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THE INFLUENCE OF ELECTRON EMISSION AT THE DIVERTOR TARGET OF A TOKAMAK FUSION REACTOR

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Abstract

Some consequences of the release of electrons at a divertor target have been considered with particular reference to the collisionless exhaust of a D-T reactor. These electrons share the energy of the thermonuclear α particles and thereby cool the divertor plasma and lower the sheath potential at the target. A limit is set by space charge saturation in the sheath and some target materials have sufficiently large yields of secondary electrons for saturation to occur. Even so, the sheath potential will be in excess of the thresholds for unipolar arcing.

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April 1978

1. Introduction

The emission of secondary electrons due to particle bombardment of a surface can have a significant effect upon the plasma within a fusion device. This paper discusses the specific case of secondary electron emission at the divertor target of a Tokamak reactor. Such a reactor, fuelled with a deuterium-tritium mixture and operating in a steady state, must continuously dissipate the power carried by α particles that are produced in the thermonuclear reactions. For the typical case of a 5000 MW (thermal) reactor the α particles carry some 800 MW. In some conceptual designs, for example UWMAK-III(1), virtually all of this power is transported by electrons and ions and deposited upon a divertor target. Practical considerations of the surface and bulk properties of the target limit its power loading and the range 1 to 10 MW m^{-2} is generally regarded as realistic(1,2). With these power loadings the density of the high temperature plasma (many keV) that flows along suitably shaped magnetic fields and impacts upon the target is very low, in the range of 10^{14} to 10^{16} m^{-3}. Thus the divertor plasma can be regarded as collisionless although it must of course originate in a much more dense, collision dominated region within the Tokamak device where particle collisions can take place.

A steady state reactor must be refuelled with deuterium and tritium and it must exhaust any unburnt fuel in addition to the thermonuclear α particles. Practical limits dictate that only a small percentage of the fuel input can be burnt, the remainder must be carried as a fully ionized plasma to the divertor target. An electron repelling plasma sheath must be formed in front of the divertor target in order that the loss rate of electrons and ions can be so balanced that the global loss of charge from the Tokamak be zero. For a hot, reactor plasma both the electrons and ions that strike the target have sufficient energy to release appreciable numbers of secondary electrons. These electrons are accelerated into the divertor plasma by the action of the sheath potential. They can travel, guided by the magnetic field, back through the collisionless plasma and then interact with the collision dominated plasma where they thermalise before returning to the divertor. This increases the ability of the collisionless plasma to transport energy to the divertor target.

The objectives of this study must therefore be to assess, for reactor conditions, the effects of secondary electron emission upon the particle and energy transport through a collisionless regime and through the sheath and also upon the potential of the sheath.

2. The properties of the collisionless divertor plasma and sheath

Non-radiative transport of energy down a collisionless divertor channel must be convective and therefore it is dependent upon the plasma temperature. The power input is defined by the thermonuclear α particle power and so the temperature of the divertor plasma depends upon how many particles can share in the energy (E_α = 3.52 MeV) of each thermonuclear α particle.

Some of the energy is shared with the unburnt fuel whose burn-up fraction, f_B, can be defined as

$$f_B = \frac{\Phi_\alpha + \Phi_{neutrons}}{\Phi_D + \Phi_T} = \frac{2\Phi_\alpha}{\Phi_D + \Phi_T} \quad . \tag{1}$$

Here Φ is the fluence (flux x area) of particles leaving the reactor and the subscripts are self-explanatory. The energy can also be shared with the secondary electrons that are accelerated through the sheath and flow back into the collision dominated plasma. The effects of this flow of secondary electrons upon particle and non-radiative energy transport through the collisionless plasma and sheath have been assessed by means of a one-dimensional model(3). This model establishes the maximum emission of secondary electrons that can be accepted by the plasma and sheath. The limit is set by space charge saturation in the sheath and it is insufficient to cause collisionality within the plasma.

