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Kinetic Depletion Model and Toroidal Effects on Pellet Ablation

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Introduction

Understanding the mechanisms, which affect the pellet ablation in high temperature plasmas, is significant for development of fuelling and diagnostic systems for tokamaks and stellarators. Very special regimes of ablation are predicted theoretically and observed experimentally when pellets penetrate through regions with low shear value (the central zone or an island nearby a rational magnetic surface). So called self-limiting ablation is caused by the depletion effect [1,2]. Toriodal effects on ablation are also very significant and recently they initiated the program of high field side injection for improvement of the fueling efficiency [3]. This paper deals with a kinetic model for the depletion effect, which takes into account three-dimensional distribution of the ablation over the pellet surface. A new effect of the analysis presented is the deceleration of a pellet in low shear regions. Modification of the electron distribution function in toroidal configuration reduces the ablation rate for the high field side injection and increases it for the low field side compared to the case of linear magnetic field lines. The effect is evaluated quantitatively below.

Depletion model

Let us consider a spherical pellet with radius r_p that at time t=0 started to move with velocity v_p across a rational magnetic surface with length L. For collisionless case, the problem is close to the classical problem dealing with one-dimensional expansion of finite-length gas cloud into vacuum [4]. The Maxwellian electron distribution function at the pellet surface varies with time loosing a cut tail beginning from the velocity

$$v = \frac{L}{y} v_p \qquad (1)$$

Here y is the shadow distance [2]. Fig. 1 shows definitions as well as the distribution function $f(E)$ for different y values. For evaluating the depletion effect on ablation rate it is necessary to make calculations of heat transfer through the neutral gas cloud and to average depletion factor D over the pellet surface. To account for modifications of the distribution function due to depletion it is sufficient to add the Heaviside step function H into the integral defining the heat flow onto the pellet surface (see for details Ref. [2])

$$Q_e(Sn,y) = \frac{2}{m_e^{1/2}\cdot\pi^{1/2}} \int_0^1 \int_0^\infty E^2 \cdot nf(E,z,Sn)\cdot z \cdot H\left(L - \sqrt{\frac{2\cdot E}{m_e}} \cdot \frac{y}{v_p}\cdot z\right) dEdz \qquad (2)$$

The local ablation rate density can be determined using gas dynamic scaling for the cloud [5]

$$\Gamma_s = 0.383 \cdot \left[\frac{5}{2}\cdot\frac{\gamma-1}{m_i}\cdot Qe \cdot \left(\frac{Sn}{r_p}\right)^2 \right]^{1/3} \qquad (3)$$

when m_i is the pellet molecular mass, γ is the specific heat ratio for the pellet material. The integral pellet ablation can be obtained after averaging the local ablation rate over the pellet surface.

$$\frac{dN}{dt} = \frac{2}{\varepsilon}\cdot \int_0^{\frac{\pi}{2}} \int_0^{2\pi} Q_e\left(Sn^*, y\right)\cdot cos(\alpha)\cdot sin(\alpha) d\alpha d\varphi \qquad (4)$$

Here Sn^* is found from the local balance $Q_e\left(Sn^*\right) = \varepsilon \cdot \Gamma_s\left(Sn^*\right)$ (ε is the sublimation energy), and the shadow distance y being expressed via the angles in spherical coordinate system Fig2

$$y(\alpha,\varphi) = r_p \cdot \left[\left(cos(\alpha)^2 + sin(\alpha)^2 \cdot cos(\varphi)^2 \right)^{1/2} - sin(\alpha) cos(\varphi) \right]\cdot \qquad (5)$$

The reduction of local ablation rate with the y-value is almost exponential (see Fig. 4, 5 in Ref. [2]), so the depletion effect can be approximately described by a depletion factor D ($\ln D \sim y$). For typical tokamak/stellarator conditions, the pellet radius r_p is greater than the shadow distance y, which corresponds to decreasing the local ablation rate by a factor of e. So, the ablation rate is distributed over the pellet surface non-uniformly. This produces a substantial deceleration effect on a pellet at low shear regions. The force F acting on the pellet is equal to

