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Stopping Power and Partial Stopping Power Effective Charge in The Plasma

Maryam Y. Abdullah, Baida M. Ahmed, Khalid A. Ahmad[*]

Department of Physics, College of Science, Mustansiriyah University, Baghdad, IRAQ.

*Correspondent author email: kkmsl4591@uomustaniriyah.edu.iq

ABSTRACT

The energy losses of ions moving in an electron gas can be studied through the stopping power of the medium. A large number of calculations of the stopping power of ions and electrons in plasmas have been carried out using the random phase approximation (RPA) in the dielectric formalism, for low and high energies. Then we calculated the partial stopping power effective charge (PSPEC) from the energy loss of an incident proton, Ar-ion, and He-ion in target plasma. The Brandt-Kitagawa (BK) model is used to describe the projectile charge fraction (q) and calculate the stopping power and PSPEC, which depends on temperature and electron density $\rho_{(k)}$ of the plasma. This is a topic of relevance to understanding the beam-target interaction in the contexts of particle driven fusion. The presented study is formulated in terms of classical dielectric functions. The programming language Fortran - 90 was used for a required calculation. In the present work, three systems of plasma (Z-pinch, Tokamak, ICF) for different temperatures and densities were covered. Additionally, a comparison has been done with the previous work of plasma.

KEYWORDS: Stopping Power; partial stopping power; Charge state in plasma; Energy loss; Dielectric function.

INTRODUCTION

Stopping power is a general concept of interacting with the material medium. It is normally utilized for charged particles (ions or electrons). It depends on the type of charged particle or projectile (usually some ionized atom), the target material or host (phase, density and temperature conditions), Also it depends on the kinetic energy (typically in keV or MeV) or equivalently in the velocity of the charged particle[1]. The charge density of the projectile is described by the statistical model proposed by Brandt and Kitagawa (BK), where the effective charge of energetic ions is calculated in the dielectric response approximation[2]. In the dielectric formalism, the electron response of a homogeneous material to a perturbation produced by an external charge density, $\rho_{ext}(r,t)$, is contained in the dielectric function (DF) to calculate the electronic stopping is well known, in the atomic unit, a.u.[3],

$$S = \frac{2(Ze)^2}{\pi v^2} \int_0^\infty \frac{dk}{k} [\rho_{ext}(k,\omega)]^2 \int_0^{kv} \omega . d\omega . Im\left[\frac{-1}{\epsilon(k,\omega)}\right] \quad (1)$$

where $\rho_{ext}(k,\omega)$, is Fourier transforms of the projectile charge density, v is velocity, in a medium characterized by a dielectric function $\epsilon(k,\omega)$, in terms of the wave vector k and frequency ω .The charge-state q of a projectile, with atomic number Z, moving through a condensed medium can vary due to electron-capture and -loss processes[4].

Since then, the theory of energy losses has been related to the employment of the dielectric formalism. The ions moving within condensed matter lose their energy due to various interactions with atoms, ions and electrons[5]. Dielectric formalism has become one of the most used methods to describe stopping power. The use of this formalism was introduced by Fermi[6]. Subsequent developments made it possible to extend the dielectric formalism to provide a more comprehensive description of the stopping of ions in the matter[7],[8]. The main purpose of this work is to understand the interaction of protons beams with high temperature and density targets, partially or fully ionized plasma. Besides, it can

be extended to other fields of plasma physics like plasma analysis, heating, and doping, X-ray production and Scattering, production and diagnostics of warm dense matter and cosmic rays. The choice of the proton, as the constituent particle of a beam that interacts with the plasma, has the advantage that stopping power only depends on the medium characteristics, ion and electron density, temperature, etc.[9].

