Ions energy loss measurements in low and high temperature plasma

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Abstract

Stopping power due to collisions ions with free and bound electrons in a plasma targets, is analyzed dependent on the classical-Bohr and quantized-Bloch for different temperatures. The energy loss and stopping power of ions calculated by using dielectric formalism $\varepsilon^{-1} (q, \vec{q}, \vec{v})$ and study different affects plasma parameters on the movement ions channeling in plasma target, at low (1, 1.5) eV and high (103) eV temperatures, density ($n_e = 10^{20}$) cm$^{-3}$ and Debye length ($\lambda_D = 0.2$) a.u. The results are obtained for dielectric function equation. Showed the stopping power and energy loss dependent on the plasma parameters and movement ions increases about 30%.

Keywords: Stopping power, energy loss ions, Temperatures plasma, Plasma parameters.

1. Introduction

The interaction of charged particles (incident particles) with other plasma particles is one of the main topics of complex plasmas. The study of the interaction between different particles of various targets is important for understanding the transport properties of complex plasmas, such as stopping, energy loss, frequency and Debye length. The study of the collisions particle interaction with plasmas is importance for plasma applications.[1], [2]

Stopping power has been developed in many directions. Many phenomena must be happened to complete the characterization of stopping power or energy loss in plasma. We have collected the mathematical expressions, Bloch and Beth. Many
parameters affected stopping ions in plasma and crystal such as frequency, incident angle, and velocity and ion energy.[3] [4]

Dielectric formalism important to study collisions between incident particles and electron target to describe stopping power, when the particle moves in plasma gas cause to elastic or inelastic interaction with (ion, atoms and electrons), The equation of thermal move electron is \( \nu_T = \sqrt{k_B T/m_e} \), where the thermal speed of electrons due to their random motion, and \( T \) represent plasma temperature.[5] [6]

A fast ion moving into a plasma with velocity \( \nu \) produces a wake wave behind itself, And generated thermal velocity, the range of this velocity for ions relative to the electrons is \( \nu_i > \nu_e \). The collisions of the charged particles of incident ion and ions target from order \( \frac{\nu_i}{\nu_e} / \lambda_p \) determine from the velocity and screening length \( \lambda_p \).[7][8]

Stopping in plasma is the most important method to study atoms collision. When an ion is an incident on material, many physical phenomena occur such as energy loss processes, elastic, inelastic collision, and electron scattering. All these processes depend on different parameters in target gas or plasma.[9] When electrons-target density is less than the movement of the channeling ions between the planes inside target, The energy loss of random injection becomes smaller than that of channeling ions (electrons that move between ions). [10][11][12]

The formation of channeling usually happens when ions are incident on long symmetry axes. Then, ions suffer a series of small-angle scatterings, between rows or atoms they would penetrate much further than non-channeled ions [13][14]

2. Theory

2.1 Energy loss in the plasma gas

The Bethe-Bloch stopping power formula can be used to calculate the energy loss of fast ions depending on momentum transform between particles and any type of target electrons (solid liquid gas and plasma). So, many phenomena must
be included to formulate an appropriate description for the energy loss.[15] The formula is used to calculate several physical properties, which finally gives an ability to merge atomic physics with solid-state and plasma physics.[16]

The stopping power can be divided into two parts: one includes the study of close collisions, and the other one is originated from plasma resonance by distant collisions. The aggregate form of the energy-loss formula can be taken out from a classical statement.[17] [18]

The energy-loss formula can be taken out from classical arguments. [19]

\[ S_q(v) = \frac{dE}{dx} = \frac{1}{2\pi^2 v} \int \mu d^3 q |E(\vec{q})|^2 \times \frac{\vec{q} \cdot \vec{v}}{q^2} Im \left[ \frac{-1}{\epsilon(q, \vec{q}, \vec{v})} \right] \]  

Where \( S_q(v) \) is the stopping ion with velocity \( v \) in plasma, \( E(\vec{q}) \) is the form factor of the incident ions in the plasma, \( (Im) \) is the imaginary part, \( \frac{-1}{\epsilon(q, \vec{q}, \vec{v})} \) represent the dielectric function is a function to the \( q \) and \( \omega \) where \( \omega = \vec{q} \cdot \vec{v} \) and \( \epsilon(q, \vec{q}, \vec{v}) \) is the dielectric function in plasma gas. Function \( E \) is given by the following

\[ E(\vec{q}) = \int d^3 r \rho(\vec{r}) e^{i(q \cdot \vec{r})} \]  

