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The Use of Synchrotron Radiation to Provide Ionization of Wall Originated Impurities in a Thermonuclear Reactor*

by

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In thermonuclear reactors, wall originated impurities can cause enhanced bremssthralung and charge exchange loss from the plasma. The increased photon and/or particle flux to the wall can in turn increase wall originated impurities and the process grows resulting in deleterious effects on the plasma and first wall. To circumvent some of these problems, divertors are proposed to handle both the plasma loss and wall impurity influx.[1] Unfortunately, any diversion by magnetic fields is limited to charged particles and in all likelihood those particles originating from the vacuum wall or divertor pump region are likely to be neutral atoms or molecules.

We propose here a method whereby neutral particles from external sources entering the diverted field region are ionized and therefore can be guided from the system. To do this, it is suggested that electron synchrotron radiation from the plasma is sufficiently intense that neutrals become ionized before crossing the separatrix and reaching the reacting plasma.

To evaluate this concept we take a cylindrical plasma of radius r_p and a vacuum wall radius r_w with the separation $(d = r_w - r_p)$ greater than the gyrodiameter of any reaction produced ions but substantially smaller than r_p. If we further assume the divertor region d to be filled with a tenuous plasma of density n_d and electron temperature T_{ed}, then the mean free path for ionization becomes

$$\lambda_i = \frac{v_n}{n_d \langle \sigma_i v_{ed} \rangle} . \tag{1}$$

Here v_n is the thermal velocity of the neutral and $\langle \sigma_i v_{ed} \rangle$ is the electron impact ionization rate. Typically $\langle \sigma_i v_{ed} \rangle$ is approximately constant for electron temperatures above a few times the ionization potential. If we consider a refractory metal wall and evaluate Eq.(1) for an 0.1 eV Nb atom with $d = 30$ cm, we find $n_d \geq 5 \cdot 10^{10}$ cm^{-3} for $\lambda_i \leq d$. Of course, if the wall impurity were D_2 at the same temperature we would require a density approximately five times larger.

Plasmas of the assumed temperature and calculated density may occupy the divertor region because of diffusion from the thermonuclear plasma. In fact, this flux may typically reach values of from 10^{15}-10^{16} ions/cm^2-sec depending on the density (n) and confinement time (τ). Whether this source of energetic particles is adequate or not remains to be seen. However, let us determine the power required to maintain this divertor plasma where we assume the only loss is through ionization and neglect the direct electron loss through the divertor. The power per unit length can be written as

$$P_L = \Phi_n \, 2\pi r_w \, \chi_i \tag{2}$$

where Φ_n is the neutral flux from the wall, χ_i is the average energy loss per ionization of the neutrals and the calculation is done per unit length of the system. If we take $\Phi_n = 10^{14}$ atoms/cm^2-sec, $r_w = 186$ cm and $\chi_i = 30$ eV, then from Eq. (2), $P_L = 0.56$ watts/cm. Actually such small amounts of power could be supplied from an external resonant microwave source of frequency $\omega = \omega_c > \omega_p$ where ω_c is the electron cyclotron frequency and ω_p the plasma frequency.

A more attractive possibility is to use the electron synchrotron radiation from the reacting plasma. If this plasma has a self-absorption length greater than or about equal to its dimension (r_p) for the low synchrotron harmonic numbers, we can assume it to radiate like a black body. If it has an electron tamperature kT_{ep}, the power radiated per unit frequency and length is given by the Rayleigh-Jeans approximation

$$\frac{dP_R}{d\omega} = \frac{\omega_c^2 kT_{ep} r_p}{4\pi c^2} \tag{3}$$

Assuming this surface radiation makes a single 100% reflection from the wall and is reabsorbed by the reacting plasma, the (unperturbed) electric field distribution in the divertor region is

$$\frac{dE^2}{d\omega} = \frac{1}{\varepsilon_o c 2\pi r_p}\frac{dP_R}{d\omega} = \frac{\omega_c^2 kT_{ep}}{8\pi^2 \varepsilon_o c^3} .$$

The power absorbed by the divertor plasma per unit volume can be calculated using ohm's law

$$\frac{dP_A}{dV} = \sigma E^2 = \int_o^\infty \sigma(\omega)\ \frac{dE^2}{d\omega}\ d\omega .$$

For radiation near the cyclotron frequency the perpendicular component of the conductivity dominates the absorption and $\sigma(\omega)$ is given by[2]

$$\sigma(\omega) = \frac{\varepsilon_o \omega_p^2 \nu \left(\omega^2+\omega_c^2\right)}{\left[\left(\omega^2-\omega_c^2\right)^2+4\omega^2\nu^2\right]} . \tag{4}$$

The power absorbed per unit length is then

$$\frac{P_A}{L} = \frac{\pi^2}{2}\ \frac{\omega_p^2}{\omega_c}\ \frac{kT_{ep}}{\lambda^3}\ r_w d \tag{5}$$

where λ is the free space wavelength at the cyclotron frequency and where we assume the collision frequency ν to be small compared to the electron cyclotron frequency ω_c. A more precise determination of the absorbed power which includes the field perturbation gives

$$P_{ab} = P_o P_{calc}/(P_o + P_{calc})$$

where P_o is the total radiated power and P_{calc} is given by Eq. (5).

If we evaluate Eq. (3) for a tokamak system operating under the assumptions of Golovin et al.[3] we find the power per unit length to be $2.4 \cdot 10^6$ watts/cm. While most of this power is reabsorbed by the plasma, it does say that the level is significantly above that required to maintain the ionization given by Eq. (2).

Another way to look at this problem is to equate Eqs. (2) and (5), use Eq. (1) to eliminate the density and divertor thickness ($d = \lambda_i$) to find

$$\Phi = \frac{\pi}{4} \frac{\omega_p^2}{\omega_{ce}} \frac{r_p}{r_w} \frac{kT_{ep}}{\chi_i} \frac{d}{\lambda^3}$$

$$= \frac{\pi}{4} \frac{e}{\varepsilon_o B} \frac{v_n}{\lambda^3 \langle \sigma_i v_{ed} \rangle} \frac{r_p}{r_w} \frac{kT_{ep}}{\chi_i} . \qquad (6)$$

Solving this for the same tokamak system as before,[3] we find the synchrontron radiation power density is sufficient to take care of a wall neutral flux of $\Phi_n = 7.4 \cdot 10^{13}$ atoms/cm^2-sec.

From this we conclude that a tenuous warm plasma can be maintained through energy supplied by synchrotron radiation from the reacting plasma. This secondary plasma can in turn ionize wall originated impurities and when coupled with an effective divertor can significantly reduce first wall surface effects.

References

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1. L. Spitzer, D. Grove, W. Johnson, L. Tonks and W. Westendorp, USAEC Report NYO-6047, 1954.
2. J.C. Sprott, Phys. Fluids 14, 1795 (1971).
3. I.N. Golovin, Yu. N. Dnestrovsky and D.P. Kostomarov, Proceedings BNES Nuclear Fusion Reactor Conference, Culham (1969).