THEORY

Dielectric function
The first problem to be considered now is the evaluation of the energy loss, using the dielectric formulation. The present study covers the ranges of interest for inertial confinement fusion, Z-pinch and Tokamak plasmas. Energy loss of ions penetrating dense plasmas is given by equations stopping power. Where the stopping power of a point particle moves in the medium as plasma with charge Ze and velocity v , described by a dielectric function $\in_{(k,\omega)}$ inform wave vector kind energy transfer frequency ω[10]as,

$$S = \frac{2(Ze)^2}{\pi v^2}\int_0^\infty \frac{dk}{k}\int_0^{kv}\omega . d\omega . Im\left[\frac{-1}{\in(k,\omega)}\right] \qquad (2)$$

In classical plasma

$$\in(k,\omega) = 1 + \left(\frac{k_D}{k}\right)^2 W(\xi) \qquad (3)$$

$W(\xi)$ is the plasma dispersion function.

$$\xi = \frac{(\omega + i\Upsilon)/\omega_p}{(k/k_D)} \qquad (4)$$

For collision plasma, we will take the damping $\Upsilon \to 0$,
Where ω_p is the plasmon frequency and k_D is the wavenumber.

$$\omega_p = \sqrt{\frac{4\pi n_p e^2}{m}}, \quad v_T = \sqrt{\frac{K_B T}{m}}, \lambda_D = K_D^{-1} = \left(\frac{v_T}{\omega_P}\right) = \frac{1}{k_D}$$

Where n_p is the density, T is the electron temperature, λ_D is Debye length, v_T is the thermal velocity, and K_B is Boltzmann constant.
Let:

$$W(u) = X(u) + iY(u) \qquad (1)$$

Where the functions,

$$X(u) = 1 - u\, e^{-u^2/2}\int_0^u dx\, e^{x^2/2} \qquad (2)$$

$$Y(u) = \sqrt{\frac{\pi}{2}}u\, exp(-u^2/2) \qquad (7)$$

With $u = (\omega/\omega_P)/(k/k_D)$, the imaginary parts of Eq(1):

$$Im\left[\frac{-1}{\in(k,\omega)}\right] = \frac{\left(\frac{K}{K_D}\right)^2 Y(u)}{\left[\left(\frac{K}{K_D}\right)^2 + X(u)\right]^2 + Y^2(u)} \qquad (3)$$

Therefore, the stopping power becomes,

$$S_O = \frac{Z^2 2\omega_P{}^2}{\pi v^2}\int_0^\infty \frac{k^3 dk}{k_D{}^4}\int_0^{v/v_T} ZdZ \frac{Y(u)}{\left[\left(\frac{K}{K_D}\right)^2 + X(u)\right]^2 + Y^2(u)} \qquad (9)$$

The stopping power formula will be given in the atomic units.

Charge state in plasma
The charge state model for a projectile of atomic number Z with N_e bound electrons; the partial effective charge (q) of stopping power is defined by [11]:

$$\xi_{(q)}^2 = \frac{S_{(q)}}{S_{(q=1)}} \qquad (10)$$

where $q = 1 - (N_e/Z)$ is the ionized fraction of the projectile (charge fraction), $S_{(q=1)}$ is the stopping power for the nucleus of the projectile. The stopping power of a single charged projectile $S_{(q)}$ can be expressed in an integral in terms of the random-phase approximation (RPA) dielectric function [2],[12]. The stopping power of a singly charged projectile can be expressed S_q as in equation (1), $\rho_{(k)}$ is given by[2]:

$$\rho_{(k)} = Z\frac{q + (k\Lambda)^2}{1 + (k\Lambda)^2} \qquad (11)$$

Where Λ is the screening length given by Brandt-Kitagawa (1982)[2],

$$\Lambda = \frac{0.48N}{Z - (N/7)} \qquad (12)$$

The Λ parameter value increases with the number of electrons bound to the projectile. Moreover, with the increasing atomic number of the projectile Z, the value of Λ for N=Z is lower[3]. Therefore, at $q \to 1$, $\rho_{(k)} \to Z$. An important aspect when calculating the electronic stopping of ions must know the projectile charge state. The charge state of projectiles passing through fully ionized plasmas was first studied by Nardi and Zinamon[11],[13]who showed theoretically that the charge state is significantly higher than when the same projectiles pass through solids. Later, this effect was verified experimentally [14]. The charge state of the projectile increases when passing through a target (projectile loses electrons) principally by collisions with target ions, but it also decreases due to the capture of the electrons bound to the ions. There are other effects

that change the charge state of the projectile, but these are the two dominant mechanisms[2].

