



Influence of dynamic screening on the electron-ion bremsstrahlung process in turbulent plasmas

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Introduction

- The bremsstrahlung process has received considerable attention in many areas of physics and x-ray astronomy since this process is known to be one of the most fundamental radiation processes in astrophysical plasmas and the bremsstrahlung radiation due to the electron-ion binary encounters has been widely used as the plasma diagnostic tool for investigating various plasma parameters.
- In turbulent plasmas, it has been shown that that the projectile electron in a plasma would be affected by the random fluctuating electric fields since the response of the random field fluctuations plays an important role in the binary encounters and interaction potentials.
- The effective screened potential model including the far-field term obtained by the longitudinal non-linear dielectric function associated with turbulent plasmas has been applied to describe the screened electron-ion interactions in turbulent plasmas.



- Additionally, it has been known that the statically screened interaction potential would not be reliable to describe the electron-ion collision in plasmas when the velocity of the projectile particle is comparable to or smaller than the velocity of the plasma electron since the projectile particle readily polarizes the surrounding plasma particles.
- Hence, the electron-ion interactions in turbulent plasmas would be different from those in non-turbulent plasmas due to the influences of the dynamic screening and random fluctuation of the electric field.
- The dynamically screened effective potential is obtained by the effective interaction potential including the influence of the plasma turbulence due to the random fluctuating electric fields apart from the standard Debye-Hückel shielding term with the dynamic Debye screening length to describe the appropriate electron-ion interaction in turbulent plasmas.
- The impact-parameter analysis is applied to investigate the dynamically shielded electron-ion bremsstrahlung cross section in astrophysical turbulent plasmas as a function of the Debye length, diffusion coefficient, impact parameter, projectile energy, photon energy, and thermal energy.

Calculations

- For the case of dipole emission by the projectile electron, the photon emission probability for all impact parameters b :

$$dw_{\omega}(b) = \frac{8\pi e^2}{3\hbar c^3} |\mathbf{a}_{\omega}|^2 \frac{d\omega}{\omega}$$

- Fourier transform of the electron acceleration: $\mathbf{a}_{\omega}(b) = (2\pi)^{-1} \int_{-\infty}^{\infty} dt \mathbf{a}(t) e^{i\omega t}$

- The expression of the electron-ion bremsstrahlung cross section is given by the integration over the impact parameter b :

$$d\sigma = 2\pi \int db b dw_{\omega}(b) = \frac{16\pi^2 e^2}{3\hbar c^3} \int db b |\mathbf{a}_{\omega}(b)|^2 \frac{d\omega}{\omega}$$

- The effective interaction potential $V_{eff}(r, \theta)$ between the electron projectile and ion target with nuclear charge Ze for $v < v_T$ and $r > \lambda_D$ including the additional terms caused by the random fluctuating electric fields in turbulent plasmas would be obtained by

$$V_{eff}(r, \theta) = -\frac{Ze^2}{r} \exp\left[-\frac{r}{\lambda_D(1+v^2/v_T^2)^{1/2}}\right] - \frac{Ze^2}{r} \frac{2\sqrt{2}}{\sqrt{\pi}} \cos\theta \left[\frac{\lambda_D(1+v^2/v_T^2)^{1/2}}{r}\right]^2 \left(\frac{v}{v_T}\right) \left(1 - \frac{9}{4}\sqrt{\pi} \frac{D}{v_T^3} r\right) \quad (\text{Shukla \& Spatschek})$$

$r [= (b^2 + z^2)^{1/2}]$, θ : the angle between \mathbf{v} and \mathbf{r} .

- The effective interaction potential $V_{eff}(r, \theta)$ encompasses the additional terms owing to the influence of random fluctuating electric fields apart from the standard Debye-Hückel term.

- The scaled parallel and perpendicular Fourier force components:

