Jour. Ind. Inst. Sc. 61 (B), Oct. 1979, Pp. 187–190
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Short Communication

RF injection for refueling and impurity control of fusion reactors

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Received on March 12, 1979; Revised on July 10, 1979

Abstract

RF fields may be used to enhance the effective ion-impurity collisional friction, resulting in an outflow of higher Z ions and a net influx of low Z fuel.

Key words : Nuclear fusion, RF injection and plasma physics.

The impurities present in a Tokamak plasma are a major obstacle in attaining controlled thermonuclear fusion. Even very small concentrations of high Z impurities can raise the ignition condition substantially due to increased line, recombination, and bremsstrahlung radiation[1,2]. This problem tends to be exacerbated since classical transport mechanisms[3–6] predict impurity transport towards the region of highest plasma density which is normally at the plasma center. Simultaneously, one must find a means of removing the higher Z fusion reaction products (thermalized, cold alpha "ash") and supplying fresh low Z fuel.

It has recently been shown[7,8] that in the Pfirsch-Schluter and plateau regimes appropriate external sources and sinks of particles and/or energy may reverse the inward transport of higher Z particles (impurities or ash). In terms of the force balance equation the radial inward flux of higher Z ions is coupled to the outward radial flux of low Z ions according to

$$n_i Z_i v_{ir} = - n_I Z_I v_{Ir} = R_{\parallel} B/(eB_\theta B_\phi) \tag{1}$$

where the component of the frictional force parallel to the magnetic field B is

$$R_{\parallel} = - \frac{C_1 m_i n_i u_{\parallel}}{\tau_{iI}} - C_2 n_i \nabla_{\parallel} T_i \tag{2}$$

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Here the ion-impurity relative velocity is

$$u_{\parallel} = v_{i_{\parallel}} - v_{I_{\parallel}} \tag{3}$$

and

$$\nabla_{\parallel} T_i = (B_\theta / rB)\, \partial T_i / \partial \theta. \tag{4}$$

Therefore the sign of $R_{\parallel}$ can be reversed by reversing the sign of $u_{\parallel}$ or $\nabla_{\parallel} T_i$, the gradient of the ion temperature, which suggests sources and/or sinks of particles and/or energy. Here C_1 and C_2 are coefficients of order unity[7], n_i, n_I, Z_i, Z_I, m_i and m_I are the densities, charge, and masses of the plasma ions and impurities, respectively, v_r are the radial velocity components, τ_{iI} is the ion-impurity classical coulomb collision time, and r ϕ, and θ are the toroidal coordinates.

Some very preliminary experiments performed on the ISX device[9] at Oak Ridge National Laboratory were encouraging if not really conclusive. Unfortunately, the magnitude of the external perturbations required for impurity flow reversal are of the order of the ambient plasma recycling and are likely to be prohibitive. The particle throughout required, for instance, is given approximately by

$$dN/dt \cong 16\pi \frac{n_i(0)\, T_i(0)}{|e B_{\phi_0}|} \lambda \tag{5}$$

where λ is the scrape-off dimension, roughly an ionization mean free path, and the zeros indicate central values of the various quantities, rather than edge values. For a medium size Tokamak of current vintage $dN/dt \cong 10^{22}\, s^{-1}$! Furthermore, fusion plasmas in the reactor regime are likely to be dominated by anomalous transport mechanisms[10] and not neo-classical transport.

We have, however, suggested an improvement on the flow reversal scheme which may overcome this limitation[2]. One can hope to significantly modify the parallel frictional force[11] by means of externally injected RF fields or by naturally occurring microinstabilities.