RESULT AND DISCUSSION

The main purpose of this work is to understand the interaction of ion beams with these high temperatures and density targets, partially or fully ionized plasma. In this work, we calculate stopping power and partial stopping power effective charge (PSPEC) by studying the interaction of particles (heavy ion) on the plasma and the effects of the charge state in it by using a program (Fortran 90), which is shown in the diagram (appendix A). The effects of charge state on stopping power in plasma for different velocities and different charge fractions q in three systems (Z-pinch, Tokamak, ICF). Figure 1 Shows the stopping power as a function of velocity, $q \rightarrow 1$, $\xi_{(q \rightarrow 1)}$ and at different values of charge fraction, q, $\xi_{(q)}$. The stopping power at fully ionized, $q \rightarrow 1$, (i.e $\rho_{(q \rightarrow 1)} \rightarrow 1$ is higher than the stopping power as a function of charge exchange q, and $\rho_{(q)}$.
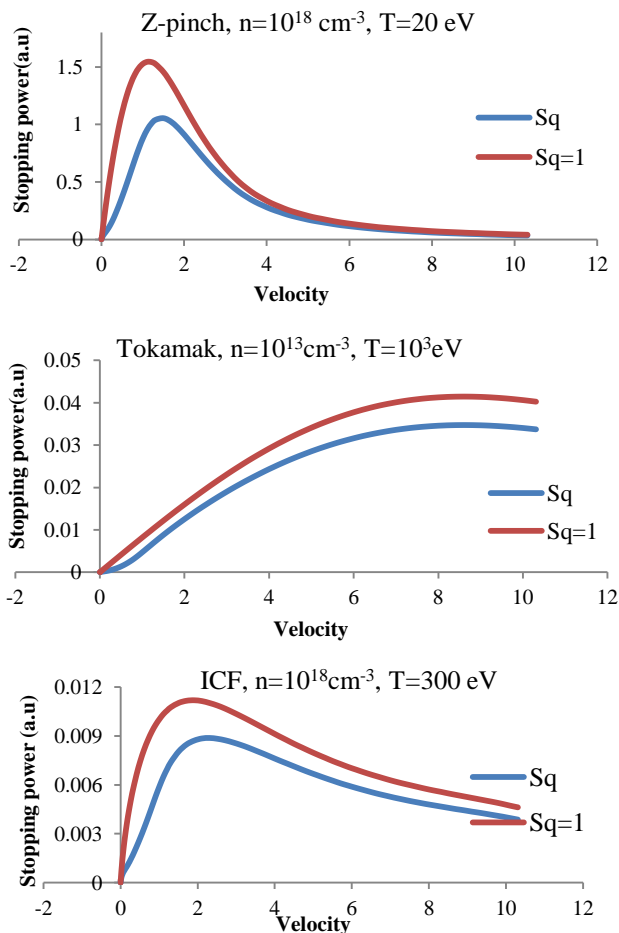

Figures Show the stopping power as functions of velocity by charge fraction effects, when incident proton in Z-pinch systems, obvious the stopping power (interactions between ion and medium) increasing at the nuclear zone and show a peak at a point 0.88 approximately then it starts to get down so fast at the electronic zone. this means Z-pinch system works in the nuclear zone larger than the electronic zone.

In Tokamak system stopping power direct proportional with velocity v, its increasing at the nuclear zone, then it becomes fixed at 0.0339 approximately. these mean work at low velocity more (nuclear interaction).

In the ICF system stopping power increasing at the nuclear zone and get down so slow at the electronic zone and compared with paper W. Brandt and M. Kitagawa (1982) [2].

Effects of the atomic number of PSPEC

Partial stopping power depends strongly on the atomic number of incident ions. Where the atomic number Z depends on charge fraction $q = 1 - \frac{N_e}{z}$. This means, q increases with Z, so the stopping power must have effects with the variation of ions atomic number Z.

For three systems, note the effect of the charge (q) on the partial stopping power effective charge (PSPEC) by changing the atomic number. Figures 2 and 3 show the PSPEC for different incident ions (different atomic numbers). Using helium (He) z=2 and argon (Ar) z=18 in three systems Z-pinch, Tokamak, and ICF plasma. Obvious where the incident (He) on plasma, energy loss becomes higher than (Ar), due to the atomic number as shown in Table 1.

