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Heat and particle fluxes from collisionless scrape-off-layer during tokamak plasma disruptions

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Abstract

The structure of collisionless scrape-off-layer (SOL) plasma in tokamak reactors is being studied to define the electron distribution function and the corresponding sheath potential between the divertor plate and the edge plasma. One feature of the collisionless SOL plasma is that the edge plasma acts as an electrostatic trap for electrons because electrons that originally have parallel energy lower than the wall potential will be trapped between the inner and outer divertor plates. Trapped electrons are very important in collisionless SOL plasma and are mainly responsible for charge neutralization of ions. Therefore, a full solution of the kinetic equation of particle transport to determine various electron fluxes is required. In this study, the dynamics of the SOL plasma during disruption was investigated with a 2-D numerical model that solves the kinetic Fokker–Planck equation for electron distribution. The main component of the electric potential exists within a region where the SOL ions are absorbed, i.e., at the front of the expanding vapor cloud. © 2001 Published by Elsevier Science B.V.

Keywords: Scrape-off layer; Disruption; Low recycling; Heat flux; Divertor material; HEIGHTS package

1. Introduction

The steady operation of a plasma device is largely determined by the boundary conditions at the divertor or the limiter plates. The plasma processes at these boundary walls are complex and usually require extensive numerical simulation codes to obtain insight into the relative importance of the various interacting phenomena and the desired optimal conditions for enhanced operation. The divertor plate, for example, in future fusion power device is a key component in removing particle and heat fluxes. In conventional divertor operation of existing tokamaks, as well as in future devices, the plasma in the scrape-off-layer (SOL) is highly collisional ($T \approx 100$ eV). This means that the particle mean free path λ is much shorter than the parallel or longitudinal distance L of the SOL between the two opposite (inner and outer) divertor plates.

During normal operation of these devices, power to the divertor plates usually does not exceed the critical values at which melting or sublimation can occur. However, during plasma instabilities such as hard disruptions the high incident power ($\geqslant 10^7$ W/cm^2) from the SOL will cause significant erosion of the divertor plate from surface vaporization and splashing [1]. Although the actual heat flux arriving at the divertor plate during these events is significantly reduced due to the self-shielding effect from the divertor's own eroded material, the net erosion depth can still exceed hundreds of micrometers per event, which would lead to serious lifetime issues for these components. From numerical simulations and modeling experiments, the erosion lifetime of the divertor plate material has been found to depend on both the magnitude of the incident heat flux from the SOL and the energy distribution of ion/electron fluxes to the divertor plate [2]. Therefore, to more accurately predict plasma instability effects and to design better laboratory simulation experiments, we must have

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a good understanding of SOL physics and the parameters that affect it.

During plasma instability events, the loss of confinement will cause most of the core-particle flux, to arrive at the SOL with a relatively high temperature $T \approx T_0$, where T_0 (20–30 keV) is the core plasma temperature. This is in contrast to the normal operation scenario wherein the temperature of the escaping particles from the core plasma to the SOL is relatively lower, i.e., $T < 1$ keV, and the plasma is collisional. Because of the high temperature of the escaping particles during such events, the SOL plasma becomes collisionless and thus requires different treatment than that of the SOL during normal operation [3,4].

Collisionless SOL plasma behavior is also encountered during normal phases of operation with enhanced confinement [5]. This operation with low particle recycling and high temperature near the divertor plate was demonstrated during recent device discharges of the JT-60U with the use of boron-coated wall [6]. The plasma temperature in the SOL can be several keV, which will lead to a collisionless-plasma condition. The collisionless behavior of a SOL during similar normal operations of large helical fusion devices with enhanced particle confinement was recently studied by Monte-Carlo numerical simulation methods [7]. A non-Monte-Carlo (statistical fluctuation-free) Fokker–Planck model has been recently applied to study kinetic effects in SOL [8].