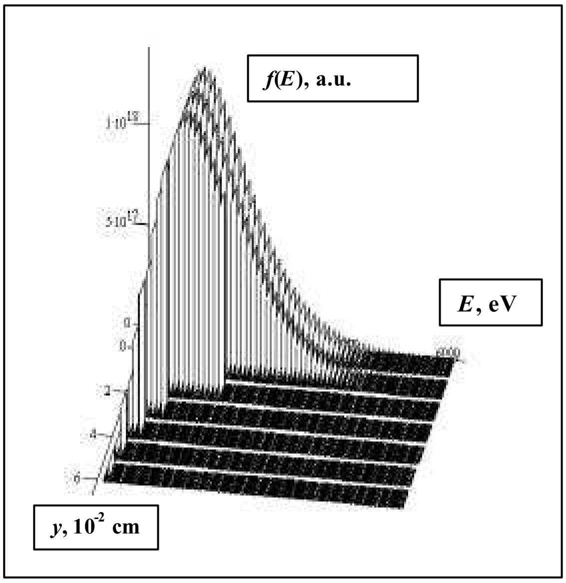

Fig. 1. The evolution of the distribution function in the pellet shadow.

$$F = 2\cdot\frac{Q\left(Sn^*,0\right)}{\varepsilon}\cdot m_i \cdot U \cdot r_p^2 \int_0^{\frac{\pi}{2}} cos(\alpha)\cdot sin^2(\alpha) \int_0^{\pi} D(y(\alpha,\varphi))\cdot cos(\varphi) d\varphi d\alpha \qquad (6)$$

$$U = 86.6 \cdot r_p^{1/3} \cdot n_e^{1/3} \cdot T_e^{-0.07}$$

For T-10 conditions (R=150 cm, L=1000 cm, r_p=0.05 cm, v_p=500 m/s, T_e=500 eV, n_e=10^{13} cm^{-3}) F=6.87 kdyne directed outward plasmas produces acceleration of the pellet equal to $4.1\cdot10^8$ cm/s^2. For the region with zero magnetic field shear, the losses of pellet velocity will be as large as 82 m/s per centimeter (~16.5%). The effect should be seen in experiments near magnetic islands where a rational number q region of centimeter spatial scale having a low shear is possible.

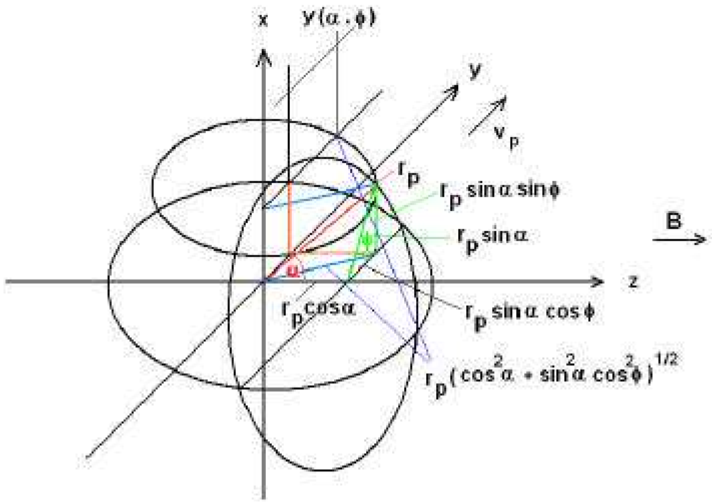

Fig. 2: Coordinate system for the averaging procedure.

Toroidal Effects on Ablation

Magnetic surfaces in tokamaks and stellarators are shifted outward due to the Shafranov shift [6]. Accordingly, density and temperature gradients are higher for the low field side. The results of pellet penetration into ITER-like plasmas with the pressure gradients, which differ from each other by a factor of 2, are presented in Table 1.

r_p, cm	dn_e/dr, dT_e/dr $20\cdot10^{13}$ cm^{-3}per 280 cm; 14000 eV per 280 cm, HFS	dn_e/dr, dT_e/dr $28\cdot10^{13}$ cm^3 per 280 cm; 20000 eV per 280 cm, LFS	Penetration Ratio HFS/HFS
0.5	80 cm	62.5 cm	1.28
0.1	33 cm	26.5 cm	1.29

Although the penetration depth is longer for the HFS case, the pellet still does not reach the same pressure level (1.29<2) as the LFS case gives. This means that for fueling at least the LFS injection gives advantages due to the profile effect.