$$\begin{aligned} \bar{F}_{\parallel\omega}(\bar{b}, \eta, v, v_T, \bar{r}_D, \bar{D}) &= -\frac{\pi v a_z}{Ze^2} \left(\frac{\mathbf{v} \cdot \mathbf{F}_{\parallel\omega}}{v} \right) \\ &= \int_0^\infty d\tau \cos(\eta\tau) \left[-\frac{2\sqrt{2}}{\sqrt{\pi}} \bar{r}_D^2 \left(1 + \frac{v^2}{v_T^2} \right) \left(\frac{v}{v_T} \right) \left(-\frac{4\tau^2}{\bar{r}^6} + \frac{1}{\bar{r}^4} \right) \right. \\ &\quad \left. + \frac{9\sqrt{2}}{2} \bar{r}_D^2 \left(1 + \frac{v^2}{v_T^2} \right) \left(\frac{v}{v_T} \right) \bar{D} \left(-\frac{3\tau^2}{\bar{r}^5} + \frac{1}{\bar{r}^3} \right) \right] \\ &\quad + i \int_0^\infty d\tau \sin(\eta\tau) \left(\frac{\tau}{\bar{r}^3} + \frac{\tau}{\bar{r}^2 \bar{r}_D (1 + v^2/v_T^2)^{1/2}} \right) \exp\left(-\frac{\bar{r}}{\bar{r}_D (1 + v^2/v_T^2)^{1/2}} \right) \end{aligned}$$

$$\begin{aligned} \bar{F}_{\perp\omega}(\bar{b}, \eta, v, v_T, \bar{r}_D, \bar{D}) &= -\frac{\pi v a_z}{Ze^2} \left(\frac{\mathbf{b} \cdot \mathbf{F}_{\perp\omega}}{b} \right) \\ &= \int_0^\infty d\tau \cos(\eta\tau) \left(\frac{\tau}{\bar{r}^3} + \frac{\tau}{\bar{r}^2 \bar{r}_D (1 + v^2/v_T^2)^{1/2}} \right) \exp\left(-\frac{\bar{r}}{\bar{r}_D (1 + v^2/v_T^2)^{1/2}} \right) \\ &\quad + i \int_0^\infty d\tau \sin(\eta\tau) \left[-\frac{2\sqrt{2}}{\sqrt{\pi}} \bar{r}_D^2 \left(1 + \frac{v^2}{v_T^2} \right) \left(\frac{v}{v_T} \right) \left(-\frac{4\tau^2}{\bar{r}^6} + \frac{1}{\bar{r}^4} \right) \right. \\ &\quad \left. + \frac{9\sqrt{2}}{2} \bar{r}_D^2 \left(1 + \frac{v^2}{v_T^2} \right) \left(\frac{v}{v_T} \right) \bar{D} \left(-\frac{3\tau^2}{\bar{r}^5} + \frac{1}{\bar{r}^3} \right) \right] \end{aligned}$$

- The electron-ion bremsstrahlung cross section in turbulent plasmas:

$$d\sigma(\bar{b}, \eta, v, v_T, \bar{r}_D, \bar{D}) = \frac{16}{3} \frac{\alpha^3 a_0^2}{\bar{E}} \frac{d\omega}{\omega} \int d\bar{b} \bar{b} \left[\left| \bar{F}_{\square\omega}(\bar{b}, \eta, v, v_T, \bar{r}_D, \bar{D}) \right|^2 + \left| \bar{F}_{\perp\omega}(\bar{b}, \eta, v, v_T, \bar{r}_D, \bar{D}) \right|^2 \right]$$

- The dynamic bremsstrahlung radiation cross section $d\chi/d\bar{\varepsilon} \equiv (d\sigma/\hbar d\omega)\hbar\omega$:

$$\begin{aligned} \partial^2 \bar{\chi}(\bar{b}, \bar{\varepsilon}, \bar{E}, \bar{E}_T, \bar{r}_D, \bar{D}) = & \frac{16}{3\pi} \frac{\alpha^3}{\bar{E}} \bar{b} \left\{ \left| \int_0^\infty d\tau \cos\left(\frac{\tau\bar{\varepsilon}}{2\bar{E}^{1/2}}\right) \bar{r}_D^2 \left(1 + \frac{\bar{E}}{\bar{E}_T}\right) \left(\frac{\bar{E}}{2\bar{E}_T}\right)^{1/2} J(\tau, \bar{b}, \bar{D}) \right|^2 \right. \\ & + \left| \int_0^\infty d\tau \sin\left(\frac{\tau\bar{\varepsilon}}{2\bar{E}^{1/2}}\right) \left[\frac{\tau}{(\bar{b}^2 + \tau^2)^{3/2}} + \frac{\tau(1 + \bar{E}/\bar{E}_T)^{-1/2}}{(\bar{b}^2 + \tau^2)\bar{r}_D} \right] \exp\left(-\frac{(\bar{b}^2 + \tau^2)^{1/2}}{\bar{r}_D(1 + \bar{E}/\bar{E}_T)^{1/2}}\right) \right|^2 \\ & + \left| \int_0^\infty d\tau \cos\left(\frac{\tau\bar{\varepsilon}}{2\bar{E}^{1/2}}\right) \left[\frac{\bar{b}}{(\bar{b}^2 + \tau^2)^{3/2}} + \frac{\bar{b}(1 + \bar{E}/\bar{E}_T)^{-1/2}}{(\bar{b}^2 + \tau^2)\bar{r}_D} \right] \exp\left(-\frac{(\bar{b}^2 + \tau^2)^{1/2}}{\bar{r}_D(1 + \bar{E}/\bar{E}_T)^{1/2}}\right) \right|^2 \\ & \left. + \left| \int_0^\infty d\tau \sin\left(\frac{\tau\bar{\varepsilon}}{2\bar{E}^{1/2}}\right) \bar{r}_D^2 \left(1 + \frac{\bar{E}}{\bar{E}_T}\right) \left(\frac{\bar{E}}{2\bar{E}_T}\right)^{1/2} K(\tau, \bar{b}, \bar{D}) \right|^2 \right\} \end{aligned}$$