To understand the influence of atomic number in plasma stopping power, we have performed a simulation, where helium (He) or argon (Ar) ions travel inside a plasma target. By increasing the atomic number, the ion becomes heavy and the ability to energy loss in the target decreases and compared with paper M. D. Barriga-Carrasco (2013) [3].

Figure 1. Stopping power of proton as a function of velocity at q and q=1, for Z-pinch, Tokamak, and ICF systems.

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Table 1. The partial stopping power $\xi_{(q)}$ at q=0 for Z-pinch, Tokamak, and ICF plasma with the different atomic numbers of incident ions z=(2,18) with different velocity.

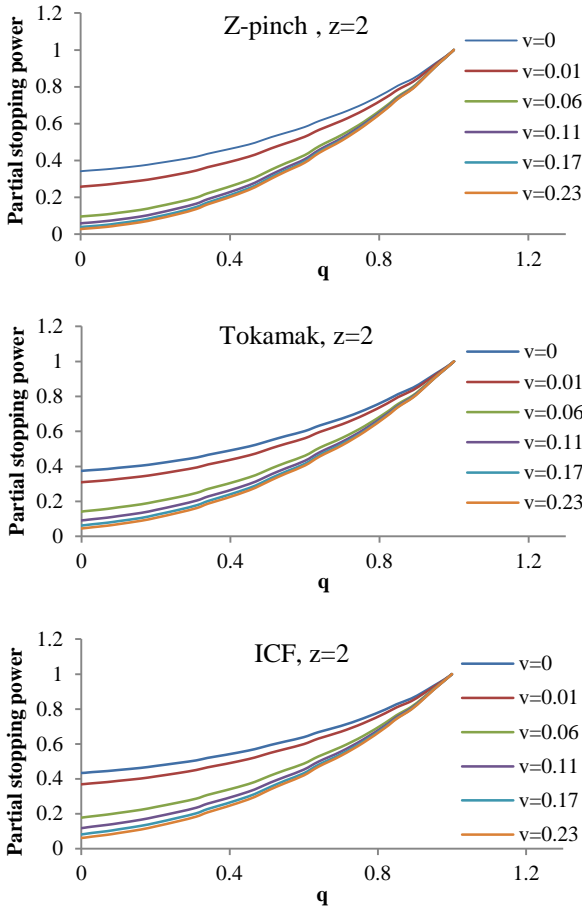|	z-pinch		Tokamak		ICF	
v	$\xi_{(q)}$ Z=2	$\xi_{(q)}$ Z=18	$\xi_{(q)}$ Z=2	$\xi_{(q)}$ Z=18	$\xi_{(q)}$ Z=2	$\xi_{(q)}$ Z=18
0	0.341	0.263	0.374	0.289	0.434	0.335
0.01	0.257	0.184	0.309	0.221	0.369	0.264
0.06	0.095	0.048	0.141	0.071	0.178	0.09
0.11	0.058	0.025	0.091	0.039	0.118	0.051
0.17	0.038	0.014	0.062	0.023	0.082	0.031
0.23	0.027	0.01	0.045	0.016	0.062	0.022

Figure 2. Partial stopping power effective charge (PSPEC) of helium (He) beam z=2 as a function of their charge fraction (q) at different velocities, for Z-pinch, Tokamak, and ICF systems.
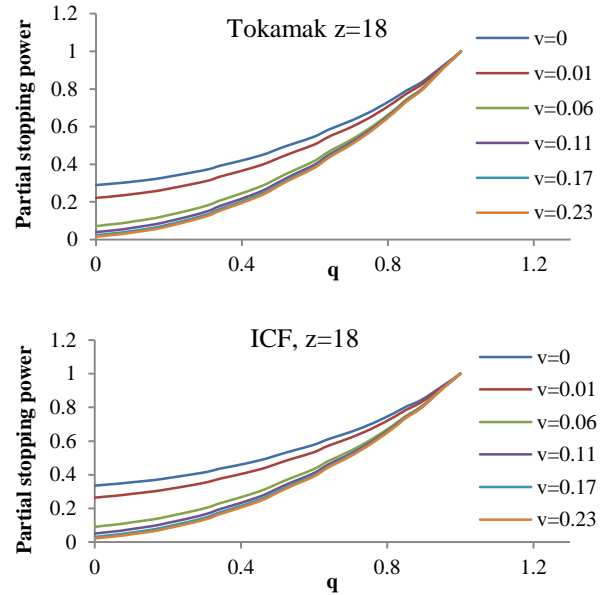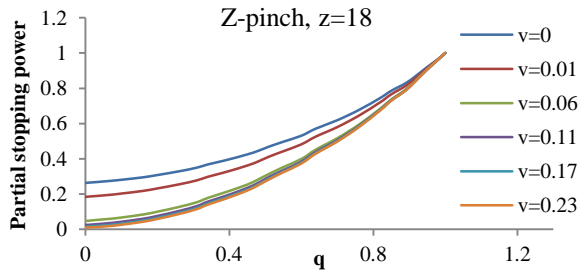

