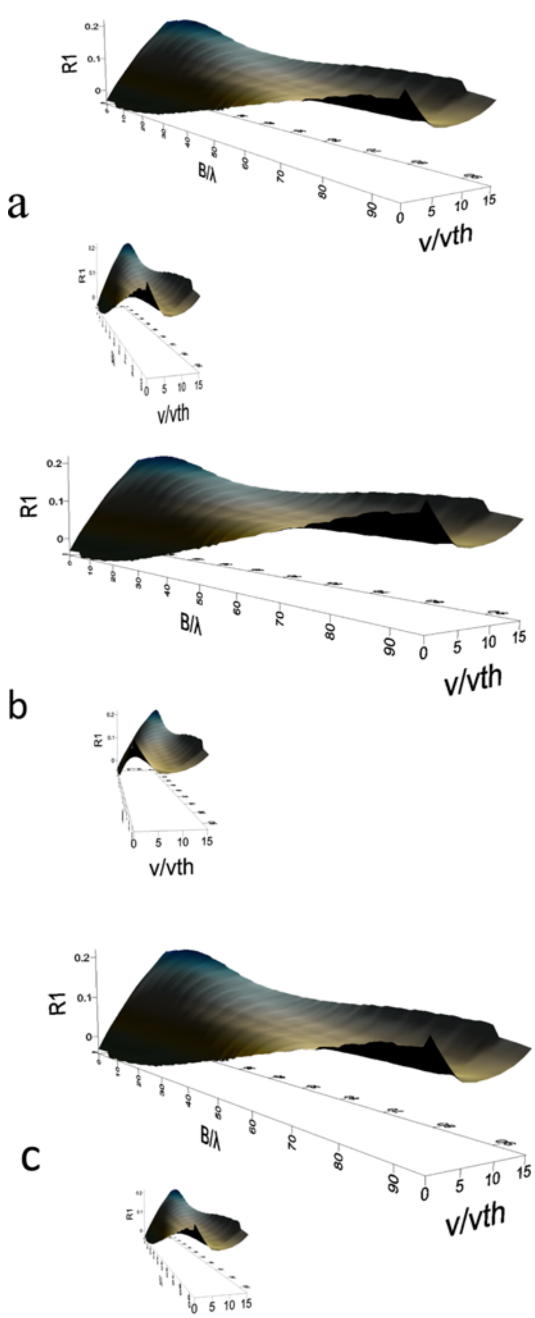

Fig. 2. Enhanced diclustr proton by use Eq. (19) where $R = \lambda_D$ for dicluster of proton with $z_1 = z_2 = z$, of dimentionless parameter, $ne = 2 \times 10^{17}$ cm^{-3}, (a) $T = 2$ eV, (b) $T = 6$ eV, (c) $T = 10$ eV.