$$- J(\tau, \bar{b}, \bar{D}) \equiv \frac{4}{\sqrt{\pi}} \left[\frac{4\tau^2}{(\bar{b}^2 + \tau^2)^3} - \frac{1}{(\bar{b}^2 + \tau^2)^2} \right] - 9\bar{D} \left[\frac{3\tau^2}{(\bar{b}^2 + \tau^2)^{5/2}} - \frac{1}{(\bar{b}^2 + \tau^2)^{3/2}} \right]$$

$$- K(\tau, \bar{b}, \bar{D}) \equiv \frac{4}{\sqrt{\pi}} \frac{4\tau\bar{b}}{(\bar{b}^2 + \tau^2)^3} - 9\bar{D} \frac{3\tau\bar{b}}{(\bar{b}^2 + \tau^2)^{5/2}}$$

• The static bremsstrahlung radiation cross section:

$$\begin{aligned} \partial^2 \bar{\chi}'(\bar{b}, \bar{\varepsilon}, \bar{E}, \bar{E}_T, \bar{r}_D, \bar{D}) = & \frac{16}{3\pi} \frac{\alpha^3}{\bar{E}} \bar{b} \left\{ \int_0^\infty d\tau \cos\left(\frac{\tau\bar{\varepsilon}}{2\bar{E}^{1/2}}\right) \bar{r}_D^2 \left(\frac{\bar{E}}{2\bar{E}_T}\right)^{1/2} J(\tau, \bar{b}, \bar{D}) \right\}^2 \\ & + \left| \int_0^\infty d\tau \sin\left(\frac{\tau\bar{\varepsilon}}{2\bar{E}^{1/2}}\right) \left[\frac{\tau}{(\bar{b}^2 + \tau^2)^{3/2}} + \frac{\tau}{(\bar{b}^2 + \tau^2)\bar{r}_D} \right] \exp\left(-\frac{(\bar{b}^2 + \tau^2)^{1/2}}{\bar{r}_D}\right) \right|^2 \\ & + \left| \int_0^\infty d\tau \cos\left(\frac{\tau\bar{\varepsilon}}{2\bar{E}^{1/2}}\right) \left[\frac{\bar{b}}{(\bar{b}^2 + \tau^2)^{3/2}} + \frac{\bar{b}}{(\bar{b}^2 + \tau^2)\bar{r}_D} \right] \exp\left(-\frac{(\bar{b}^2 + \tau^2)^{1/2}}{\bar{r}_D}\right) \right|^2 \\ & + \left. \int_0^\infty d\tau \sin\left(\frac{\tau\bar{\varepsilon}}{2\bar{E}^{1/2}}\right) \bar{r}_D^2 \left(1 + \frac{\bar{E}}{\bar{E}_T}\right) \left(\frac{\bar{E}}{2\bar{E}_T}\right)^{1/2} K(\tau, \bar{b}, \bar{D}) \right\}^2 \end{aligned}$$