To apply the model to the present problem it is convenient to define an effective coefficient of electron emission (or emission coefficient, for brevity) namely

$$\Gamma_s = \frac{\gamma^+ + \gamma^-}{1 - \gamma^-} \qquad 0 < \Gamma_s \lesssim 10 \ . \tag{2}$$

Here γ^+ and γ^- are respectively the secondary electron emission coefficients for ions and electrons and, in a D-T plasma, the space charge saturation limit of Γ_s is about 10. The average energy transported by each ion through the collisionless plasma can be expressed in terms of $\delta_i kT$ where T is the plasma temperature, k is Boltzmann's constant and δ_i is an energy transport coefficient of order unity. The ions gain additional energy by acceleration through the sheath potential difference U and if U is expressed in non-dimensional form ($\phi = eU/kT$) then a total energy transport coefficient can be expressed as

$$\delta_t = (\delta_i + \phi) + 2 + 2\Gamma_s \ . \tag{3}$$

Here the coefficient $(\delta_i + \phi)$ is associated with the ions, the coefficient associated with their paired electrons is 2 and for the secondary electrons it is $2\Gamma_s$. The sheath potential is dependent upon the emission coefficient and their relationship is shown in Fig.1 for various values of f_B. This relationship is used in conjunction with eq.(3) to determine δ_t as a function of Γ_s. When there is no secondary emission the value of δ_t is about 6 for a D-T plasma but emission causes δ_t to increase and the model indicates that space charge saturation occurs when $\delta_t \stackrel{\sim}{\sim} 23$.

The temperature of the exhaust plasma in the divertor can now be determined approximately from

$$kT \stackrel{\sim}{\sim} E_\alpha f_B / 2\delta_t \qquad (4)$$

and this temperature is shown in Fig.2 for values of f_B ranging from 1 to 10%. It is evident that the emission of secondary electrons causes substantial reductions in both plasma temperature and sheath potential and this effect is most significant for the larger values of Γ_s below the space charge limit. It should also be noted that the concept of a collisionless exhaust restricts the burn-up fraction to values below about 5%, otherwise both the plasma temperature and sheath potential become excessive for practical consideration. One consequence is that the divertor target will be subjected to very substantial ion fluxes of unburnt fuel; for a 5000 MW (thermal) reactor the target current is 10^4 A when $f_B \stackrel{\sim}{\sim} 5\%$.

3. Emission properties of target materials

In practice the characteristics of a divertor plasma are dependent upon the secondary electron yields of target materials and it is necessary to determine Γ_s as a function of plasma temperature. Available data for γ^- pertain to mono-energetic electrons and must therefore be integrated over a Maxwellian distribution of incident electron velocities corresponding to the plasma temperature T. Ideally the integration should be carried out over all angles of incidence because the electrons that strike the target have the same random directions of motion as those entering the sheath. By contrast, ions striking the surface tend to be normally incident and mono-energetic because a substantial fraction of their energy is gained by acceleration in the electric field of the sheath, see eq.(3). The sheath potential is related to plasma temperature as can be seen in Figs.1 and 2 where the parameters are shown as functions of Γ_s. Thus it is possible by iteration to determine the appropriate ion energy and hence γ^+.

The results for a selection of typical target materials are shown in Fig.3. Tungsten and molybdenum represent materials which have been used for limiters and divertor targets. Titanium is also used as a target and moreover its secondary yields are comparable in magnitude to those of the constituents of stainless steel, ie iron, nickel, etc. Sapphire ($A\ell_2O_3$) is included as an example of an insulating target material. There is a peak in Γ_s at a temperature of about 200 eV for each material and this corresponds to its peak in γ^-. Contributions from γ^+ are relatively small (10 to 20%) but their effect can be seen by the slight increase in Γ_s for some metals at high plasma temperatures. It is evident that both W and $A\ell_2O_3$ targets have sufficient emission to cause space charge saturation in the temperature regime of a reactor (ie 1 to 20 keV). Emission from Mo is less likely to be saturated whereas that from Ti (and also Fe, etc) is unlikely to be saturated.

Data are required over a wide range of energies to cover the regimes of reactor temperatures and, in the present evaluation, some data have been empirically extrapolated to higher energies. Further, all the data used are for normally incident particles because, with the exception of W, the variation of γ^- with angle of incidence is not known. If full account is taken of this variation, then the values of Γ_s will be increased. The sensitivity of Γ_s to the spread in available data for γ^- is shown by the two curves for Mo.