The term 'collisionless' in this paper does not mean that collisions can always be neglected. It is used only to indicate that the particle path length is much greater than the length of the SOL, i.e., the distance between the two opposite divertor plates along magnetic field lines. The full solution of the particle kinetic equation is still required to describe particle distribution functions in the SOL. This is because the lifetimes of particles that oscillate between plates at distances much shorter than the length of the particle path (collisionless in space) will be determined by collisions (collisional in time).

In a collisionless SOL plasma, the edge plasma acts as an electrostatic trap for electrons, because electrons that originally have parallel energy lower than the wall potential energy will be trapped between the inner and outer divertor plates. In a collisional SOL, however, because of the short path length of both ions and electrons, neutralization of the ion charge is mainly due to the SOL electrons moving toward the divertor plate. Therefore, in contrast to the collisional SOL, charge neutralization of ions in collisionless SOL plasma (see above definition) occurs mainly because of these trapped electrons. In more recent analyses, a collisionless SOL plasma was studied without taking into account trapped particles oscillating between the two negatively charged inner and outer divertor plates [9]. In this case, the full kinetic equation was not used. However, the existence of trapped particles is quite important and requires that the particle kinetic equation be solved to determine the major parameters that are needed of the SOL, such as negative potential and net heat load to divertor plates [1].

2. Description of collisionless SOL plasma

The electrons in the SOL comprise three different populations, based on their origins: the primary escaping electron flux, the cold electrons, and the trapped electrons [3]. The primary escaping electron flux consists of the hot electrons coming from the SOL and containing enough parallel energy to overcome the negative stopping potential at the wall. The cold electrons are those emitted from the cold dense plasma near walls (i.e., walls of inner and outer divertor plates). The residence time of both fluxes have $\tau^{\mathrm{e}} \approx L/V_{\mathrm{Te}} \leqslant 10^{-5}$ s, is much less than the electron collision time $\tau^{\mathrm{ee}} \geqslant 3 \times 10^{-4}$ s, and the residence time of the hot ions in the SOL $\tau^{\mathrm{i}} \approx L/V_{\mathrm{Ti}} = \sqrt{m_{\mathrm{i}}/m_{\mathrm{e}}}\tau^{\mathrm{e}}$, where V_{Te}, V_{Ti} are electron and ion thermal velocity, respectively. Therefore, the resulting electron density of such fluxes is low, and its contribution to the charge equilibrium ($n_{\mathrm{e}} = n_{\mathrm{i}}$) can be neglected.

Some of the hot electrons with $E_{\parallel} < |e\varphi|$ will be trapped in the established electrostatic potential between the two divertor plates. The characteristic lifetime of these trapped electrons is determined by their diffusion from Coulomb collision in momentum space [3]. These electrons are then considered collisionless in space but collisional in time. Therefore, if $E_{\parallel} = P_{\parallel}^2/m > |e\varphi|$ as a result of collisions, these electrons will escape the SOL. The trapped electron density $n_{\mathrm{e}}^{\mathrm{trap}}$ is much higher than the density of both escaping and cold electrons; therefore, charge neutralization of ions $n_{\mathrm{i}} = n_{\mathrm{e}}^{\mathrm{trap}}$ is mainly due to these trapped electrons.

The ion current j_{i} in the SOL is equal to the ion flux arriving from the core plasma. Near the walls, where the potential is sharply decreased from 0 to φ_0, the ions accelerate. During normal operation and during disruptions, two types of heat fluxes arrive at the SOL from the core plasma: particle heat flux W_{p}, carried by the lost particle fluxes of both electrons (S_{e}) and ions (S_{i}); and heat flux W_k, due to heat diffusion [3]. The particle fluxes $S_{\mathrm{e,i}}$ are usually ambipolar; therefore, $S_{\mathrm{e}} = S_{\mathrm{i}} = S_{\mathrm{in}}$. The value of S_{in} can be estimated as $S_{\mathrm{in}} = n_0 2\pi R\pi r^2/\tau_{\mathrm{p}}$, where n_0 is the core plasma density, R the major radius, r the minor radius, and τ_{p} is the particle confinement time. The corresponding particle heat flux is $W_{\mathrm{p}} = 3kT_0S_{\mathrm{in}}$. The conduction heat flux W_k is estimated as $W_k = Q_0/\tau_k$, where $Q_0 = 3n_0kT_0 2\pi R\pi r^2$, τ_k is the characteristic time of heat loss due to conduction, and k is the Boltzmann constant. The total heat flux W_0 arriving at the SOL can therefore be estimated as $W_0 = Q_0/\tau_{\mathrm{E}},\ 1/\tau_{\mathrm{E}} = 1/\tau_k + 1/\tau_{\mathrm{p}}$, where τ_{E} is the energy confinement time. The ratio of W_k to W_p is $W_k/W_p = \tau_p/\tau_k$. For normal operation τ_k is usually $< \tau_p$; therefore $W_k > W_p$.