- The dynamic shielding function for the bremsstrahlung radiation spectrum due to the screened electron-ion binary scattering in turbulent plasmas :

$$\begin{aligned}
 F_{\bar{\chi}}(\bar{b}, \bar{\varepsilon}, \bar{E}, \bar{E}_T, \bar{r}_D, \bar{D}) = & \left\{ \left| \int_0^\infty d\tau \cos\left(\frac{\tau\bar{\varepsilon}}{2\bar{E}^{1/2}}\right) P(\bar{r}_D, \bar{E}, \bar{E}_T) J(\tau, \bar{b}, \bar{D}) \right|^2 \right. \\
 & + \left| \int_0^\infty d\tau \tau \sin\left(\frac{\tau\bar{\varepsilon}}{2\bar{E}^{1/2}}\right) X(\tau, \bar{b}, \bar{r}_D, \bar{E}, \bar{E}_T) \right|^2 + \left| \int_0^\infty d\tau \bar{b} \cos\left(\frac{\tau\bar{\varepsilon}}{2\bar{E}^{1/2}}\right) X(\tau, \bar{b}, \bar{r}_D, \bar{E}, \bar{E}_T) \right|^2 \\
 & \left. + \left| \int_0^\infty d\tau \sin\left(\frac{\tau\bar{\varepsilon}}{2\bar{E}^{1/2}}\right) P(\bar{r}_D, \bar{E}, \bar{E}_T) K(\tau, \bar{b}, \bar{D}) \right|^2 \right\} \\
 / & \left\{ \left| \int_0^\infty d\tau \cos\left(\frac{\tau\bar{\varepsilon}}{2\bar{E}^{1/2}}\right) Q(\bar{r}_D, \bar{E}, \bar{E}_T) J(\tau, \bar{b}, \bar{D}) \right|^2 + \left| \int_0^\infty d\tau \tau \sin\left(\frac{\tau\bar{\varepsilon}}{2\bar{E}^{1/2}}\right) Y(\tau, \bar{b}, \bar{r}_D) \right|^2 \right. \\
 & \left. + \left| \int_0^\infty d\tau \bar{b} \cos\left(\frac{\tau\bar{\varepsilon}}{2\bar{E}^{1/2}}\right) Y(\tau, \bar{b}, \bar{r}_D) \right|^2 + \left| \int_0^\infty d\tau \sin\left(\frac{\tau\bar{\varepsilon}}{2\bar{E}^{1/2}}\right) Q(\bar{r}_D, \bar{E}, \bar{E}_T) K(\tau, \bar{b}, \bar{D}) \right|^2 \right\}
 \end{aligned}$$

Results

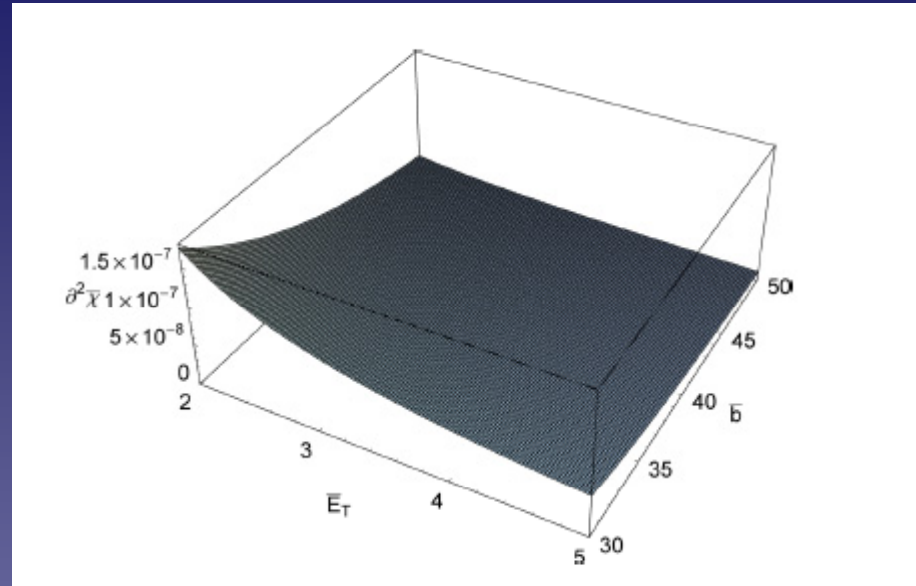


Figure 1. The surface plot of the scaled bremsstrahlung radiation cross-section $\partial^2 \bar{\chi}$ in units of $\pi \alpha_0^2$ in turbulent plasmas including the dynamic plasma shielding effect as a function of the scaled thermal energy E_T and scaled impact parameter \bar{b} when $r_D = 20$, $E = 0.8$, $\bar{\epsilon} = 0.08$ and $D = 0.05$.

- The bremsstrahlung radiation cross section decreases with increasing thermal energy and impact parameter.
- The thermal effect on the bremsstrahlung process in turbulent plasmas is more significant in small impact parameter domains.