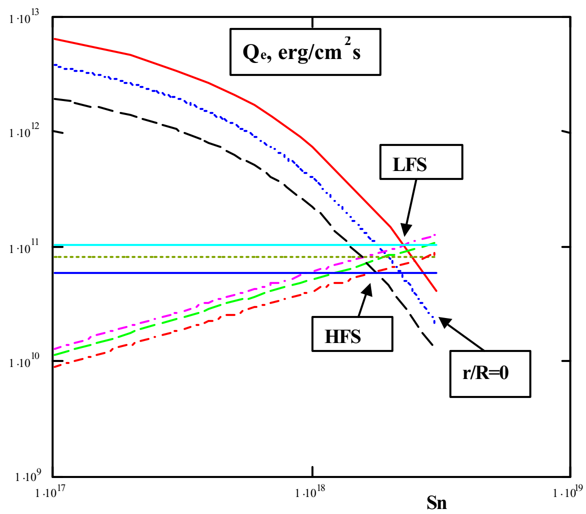

Fig. 3. Electron and ablation heat flows for LFS, HFS and uniform magnetic field cases.

Analyzing the modification of electron distribution function due to toroidal effects let us assume that electrons come to pellet from the extreme (low and high) magnetic field points. At these points placed at the distance equal to $L=\pi\ R\cdot q$ the distributions are assumed to be Maxwellian. Since the magnetic field varies with the major radius as $1/R$, the transverse energy reduces in collisionless LFS case. During electron flight to the pellet cloud the tilt angle decreases in average. For the HFS case the tilt angle increases, and the magnetic mirror reflects a part of electrons. Along with the Shafranov shift, this mirrors effect provides a higher ablation for the LFS case.

The modification of tilt angle cosine z for the case of LFS/HFS injection at different aspect ratios on the magnetic surface is described by

$$z_{new}^{LFS} = \left[1 - \left(1 - z^2\right) \cdot \left(\frac{R - r}{R + r}\right)\right]^{1/2} \qquad z_{new}^{HFS} = \left[1 - \left(1 - z^2\right) \cdot \left(\frac{R + r}{R - r}\right)\right]^{1/2} \qquad (7)$$

The distribution over z undergoes significant changes. Fig. 3 shows heat flows for the cases considered along with the corresponding to the zero-*Sn* condition ablation heat flows. The lines mark corresponding balance points. Compared with the uniform magnetic field, the ablation rate is higher for the LFS injection by a factor of 1.28 and lower for the HFS by a factor of 0.73. The effect of such difference is comparable with that of the Shafranov shift. The difference in the penetration length is presented in Table 2.

r_p, cm	dn_e/dr, dT_e/dr $20 \cdot 10^{13}$ cm^{-3}per 280 cm 14000 eVper 280 cm, HFS	dn_e/dr, dT_e/dr $28 \cdot 10^{13}$ cm^{3} per 280 cm 20000 eV per 280 cm, LFS	Penetration Ratio HFS/HFS
0.5	88	58	1.5
0.1	36	24	1.5

The penetration depth for the HFS injection becomes 1.5 times longer than for the LFS. However, the fueling efficiency for the HFS is still better because the pellet from HFS reaches the zone with 1.4 times higher pressure.

Conclusions

A kinetic depletion model is developed and pellet deceleration in the vicinity of rational magnetic surfaces is detected. For stellarators with q=1 island situated near border, the effect can be significant for pellet penetration. Penetration from LFS and HFS into toroidal machines is affected by two comparable factors. Those are Sharanov shift of the magnetic surfaces, which reduces the pressure gradient at the HFS (in tokamaks) and the modification of electron distribution function.

References

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