From the experiments performed in JET device and in TFTR machine [10,11], one may conclude that the turbulent heat conduction flux W_k may play an important role when compared with particle loss. There are no separate measurements of heat flux losses due to the heat conduction or the heat flux carried by the lost particles. The total heat flux, W_d, is usually estimated by dividing the total core plasma energy Q_0 by the disruption time τ_d. As separate measurements are not available for W_k and W_p, it is assumed that $W_p = W_d$ and $W_k = 0$. The ion density n_i in the SOL can be estimated from the stationary condition $S_\parallel^i = S_{in}$, where the ion flux, $S_\parallel^i$, from the SOL to the divertor plate is given by

$$S_\parallel^i = \frac{1}{\sqrt{2\pi}} V_{Ti} n_i 2\pi r h \frac{1}{q_s}, \quad q_s = \frac{L}{2\pi R}\frac{RB_\varphi}{rB_\theta} \quad \text{and} \quad n_i = \frac{\pi\sqrt{2\pi}Rr}{V_{Ti} h \tau_p} n_0, \tag{1}$$

where h is the SOL width, B_φ and B_θ are, respectively, the mean values of the poloidal and toroidal magnetic fields in the SOL [3]. The q_s value depends on the specific tokamak geometry and is usually close to unity in the SOL.

3. Numerical simulation model

The problem now is to solve the stationary state of the trapped electron population density in the SOL plasma. An equilibrium electron density is established between the incoming flux of electrons from the core plasma and the outgoing escaping electron flux. The incoming electron flux arrives at the trap in the SOL from the core by crossing the separatrix between the open and the closed magnetic field lines and then escapes by crossing the separatrix (in momentum space) between the trapped and escaping electrons.

The kinetic equation for the electron distribution function f is given by the Fokker–Planck equation

$$\frac{\partial f_\alpha}{\partial t} + \vec{v}\cdot\frac{\partial f_\alpha}{\partial \vec{r}} + \frac{\vec{F}}{m_\alpha}\cdot\frac{\partial f_\alpha}{\partial \vec{v}} = L_\alpha[f_\alpha] = \sum L_{\alpha,\beta}[f_\alpha], \tag{2}$$

where m_α is the mass of particles of the αth species, $\mathbf{F}_\alpha = \mathbf{F}_\alpha(\mathbf{t},\mathbf{r})$ is the external force acting on them, and $L_{\alpha\beta}[f_\alpha]$ is the Coulomb collision operator. The problem is solved in the coordinate of z, r, and ϕ used in the toroidal configuration [3]. Such multidimensional problem is quite difficult to solve and therefore, the following assumptions are made. The SOL is assumed to be homogeneous across magnetic field lines (this reduces the problem to five dimensions: two in space along z and three in momentum space). Based on this assumption the $V \times B$ force is reduced to zero. It is also assumed that the electrostatic potential is homogeneous along magnetic field lines (z-direction), i.e., $\varphi\ (0 < z < L) = 0$, but has a sharp jump at the walls, $\varphi\ (z = 0,\ L) = \varphi_0$. Thus, the velocity distribution of particles f_α does not depend on z, r, or poloidal angle ϕ, and the problem is therefore reduced from six dimensions to three dimensions, only in momentum space. After averaging on azimuthal angle the problem can be treated as two-dimensional one [12].