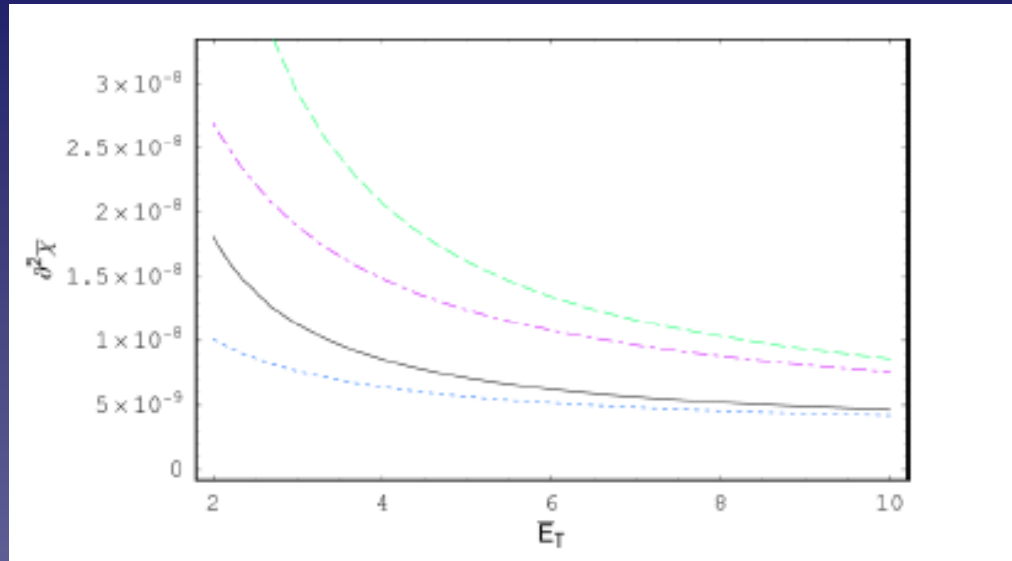


Figure 2. The scaled bremsstrahlung radiation cross-section $\partial^2 \chi$ in units of πa_0^2 as a function of the scaled thermal energy \bar{E}_T when $\bar{b} = 30$, $r_D = 20$, $\bar{E} = 0.8$ and $\bar{\epsilon} = 0.08$. The solid line represents the bremsstrahlung cross-section including the dynamic shielding effect for $\bar{D} = 0.02$. The dashed line represents the bremsstrahlung cross-section including the dynamic shielding effect for $\bar{D} = 0.03$. The dotted line represents the bremsstrahlung cross-section including the static shielding effect for $D = 0.02$. The dot-dashed line represents the bremsstrahlung cross-section including the static shielding effect for $D = 0.03$.

- The bremsstrahlung radiation cross section increases with and increase of the diffusion coefficient. The diffusion effect on the bremsstrahlung process decreases with increasing thermal energy.
- It is found that the turbulent effect caused by the fluctuation diffusion enhances the bremsstrahlung cross section in turbulent plasmas.