Figure 3. Partial stopping power effective charge (PSPEC) of Argon (Ar) beam z=18 as a function of their charge fraction (q) at different velocities, for Z-pinch, Tokamak, and ICF systems.

Effects of Debye length on PSPEC.

The Debye length is an important physical parameter for the description of the plasma. It provides a measure of the distance over which the influence of the electric field of an individual charged particle is felt by the other charged particles inside the plasma. The charged particles arrange themselves in such a way as to effectively shield any electrostatic fields within a distance of the order of the Debye length[15].

Figures 4, 5 and 6 Show the PSPEC, $\xi_{(q)}$ as a function of charge fraction q at different values of Debye length (λ_D) for Z-pinch, Tokamak, and ICF systems. One can see in Table 2 that the energy loss decreases with increasing of the Debye length because the distance between the projectiles become is large at different velocity.
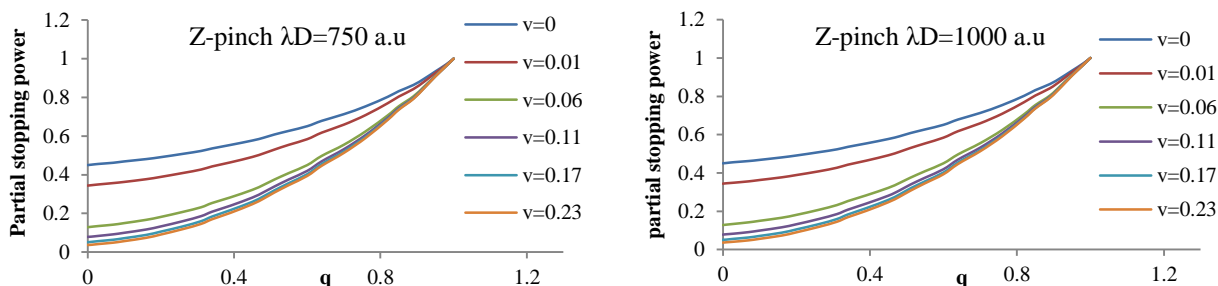
Figure 4: PSPEC of proton in plasma as a function of charge fraction q for Z-pinch system at Debye length λ_D=(750, 1000)a.u.
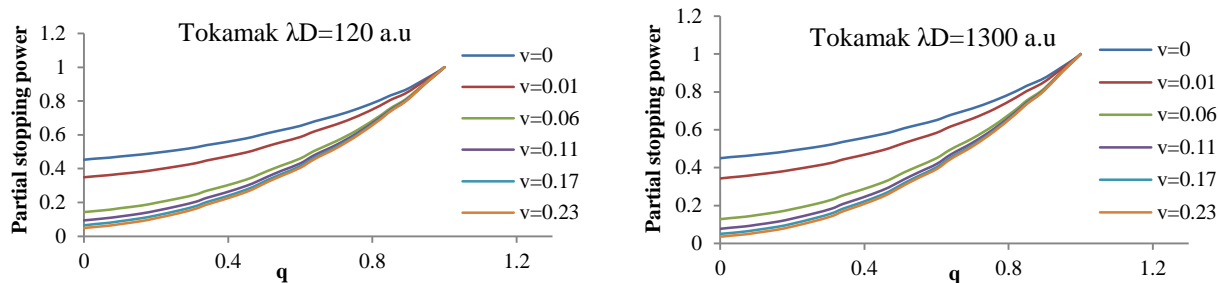