This assessment is subject to further uncertainties. Firstly, the data apply to clean surfaces and in practice the yields may be affected as a result of the substantial bombardment by energetic D^+,T^+ and He^{2+} ions and possibly neutrons. Secondly, any effects due to magnetic fields have been neglected because, if the field lies normal to the surface, it is not likely to affect the emission characteristics. Nevertheless, some of the secondary electrons may be unable to reach the collision dominated plasma due to the mirror action of inhomogeneous magnetic fields in the divertor region. As a consequence the transport of energy will be reduced.

It is worth noting that the temperatures of present-day divertor plasmas are very much lower than those predicted for a reactor and so many target materials have yields adequate to cause space charge saturation.

4. Unipolar arcing

It has been established[9] that an electrically conducting target exposed to a plasma is subject to unipolar arcing when the sheath potential exceeds a few tens of volts. The arcs are localised but are fed by electrons that return through the plasma and sheath to the surface outside the arc and are then transported within the conducting target to the arc site. Emission of arc electrons is mainly due to therionic processes which may be field enhanced[10] but there is also appreciable ejection of target atoms, eg one atom for every 10 to 100 emitted electrons. Some of these slow atoms become ionized and the space charge of slow ions is adequate to compensate for the space charge of the emitted electrons. Thus the conditions discussed in Section 2 for space charge saturation in the sheath are not relevant to the arc spots and the overall emission of the target is substantially increased. The sheath potential predicted for the divertor of a reactor, see Fig.1, appreciably exceeds the threshold for arcing. Thus arcing from a conducting target must be taken into consideration.

Emission from such a target is governed by the ability of the plasma outside the arcs to return electrons to the target and a limit is therefore set by the overall electrical neutrality of the plasma. The return of electrons is governed by convection provided that the ejection of atoms and ions of the target material does not cause a breakdown of collisionless conditions in the divertor plasma. In the case of a D-T plasma the emission limit for collisionless conditions is therefore

$$\Gamma \lesssim (m_i/m_e)^{\frac{1}{2}} = 67.$$

The additional electrons enhance the convective transport of energy and particles and δ_t is increased by a factor of about 6. Both the plasma temperature and sheath potential outside the arc regions are decreased by the same amount.

This simplistic concept must be considered with caution because the substantial yields of atoms and ions of target material may cause the divertor plasma to become collisional and then radiation and conduction will be significant processes.

5. Conclusion

The emission of electrons from the target of a collisionless divertor reduces both the plasma temperature and the sheath potential. The latter effect also lowers the sputter yield for ions impacting upon the target.

Target erosion and the release of impurities by sputtering are important but the magnitudes of these effects will be greatly enhanced if unipolar arcing takes place. As yet there are no experimental data for unipolar arcing in hot, low density plasmas characteristic of the collisionless exhaust of a reactor. Furthermore, little attention has been paid to practical methods for the suppression of arcs. In principle the target may be constructed from an insulator or a matrix of separately insulated metal segments[11] but both approaches present considerable problems because of other practical constraints.

At present there are insufficient data for electron emission from suitable target materials and, in particular, information on γ^- over a wider range of incident angles and energies is needed. Of major importance for a reactor is the need for the data to be relevant to the surface conditions that will pertain at the divertor target.