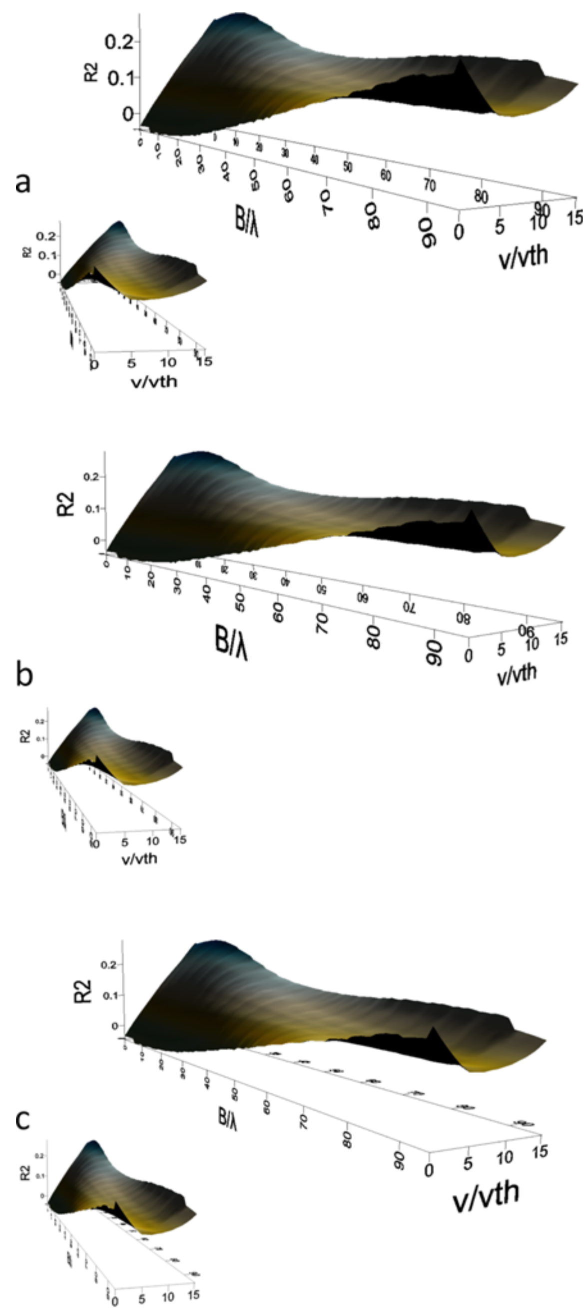

Fig. 3. Enhanced dicluster proton by use Eq. (20) where $R = \lambda_D$ for dicluster of proton with $z_1 = z_2 = z$, of dimensionless parameter, $ne = 2 \times 10^{17}$ cm^{-3}, (a) $T = 2$ eV, (b) $T = 6$ eV, (c) $T = 10$ eV.

dicluster of proton at constant density ($ne = 2 \times 10^{17}$) for different temperatures ($T = 2, 6, 10$) eV. Depicted of the term of v/vth and B/λ_D at interchange distance $R = \lambda_D$ Note, the shapes appear different in length and form of surface where increase temperature lead to increase the collisions between proton and electrons target that cause increase folds more, mean happening different stopped of proton after several collisions and (ESC) increases with v and roughly constant. That make the cloud from electrons around ions called Debye length dependent on density and temperature of target plasma according to Eq. (3).

Figure 4 has been employed enhance equations (19) and (20) at constant temperatures (2 eV) and density (2×10^{17}cm^{-3}) to show different enhanced through the two figures, where Eq. (19) shows more enhanced in the stopped because the ratio of the protons dicluster to the total stopped more interaction than the ratio of the dicluster to point-like Eq. (20) the interaction increase of the energy loss of diclusters.

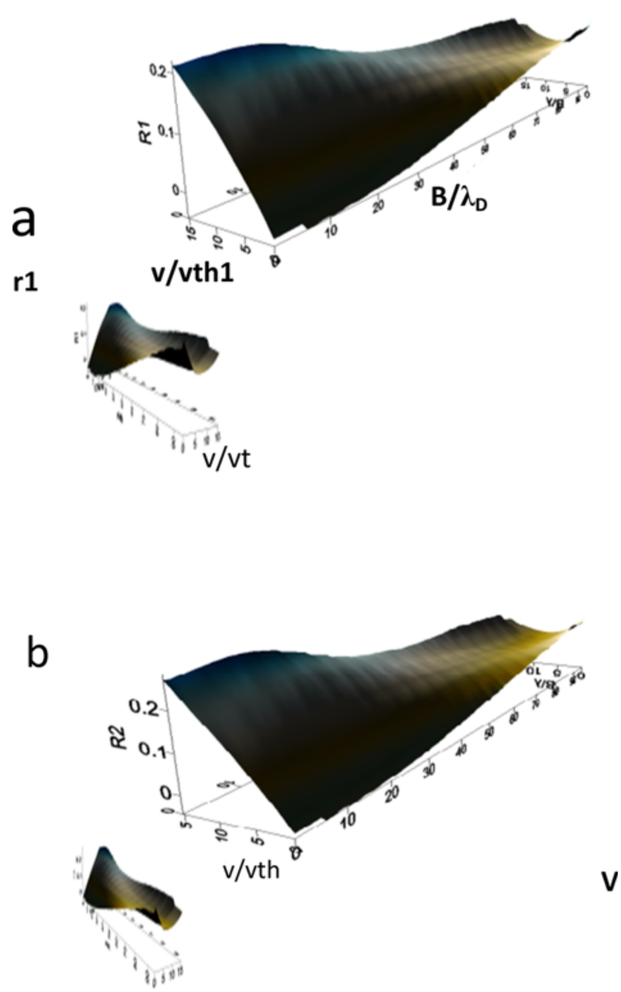

Fig. 4. (a) Eq. (19) Ratio of the correlated stopping power to the general equation of stopping power for with $z_1 = z_2 = z$, $R = \lambda_D$ and v/vth, $T = 2$ eV and $ne = 2 \times 10^{17}$. (b) same as (a) but use ratio R2 Eq. (20)

The energy loss of the incident ion affected on the target plasma is specified by the interaction of the ion with the target electrons and coulomb effect. The range of velocity incident ions depended on the number of collisions which led to lose energy and stopped .