Where \( \rho(\vec{r}) \) is the charge density of the target, can give in atomic units, stopping ions in plasma medium characterized by dielectric function \( (\epsilon^{-1}(q, \vec{q}, \vec{v})) \) in term of the wave vector \( (k) \) and frequency of plasma \( (\omega_p) \). The energy loss of formal,

\[ \epsilon^{-1}(q, \vec{q}, \vec{v}) = 1 + \left( \frac{k_D}{k} \right)^2 - \frac{\omega_p^2}{(q \cdot \vec{v})^2} \]  

\( k_D = 1/\lambda_D \), where \( \lambda_D \) is the Debby length and equal,

\[ \lambda_D = \frac{\sqrt{\frac{e^2 k_B T}{n_e e^2}}}{\omega_p} = \sqrt{\frac{e^2 n_e}{\varepsilon_0 m_e}} \]
Where \( \varepsilon \) is the permittivity, \( T_e \) the electron temperature, \( n_e \) is the electron number density, and \( e \) is the electronic charge.

\[
\frac{1}{\varepsilon(q, \bar{q}, \vec{v})} = \left( 1 + \left( \frac{k_D}{k} \right)^2 - \frac{\omega_p^2}{(\bar{q}, \vec{v})^2} \right)^{-1}
\]

\[
\frac{1}{\varepsilon(q, \bar{q}, \vec{v})} = \frac{k^2(q, v)^2 + (q, v)^2 - k^2}{k^2(q, v)^2}
\]

\( (q, v) \approx \omega \)

\[
\frac{1}{\varepsilon(q, \bar{q}, \vec{v})} = \frac{k^2\omega^2 + \omega^2 - k^2}{k^2\omega^2}
\]

\[
\frac{1}{\varepsilon(q, \bar{q}, \vec{v})} = \frac{(\omega - k)^2}{k^2\omega^2}
\]

\[
\frac{1}{\varepsilon(q, \bar{q}, \vec{v})} = \frac{(\omega - k)^2}{k^2\omega^2} \times \frac{(\omega + k)^2}{k^2\omega^2}
\]

\[
\frac{1}{\varepsilon(q, \bar{q}, \vec{v})} = \frac{4}{\omega^2(\omega + k)^2}
\]

(4)

To solve the sin and cos in this equations let \( e^{(i\bar{q}, \vec{r})} \) equal to \( e^{-it} \) and must use spatial subroutine define in Fortran program, we get

\[
E(q) = \int_{-\infty}^{\infty} e^{-it} dt
\]

(5)

\[
E(x + iy) = \int_{-\infty}^{\infty} \cos \frac{t}{x} dt - i \int_{-\infty}^{\infty} \sin \frac{t}{x} dt
\]

(6)

Then,

\[
Si(q) = \int_{0}^{x} \sin \frac{t}{x} dt \quad \text{and} \quad Ci(q) = \gamma + \ln(x) \int_{0}^{x} \frac{\cos\frac{t}{x} - 1}{t} dt
\]

(7)

\( \gamma = 0.577215664901533 \) (Euler’s constant)

\[
E(q) = -Ci(y - ix) - i \frac{1}{2} \pi - Si(y - ix)
\]

(8)

Si (x) approaches \( \pi/2 \) as \( x \to \infty \) and Ci (x) approach 0 as \( x \to \infty \), this series expansions also calculate the integrals:

\[
Si(q) = \sum_{n=0}^{\infty} (-1)^n \frac{q^{2n+1}}{(2n+1)(2n+1)!}
\]

(9)

\[
Ci(z) = \gamma + \ln(z) + \sum_{n=1}^{\infty} \frac{(-1)^n q^{2n}}{(2n)(2n)!}
\]

(10)

Where Si and Ci are complex sin and cos functions.
The $\mu$ in equation (1) can solve,
\[
\mu = \frac{q\, v}{q\, v} \Rightarrow \mu v = \frac{q\, v}{q} = \frac{\omega}{k}
\]
\[
\left( \frac{\mu}{v_{th}} \right) = \left( \frac{\omega/\omega_p}{(k/\lambda_D)} \right)
\]
\[
\lambda_D = k_D^{-1} = \frac{v_{th}}{\omega_p} \Rightarrow v_{th} = \frac{\omega_p}{k_D}
\]
\[
\left( \frac{\mu}{v_{th}} \right) = \frac{\omega}{(k\, v_{th})} = \frac{\omega}{k\, (\omega_p/k_D)} = \left( \frac{\omega/\omega_p}{(k/k_D)} \right)
\]
\[
\mu = \frac{k\, v \cos \theta}{k\, v} \Rightarrow \mu = \cos \theta
\]
\[
\sin \theta = (1 - \mu^2)^{1/2}
\]

Using eq. (4), (9) and (10) in eq.(1) and solution the equation numerically and analytically, Programming eq.(1) in a Fortran program dependent on the plasma conditions ($\lambda_D, T$) and translate the data in the form of figures.