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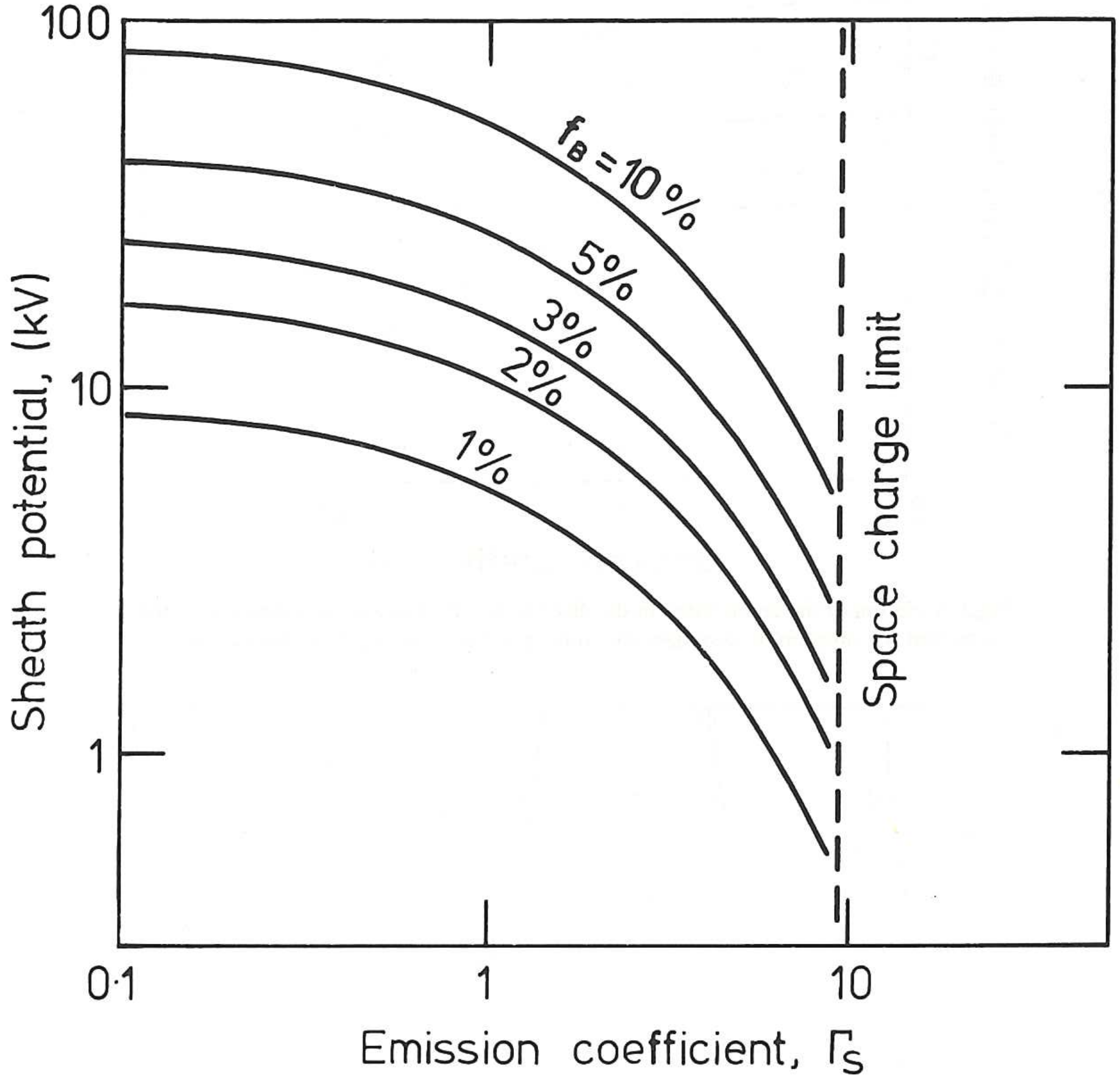

Fig.1 Variation of the sheath potential of a collisionless D–T plasma with the coefficient for emission of secondary electrons from the divertor target. All of the α particle power is assumed to be shared with the unburnt fuel and with the secondary electrons.