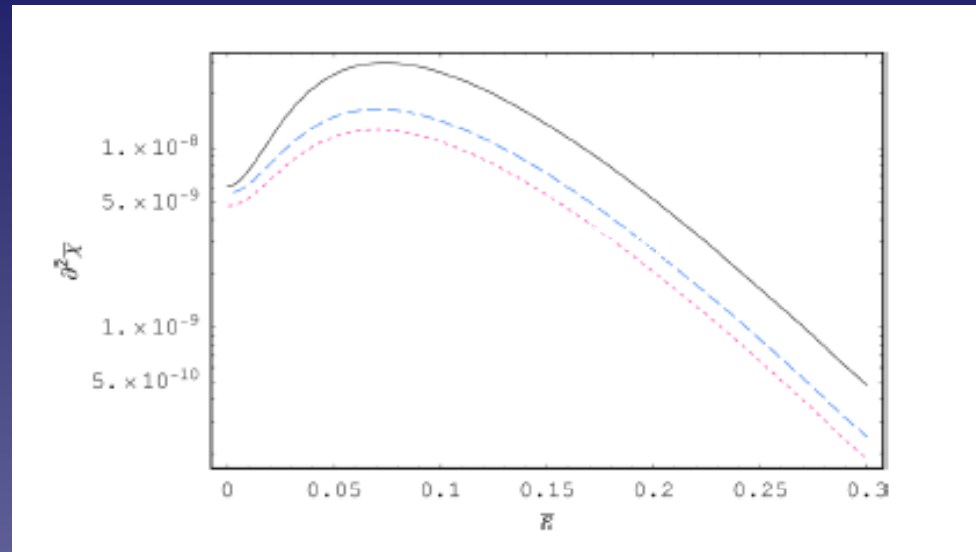


Figure 3. The scaled bremsstrahlung radiation cross-section $\partial^2 \chi$ in units of $\pi \alpha_0^2$ as a function of the radiation photon energy $\bar{\epsilon}$ when $\bar{b} = 30$, $r_D = 20$, $\bar{E} = 0.8$ and $\bar{D} = 0.03$. The solid line shows the bremsstrahlung cross-section including the dynamic shielding effect for $\bar{E}_T = 3$. The dashed line shows the bremsstrahlung cross-section including the dynamic shielding effect for $\bar{E}_T = 5$. The dotted line shows the bremsstrahlung cross-section including the static shielding effect.

- It is found that the bremsstrahlung process for the projectile energies $\bar{E} < 1$ the maximum peaks in the bremsstrahlung radiation cross section for $\bar{\epsilon} < 0.1$.
- The bremsstrahlung cross sections including the static shielding effect are always smaller than those including the dynamic shielding effect.

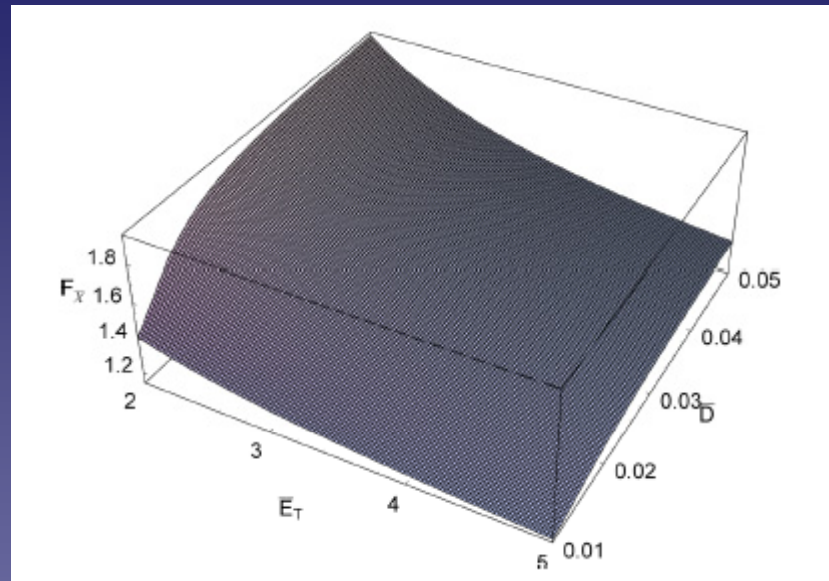


Figure 4. The surface plot of the dynamic shielding function $F_{\bar{\chi}}$ for the bremsstrahlung radiation cross-section in turbulent plasmas as a function of the scaled thermal energy \bar{E}_T and scaled diffusion coefficient \bar{D} when $\bar{b} = 30$, $\bar{r}_D = 20$, $\bar{E} = 0.8$ and $\bar{\varepsilon} = 0.08$.

- It is found that the dynamic plasma screening effect on the bremsstrahlung radiation cross section increases with an increase of the diffusion coefficient, especially, in low-thermal energy domain in turbulent plasmas.



Summary and discussions

- It is found that the bremsstrahlung radiation cross section decreases with an increase of the thermal energy for small impact parameters.
- It is found that the bremsstrahlung radiation cross section increases with increasing diffusion coefficient in turbulent plasmas.
- It is also found that that the dynamic plasma shielding effect enhances the bremsstrahlung radiation cross section for small thermal energies.
- The mean kinetic energy of the electrons in turbulent would be changed due to the dynamic diffusion effect caused by the random field fluctuation and increased in time for small collision energies.



- Additionally, it is found that the dynamic shielding effect on the bremsstrahlung radiation cross section increases with an increase of the diffusion coefficient in turbulent plasmas. Moreover, it is found that the dynamic shielding effect on the bremsstrahlung radiation cross section decreases with increasing thermal energy of the plasma.
- In this work we have found that the influence of dynamic plasma shielding and plasma turbulence due to the random field fluctuation plays significant roles in the bremsstrahlung radiation spectrum by the electron-ion encounters in turbulent plasmas.

Thank you for your attention.