Figure 5 used different distances (1, 2, 3, 4) a.u for the incident proton on target plasma obviously stopping proportion at to their distance, when increases the distance the collisions increase and the ratio of ionization.

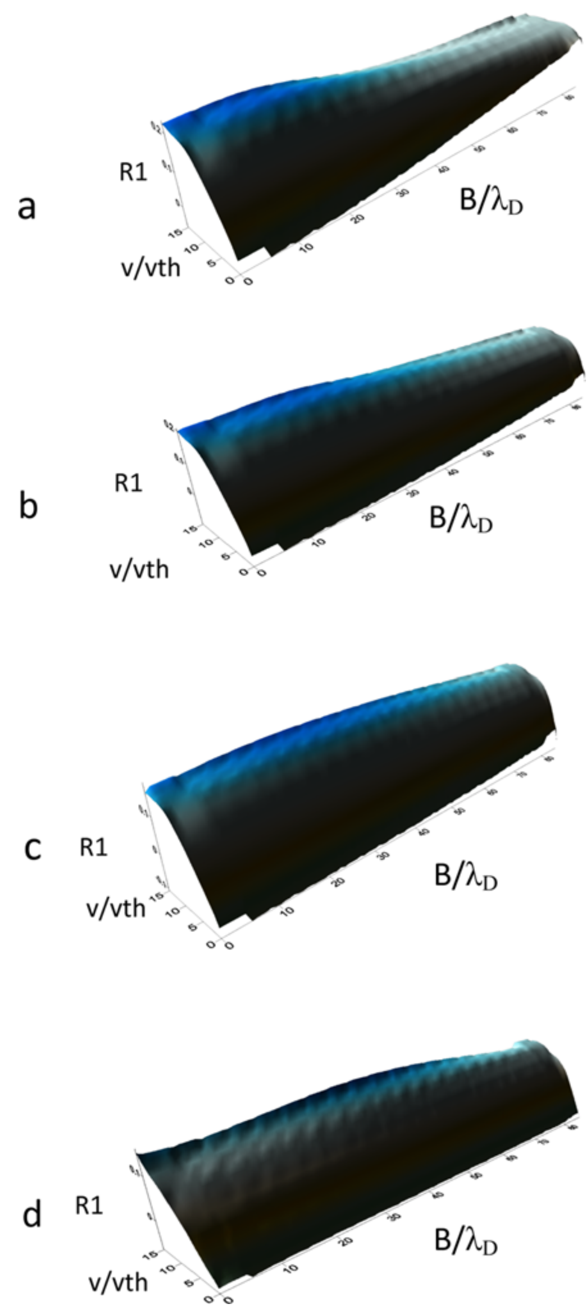

Fig. 5. (a) ratio R1 Eq. (19) for dicluster with $z_1 = z_2 = z$, $R = \lambda_D$, v/vth, T = 2 eV and $ne = 2 \times 10^{17}$ at different distence (a) $R = 1$ a.u, (b) R = 2 a.u, (c) R = 3 a.u, (d) R = 4 a.u.

4. CONCLUSIONS

Dielectric dispersion function is important in the presented work, the stopping power of proton clusters penetrating plasma has been studied theoretically and analytical for a group of parameters in classical dielectric, to calculate stopping power. Enhanced equations are solved to study stopping in plasma gas. Using these equations to study the ratio between total stopping ions to point-like and the second case represent the ratio between correlated stopping ions to point-like.

- Formation cloud of electrons around the ion called Debye length which depends on the temperature and density of the medium.
- Increasing temperature led to increase the collisions between proton and electron target. Which helpedto stop the proton in the medium such as plasma.
- Changing temperature affected on the number of folds, where the number of folds increases with increase the temperature.
- The ratio correlated ion to total stopping gave best enhanced in stopping than ratio (correlated to point-like stopping). This mean the incident ions suffer from collisions in first case more than in second case.

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