Finally for the dimensionless equation for the electron distribution function f can be written as the sum of three differential operators and source term $q(v,t)$, i.e.,

$$\frac{\partial f}{\partial t} = 1_{vv} + 1_v + 1_{\vartheta\vartheta} + q(v,t), \tag{3}$$

$$1_{vv} = \frac{\partial}{\partial v}\left(\frac{a(v)T}{v}\frac{\partial f}{\partial v}\right), \quad 1_v = \frac{\partial}{\partial v}(b(v)f), \quad 1_{\vartheta\vartheta} = \frac{c(v)}{\sqrt{2T}}\frac{1}{\sin\theta}\frac{\partial}{\partial\vartheta}\left(\sin\vartheta\frac{\partial f}{\partial\vartheta}\right) \quad \text{and} \quad q(v,t) = \alpha\frac{e^{-v^2/2}}{(2\pi)^{3/2}}, \quad \alpha = \frac{n_0}{\tau_p}\left(\frac{r}{2h}\right), \tag{4}$$

where $a(v)$, $b(v)$, and $c(v)$ are dimensionless functions. The boundary conditions are

$$\frac{\partial f}{\partial v}(v=0) = 0, \quad \frac{\partial f}{\partial\vartheta}\left(\vartheta = \frac{\pi}{2}\right) = 0 \quad \text{and} \quad \frac{\partial f}{\partial\vartheta}\left(v\cos\vartheta > u_{max} = \sqrt{2e\varphi/m}\right) = 0, \tag{5}$$

assuming that the trapped particles crossing the separatrix between the trapped and escaping electrons leave the SOL in a short time. The density of trapped n_e^{trap} electrons is defined by integrating the distribution function f over θ and w, i.e.,

$$n_e^{trap} = 2\pi\int_0^{\sqrt{2e\phi/m}}\int_0^{\pi/2} f(w)w^2\sin(\vartheta)\,d\vartheta\,dw. \tag{6}$$

The stopping potential is defined by the condition that the trapped electron plasma density in the SOL equals the ion density, i.e., $n_e^{trap} = n_i$.

4. Simulation results

For solving the Fokker–Planck kinetic equation, the 2-D SOLAS code was developed as part of the HEIGHTS package [1]. Particle distribution functions coming to the SOL from the core plasma are assumed to have a Maxwellian shape. Calculations were carried out for geometric parameters R, r, and h and various particles confinement times τ_p to find the stopping potential that determines the distribution function of particles arriving from the SOL to the wall (i.e., the front vapor cloud above the divertor plate surface).

In Fig. 1, the distribution function of the trapped electrons f_e^{trap} is given in the planes of the velocities, i.e., longitudinal $v_\parallel$ and transverse $v_\perp$ normalized to the thermal velocity of the source V_{Te}. It can be seen that f_e^{trap} is essentially anisotropic and has twin-peaks at $|v_\parallel| = 0.5$ that is similar to the value obtained in [7] by using Monte-Carlo simulation. The parallel distribution function shows truncated tails, according to the boundary condition stated in Eq. (5).

In Fig. 2, the dependence of normalized stopping potential $\psi = |e\varphi/kT_0|$ on the SOL density during disruption n_i is given for various values of parameter α, i.e., in Eq. (4), depending on tokamak characteristics (dimensions) and disruption duration. The stopping potential increases with density but decreases with α, which is in agreement with the analytical solution presented by Hassanein and Konkashbaev [3]. But the distribution function is somewhat different with the minimum of f_e^{trap} is near $|v| \approx 0$ that is not found in [3] because of the simplified assumptions used. It can be seen in Fig. 2 that the stopping potential for a wide range of parameters is relatively low, $\psi < 1$, which is very different from the collisional case in which the stopping potential is close to ambipolar, i.e., $\psi \approx 3$–4. As a consequence, the distribution function of particles coming from the SOL to the wall (the vapor cloud near surface of the divertor plate) differs with a corresponding difference in heat and particle fluxes.