We will employ the quasilinear formalism in order to investigate the influence of RF fluctuations on the initially generated fusion alpha particle distribution

$$f_\alpha = \frac{n_\alpha \delta(v - v_\alpha)}{4\pi v_\alpha^2} \left\{ 1 - \frac{d \ln n_\alpha}{dx} \frac{v_r}{\Omega_\alpha} \right\} \tag{6}$$

where

$$n_\alpha = S(r)/v_e. \tag{7}$$

The alpha particle distribution will evolve according to the quasilinear equation (given here in the slab approximation)

$$\frac{\partial f_\alpha}{\partial t} = \frac{\pi e_\alpha^2}{m_\alpha^2} \sum_{k} |\tilde{\phi}_k|^2 \left(k_{\parallel} \frac{\partial}{\partial v_{\parallel}} - \frac{k_\perp}{\Omega_\alpha} \frac{\partial}{\partial x} \right) J_0^2 (k_r \delta r)$$

$$\times\, \delta\left(\omega - k_{\|}v_{\|} - k_{\perp}\langle V_{d\alpha}\rangle\right)\left(k_{\|}\frac{\partial}{\partial v_{\|}} - \frac{k_{\perp}}{\Omega_{\alpha}}\frac{\partial}{\partial x}\right) f_{\alpha}^{0} \tag{8}$$

when fields of potential ϕ_k are present. Here, $S(r)$ is the alpha production rate at radius r, ν_e is the electron-alpha collision frequency, Ω_α is the alpha gyrofrequency, ω is the wave frequency, and the $k_{\|}$ and k_r are the parallel and radial components of the wavenumber. Whereas electrostatic drift waves are found in the current (low beta) experiments, future high beta devices[12] (in the presence of alpha particles) are likely to be dominated, instead, by the low frequency drift Alfven instabilities. The spectrum of waves will then be centered around

$$k_{\perp}^{2}\,\rho_{\alpha}^{2} \lesssim 1 \tag{9}$$

where ρ_α is the alpha's gyroradius and

$$k_{\perp} = lq/r. \tag{10}$$

These waves have $\omega/k_{\|} \sim V_A$, the Alfven speed, and both slow, $\omega/k_{\|} < V_A$, and fast, $\omega/k_{\|} > V_A$, branches exist.

For mode numbers

$$l > \frac{r\epsilon}{\rho_\alpha q^2 c_0} \tag{11}$$

with $c_0 \approx \epsilon^2 \ll 1$:

$$k_{\|}\frac{\partial}{\partial v_{\|}} < \frac{k_{\perp}}{\Omega_{\alpha}}\;\frac{\partial}{\partial x} \tag{12}$$

and configuration space diffusion tends to dominate[10] equation 8 which then takes on the (predominant) character of a diffusion equation. For ash removal the resultant diffusive flow must be large enough (in the steady state reactor assumption) to balance the fusion alpha gneration

$$\Gamma = 1/4a \int_0^a n^2 \langle\sigma v\rangle\, r\, dr \tag{13}$$

where[13]

$$\langle\sigma v\rangle \approx 3{\cdot}7 \times 10^{-12}\, T^{-2/3} \exp\left(-20\, T^{-1/3}\right) \mathrm{cm}^3\, \mathrm{s}^{-1} \tag{14}$$

which places limits on the values of ϕ_k required.

An increase in ϕ_k should increase τ_{tr}^{-1} and, hence, flow reversal action.

These waves are not found in present day experiments and it is not yet possible to determine conclusively if naturally excited waves will have sufficient amplitude in the reactor regime (or if injected fields[14] will be required). The saturated instability levels (and mechanisms responsible) are just not known for the appropriate waves. However if one assumes that all the free energy available to the linear spectrum is present in the field energy[15] we can use the preceding equations to estimate the plasma parameters for which flux balance allows a steady state ash removal. For Tokamaks having $a = 1$ to 2 meters, $R_0 = 5$ meters, $B = 4$ Tesla, $q = 2{\cdot}5$, $T = 15$ keV, and $n(0) =$ few $\times 10^{14}$ cm^{-3} steady state ash removal is satisfied and a fluctuation amplitude of $dn/n \sim$ few $\times 10^{-3}$ is obtained. For other parameters, or different assumptions, one may have to enhance the ambient wave amplitude by *RF* injection. Alfven wave injection has already been demonstrated in the course of *RF* heating experiments[16] and coupling is not expected to present an insurmountable problem.

Acknowledgement

The author acknowledges financial support from the South African Atomic Energy Board.

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