Figure 5: PSPEC of proton in plasma as a function of charge fraction q for Tokamak system at Debye length λ_D=(120, 1300)a.u.
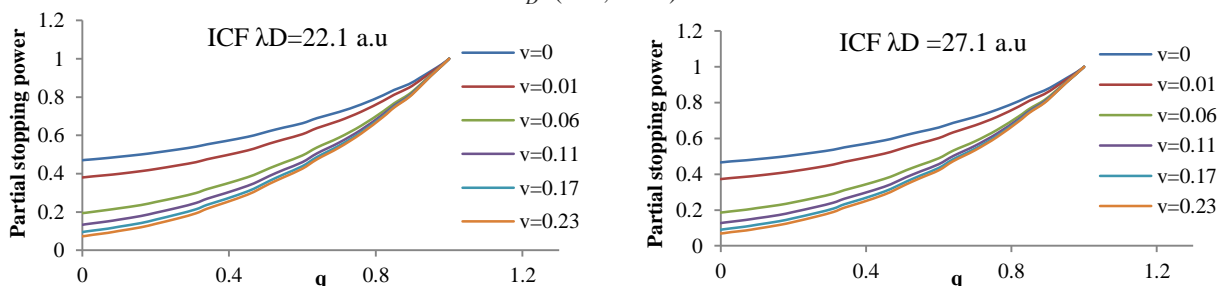

Figure 6. PSPEC of proton in plasma as a function of charge fraction q for ICF system at Debye length λ_D=(22.1, 27.1)a.u.

Notes the PSPEC,$\xi_{(q)}$ at different velocities v=(0,0.01,0.06,0.11,0.17 and 0.23 a.u) and λ_D=(750 and 1000 a.u) for Z-pinch, λ_D=(120,1300 a.u) for Tokamak and λ_D=(22.1, 27.1a.u) for ICF. One can notice that for Tokamak and ICF, $\xi_{(q)}$ inversely proportional with λ_D and for Z-pinch, approximately there is no effects of λ_D on $\xi_{(q)}$, and compared with paper E. Bringa and N. Arista (1996) [10].

Table 2: The partial stopping power (PSPEC),$\xi_{(q)}$, at q=0 for Z-pinch, Tokamak, and ICF plasma with different Debye length.

v	z-pinch		Tokamak		ICF	
	λ_D=750	λ_D=1000	λ_D=120	λ_D=1300	λ_D=22.1	λ_D=27.1
0	0.45	0.45	0.453	0.45	0.47	0.466
0.01	0.344	0.344	0.349	0.343	0.38	0.373
0.06	0.129	0.128	0.143	0.128	0.194	0.186
0.11	0.079	0.078	0.094	0.077	0.133	0.127
0.17	0.051	0.051	0.065	0.05	0.095	0.09
0.23	0.037	0.036	0.049	0.036	0.073	0.069

CONCLUSION

In this work, the energy loss of ion beams in plasmas have been calculated by (BK) model, for different systems. This energy loss caused by the stopping power for(free and bound electrons) has been analyzed using the mean for the random phase approximation RPA dielectric function. So, show the necessity of using the (BK) electron density distribution in combination with the charge state. As shown in figures $\xi_{(q)}$ inversely with incident ion velocity (v). The stopping power depends on ions velocity, and plasma properties through the

function $Im\left[\frac{-1}{\epsilon(k,\omega)}\right]$ that is usually named energy loss function. Its charge state varies for three systems as affected by the charge fraction (q) where the stopping power at $q\rightarrow1$, $\xi_{(q\rightarrow1)}$ is higher than the stopping power at q, $\xi_{(q)}$ $(S_{(q=1)}>S_q)$ in Z-pinch, Tokamak, and ICF systems. When an applied incident ion (He) the ratio PSPEC is higher than that for incident ion(Ar) for Z-pinch, Tokamak, and ICF systems. The values of (ξ) have a significant dependence on the velocity at low charge state (q=0) While the dependence becomes less important at high charge state (q>0). This means interactions dependent on the charge fraction $q=1-(N/Z)$ and screening length Λ. Also affected by applied different values of Debye length λ_D, note the energy loss is decreasing where the Debye length λ_D is increasing about 41.3%, which depends on the temperature and density of the medium.

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APPENDIX-A

Algorithm for the program (Fortran 90)