The electrons coming to the wall from the SOL consist of two populations: hot electrons overcoming the stopping potential S_e^{hot} and electrons diffusing from the electrostatic trap S_e^{trap}. The hot electron flux is

$$S_e^{hot} = \frac{1}{2} S_e^0 [1 - \exp(-\psi)], \quad S_e^0 = \frac{n_0 R r}{\tau_p h}. \tag{7}$$

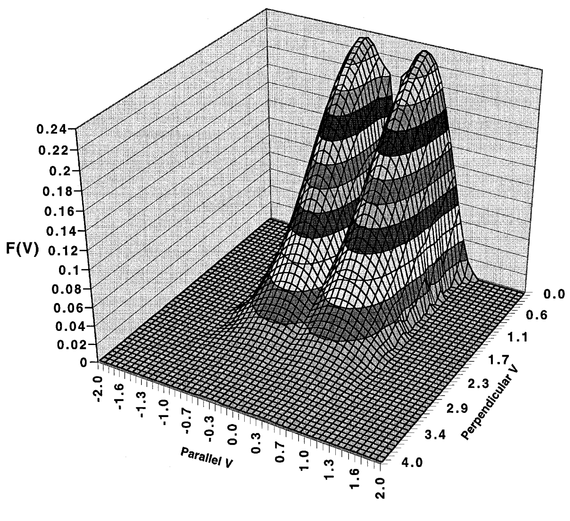

Fig. 1. Distribution function of trapped electrons in planes of normalized velocities.

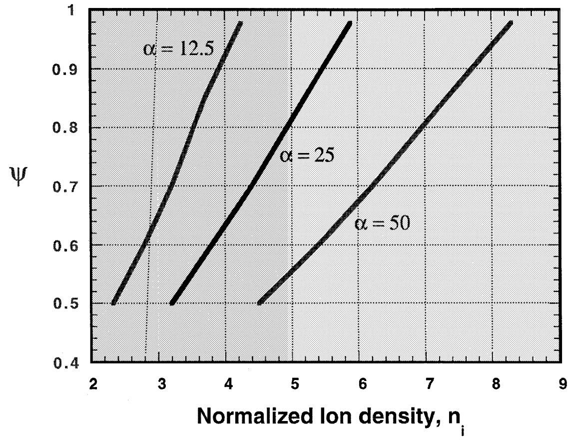

Fig. 2. Dependence of normalized potential on SOL density for various values of parameter α.

The remaining electron flux arriving from the trap is

$$S_e^{trap} = \frac{1}{2} S_e^0 \exp(-\psi). \tag{8}$$

Consequently, the heat flux carried by hot electrons with Maxwellian distribution is

$$W_e^{hot} = \frac{1}{2} S_e^0 k T_o \left\{ 1 + \frac{1}{2}\left[1 - \Phi(\psi) - \frac{2}{\sqrt{\pi}} \sqrt{\psi} \exp(-\psi) \right] \right\}, \tag{9}$$

where Φ is the error function. In the frame of applied assumptions, the energy of the trapped electrons diffusing across the separatrix between the trapped and escaping electrons is $E_\parallel \approx 0$, therefore they only carry their transverse energy. Thus, the trapped electrons energy flux is

$$W_e^{trap} = \frac{1}{2} S_e^0 k T_0 \exp(-\psi). \tag{10}$$

The remaining energy of the electrons is transferred into the potential energy of the electrostatic field in the SOL trap. Ions leaving the SOL are accelerated by this potential, and their distribution function is Mawellian but shifted in longitudinal direction in $\Delta E_\parallel = \psi$. The energy flux carried by the ions is

$$\begin{aligned} &W_i = W_i^0 + \Delta W, \quad W_i^0 = \frac{1}{2} S_i^0 \frac{3}{2} k T_0, \quad S_i^0 = S_e^0, \\ &\Delta W = W_e^0 - W_e^{hot} - W_e^{trap}, \quad W_e^0 = \frac{1}{2} S_e^0 \frac{3}{2} k T_0. \end{aligned} \tag{11}$$