From equation (11) and (12) can evaluate the angle of the collisions incident ions with target. Figure (1) appear incident ion on the material, under conditions of plasma (different temperature and density).

a) First case collision ion with electron, see the electron movement in Straight line without suffer and interaction inside material (channeling).

b) Second case represent collision ion with electron target, the electron suffer interaction with atoms and scattering with a certain angle (un channeling).
A theoretical treatment of the incident ions in plasma first provided within the dielectric formalism. The energy loss of slow or speed ions in different target plasma was analyzed for an electron gas (plasma) at low and high temperature targets besides the effects of the Debye length, velocity, frequency, and incident angle on stopping power in plasma. Using classical-Bohr correction and quantized-Bloch correction in this work.[20]

Figure 1: Critical angle for incident ion in a material

Figure 2: Random stopping power (a.u) as a function of thermal velocity in MeV for incident ions (Ar,O) on Plasma target (Na, Li)
Figure 3: Stopping power of incident ions H on Li and Au targets as a function of Debye length, $\lambda_d$, at $n_e=10^{20}$ cm$^{-3}$ and $10^3$ eV.

Figure 4: Plasma frequency as a function of velocity (Li, Fe, and Au) in the H plasma target for two temperature blue curves (1 eV) and red curve (1.5 eV).
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3. Discussion

The plasma parameters can determine from study different corrections, such as classical-Bohr and quantized-Bloch correction. Movement the ion inside plasma caused waves, from these waves can appear modes of the electrons and ions gas in the plasma. The usual definition of weakly coupled or ideal plasma is the requirement that there are many electrons inside the electron Debye sphere. This ensures that Debye shielding is a collective process and that the statistical derivation of a Debye length was correct.

From figure (1) appear the channeling of ions occurs when particles get into a target stratify with atomic planes. In bent target, the particles are fallen between atomic planes and follow the target bend being deflected. The particle is reflected in the opposite direction if it is tangent the bent crystal plane.

Figure (2) represents the stopping power in (a.u) as a function of $v_{th}$ in MeV for incident ion (O, Ar) on different targets (Ca, Fe, Rn, Na, and Li) studied, observe the velocity thermal for ion Li don’t appear and Applies on the x-axis because is the lest atomic number and don’t suffer more collisions, and the other curves increasing with thermal velocity.

Figure 5: Energy loss of incident ion (H) as a function of ion velocity in plasma target (H,Ne) at angle 30°
Affect the Debye length parameter appear in Figure (3) stopping power of incident ions H on (Li and Au) targets as a function of Debye length at $n_e=10^{20}$ cm$^{-3}$ and $10^3$ eV. Debye length increases with the atomic number and the density of electron. From Figure (4) showed effect different temperature on the frequency, when draw plasma frequency as a function of velocity for (Li, Fe, Au) in hydrogen plasma target with two temperatures (1 and 1.5) eV, the red curved appear affected the temperature on the move ions and increasing the vibration on ions inside plasma.

In figure (5) the energy loss as a function of incident ion velocity at $30^0$. where the ions move in different directions in the target between atoms channeling (H-H) so note more curves these mean particles move without collision. And when collisions (H-Ne) in the second figure, because the atomic density of Ne notes fewer curves because of the ion collisions with electrons or atoms and back with marker angle.

4. Conclusion

Investigated numerically dielectric functions in gas plasma. This is performed for different thermal velocity values $\nu(0.1$ to $150)$ MeV, to study random stopping power for the incident (O, Ar) on different targets (Ca, Fe, Rn, Na, and Li) note the reverse behavior random collisions is reduced. We observed that the oscillating wake effects occur behind the particle that is situated opposite to the direction of the particle motion in the material.

Movement ions in the channeling are investigated theoretically when incident ion glancing to atoms where the energy loss in channeled is smaller than un-channeled. That is because the number of collisions is less with atomic. Channeled occur when incident ion with an angle larger than the critical angle, where critical angle dependent on the velocity of incident ion. There is two types of collision occur
inside plasma close and distant collision. Close collision dependent on the density of electron and the distant collision un-dependent on the path of ion.

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