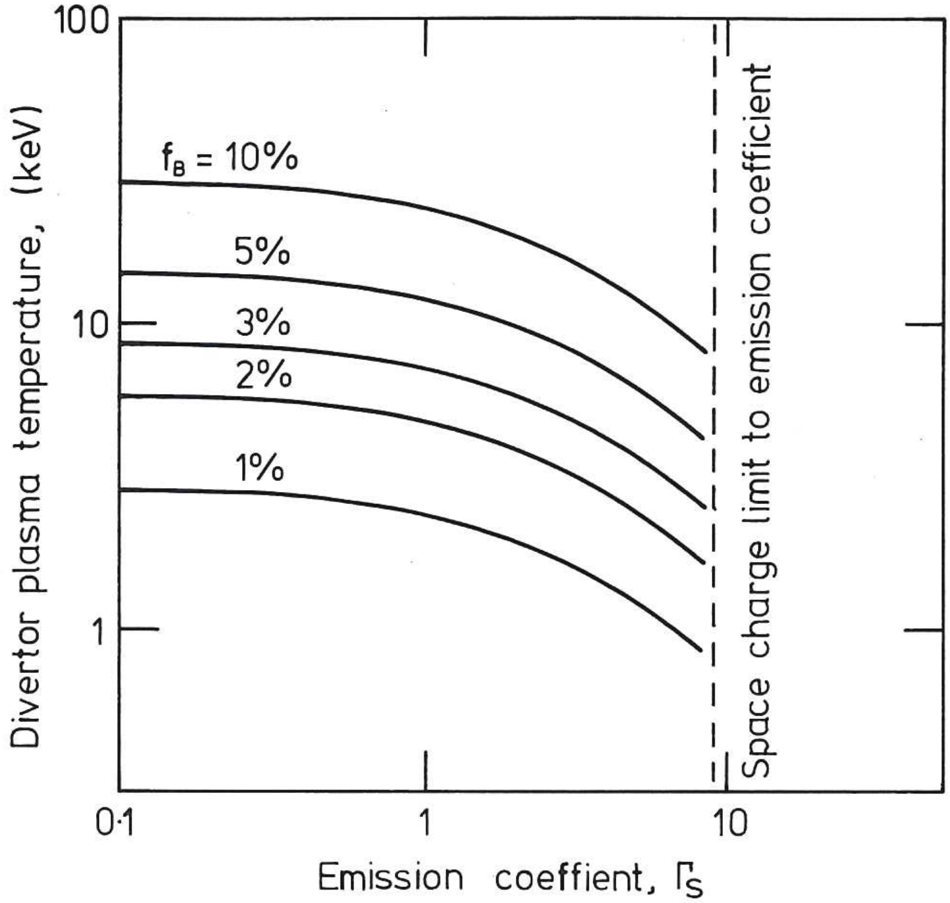

Fig.2 Variation of the temperature in the divertor of a D–T reactor as a function of the coefficient for emission of secondary electrons from the target. f_B is the burn-up rate.

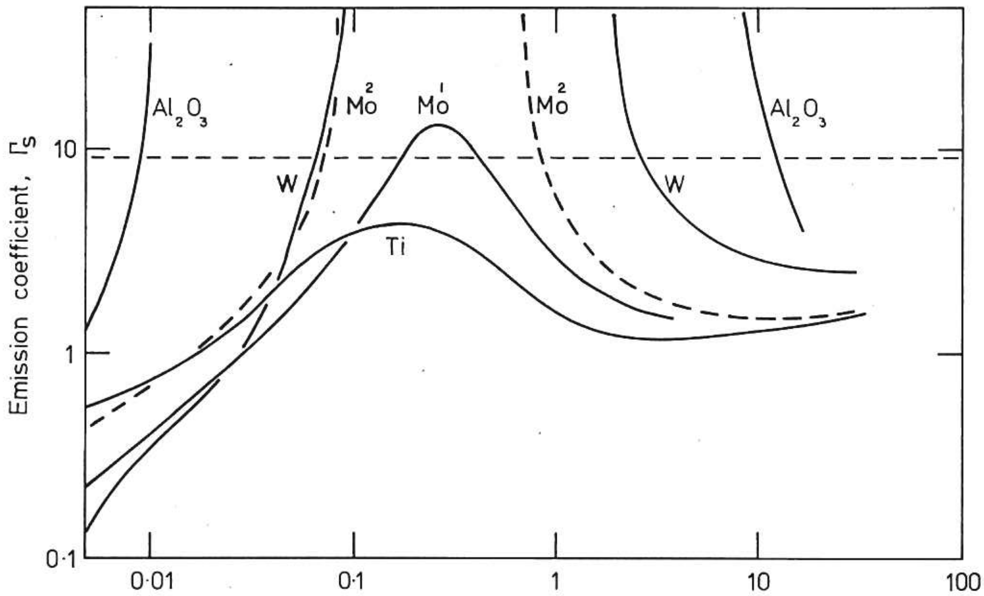

Fig.3 The temperature dependence of the emission coefficient for several target materials. The method of evaluation of Γ_S is discussed in the text and the saturation limit for a D–T plasma ($\Gamma_S \approx 10$) is shown by a dashed line. Data are taken from the following sources: Ti(4); Mo^1(5); Mo^2(6); W(7); $A\ell_2O_3$, sapphire, highly polished(8). Note, when γ^+ is not known, the value for Mo(5) has been used.