5. Summary and conclusions

The overall damage to the divertor plate and nearby components during a disruption is determined from the characteristics and the spatial distribution of the developed vapor cloud. The spatial distribution of this vapor plasma depends on the distribution function of the particles coming from the SOL to the divertor plate. During disruptions, the SOL plasma is always collisionless in both existing tokamaks and future devices. One of the main features of collisionless SOL plasma is that the edge plasma acts as an electrostatic trap for electrons, because electrons that originally have parallel energy lower than the wall potential will be trapped between the inner and outer plates. Trapped electrons are important in collisionless SOL plasma to neutralize the charge of the ions. A 2-D numerical code (SOLAS) has been developed to solve the Fokker–Planck equation to calculate electron distribution functions to provide detail modeling of wide ranges of plasma parameters. The potential between the divertor plates is relatively low, $e\varphi/kT < 1$, contrary to that of the collisional SOL plasma $e\varphi/kT \approx 3$–4. The distribution function of the trapped electrons is anisotropic and exhibits a minimum at $|V| \approx 0$. The parallel distribution function shows twin-peaks at $|V_{\parallel}| = 0.5V_{\mathrm{Te}}$ with truncated tails.

It is important to note that the situation in the case of a tokamak disruption is quite different than that during normal operation. During a disruption a dense cold vapor cloud is formed near the walls due to the incident high heat flux. The front of this cloud expands with velocity up to 100 km/s with high density of about 10^{16}–10^{17} cm^{-3} and temperature of 30–50 eV [2]. Therefore, the usual term of secondary electrons and infinite emissivity do not usually apply in the disruption case. In this case the cold electron beams arise from the vapor cloud due to the existing negative potential between the wall and SOL plasma. Also during disruption no recyling is taking place since the vapor cloud is expanding into the SOL with high velocity. This could have the effect of slightly decreasing the SOL length, which does not affect the results of this study.

The average energy of trapped electrons is determined from the stopping potential φ. Electrons arriving at the wall (the vapor plasma near the divertor plates surface) from the SOL during disruptions consist of two populations: hot electrons overcoming the stopping potential and carrying most of the electron energy from the core plasma, and electrons diffusing from the electrostatic trap and carrying much less energy flux. Part of the electron energy is spent in keeping the energy of electrostatic field in the SOL. This energy is being spent in accelerating the ions through the negative potential φ. The distribution function of escaping hot electrons has a Maxwellian form and so the electrons diffusing from trap in the transverse direction, but are monoenergetic in the longitudinal direction. The accelerated ions from the SOL have a Mawellian distribution that is shifted in the longitudinal direction, with $\Delta E_{\parallel} = \psi$. The spatial distribution of the vapor plasma parameters during a disruption, and the overall damage to the divertor plate and nearby components, are determined from the energy distribution of ions and electrons.

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References

[1] A. Hassanein, Fus. Technol. 30 (1996) 326.
[2] A. Hassanein, I. Konkashbaev, Plasma Dev. Operat. 5 (1998) 297.
[3] A. Hassanein, I. Konkashbaev, Physics of collisionless scrape-off-layer plasma during normal and off-normal tokamak operating conditions, Argonne National Laboratory Report, ANL/FPP/TM-296, 1999.
[4] I.K. Konkashbaev, Plasma Phys. Rep. 19 (8) (1993) 496.
[5] N. Ohyabu et al., Nucl. Fus. 34 (1994) 387.
[6] S. Konoshima, K. Toi, J. Plasma Phys. Res. 71 (1995) 109.
[7] W.X. Wang et al., Nucl. Fus. 37 (1997) 1445.
[8] M. Shoucri et al., J. Nucl. Mater. 266–269 (1999) 1202.
[9] P.J. Catto, R.D. Hazeltine, Phys. Plasmas 1 (6) (1994) 1882.
[10] D.J. Ward, J.A. Wesson, Nucl. Fus. 32 (1992) 1117.
[11] V.V. Mirnov, private communication, 1998.
[12] Y.N. Dnestrovskii, D.P. Kostomarov, Numerical Simulation of Plasmas, Springer, Berlin, 1983, p. 29.