*33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.**30I**, P-1.121 (2006)*

A High-Velocity Microwave-Powered Pellet Launcher for ITER

P.B. Parks and F.W. Perkins

General Atomics, P.O. Box 85608, San Diego, California 92186-5608, USA

I. Introduction

Experiments have shown that pellet fuelling of ITER will be optimized by injection of high-speed pellets ≥3km/s) from a position on the high-field side of the magnetic separatrix. Present ITER plans call for remotely energizing and injecting pellets into a guide tube, which, after several bends, arrives at the pellet launch position in the vicinity of the high-field-side divertor [1]. Unfortunately, this is a region of high flux expansion which inhibits penetration across magnetic surfaces. Moreover, the pellet velocity is limited by centrifugal force arising from guide tube bends to a velocity ≈ 0.3 km/s.

This paper introduces a novel inner wall pellet injection concept illustrated in Fig. 1 whereby pellets are injected remotely at low velocity and then accelerated only upon reaching a point on the high-field-side separatrix where the remaining portion of the pellet's trajectory is straight and normal to the separatrix magnetic surface [2]. The method relies on a pusher medium that absorbs microwave power delivered by a gyrotron tube and converts it to high gas enthalpy. The pusher uses small micron sized conducting particles imbedded homogeneously in a D_2 ice slug behind the pellet. The particles act like point sources of heat due to the induced eddy current dissipation, and thus the pusher medium acquires an effective macroscopic electrical conductivity. Joule heating rapidly converts the ice to a hot, high-pressure gas, thereby accelerating the pellet to high velocity. Absorption of the microwave power is continuous during acceleration because the power absorption length $1/(2\alpha)$ increases directly in proportion to the length of the pusher gas expanding behind the pellet — "self-matched" heating regime. High-power 1-2 MW gyrotron sources are capable of delivering the typical ~1 kJ energy necessary to achieve a velocity of 3.5 km/s, for an ITER-sized pellet. After the pellet exits the straight acceleration towards the plasma, some of the pusher gas will exit along with the pellet and enter the plasma. A diamond or sapphire window completely seals off these gases from the long (~25-100 m) waveguide runs that transports microwave power from the gyrotron, and absorbs the pellet recoil momentum. A thin Li reflector can be interposed between the pellet and pusher to allow for two-pass wave absorption, thus increasing the power absorption and heating uniformity in the streamwise direction. The length available for acceleration in ITER is ≈0.7 m.

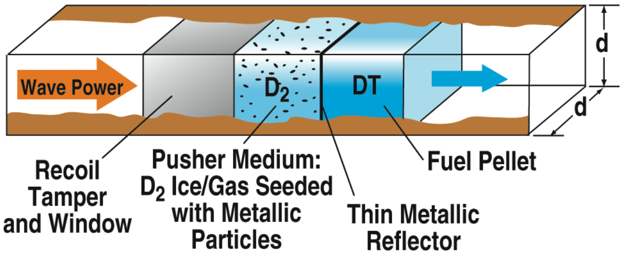

FIG. 1. The pellet-pusher module shown in a rectangular waveguide. Microwave power is transmitted through a transparent window, which also absorbs the pellet recoil momentum during acceleration.

II. Theoretical Wave Absorption Model in a Rectangular Waveguide

The main effect of the small conducting particles is to *absorb* rather than *scatter* microwave power. The form of the traveling wave for a general cross sectional waveguide shape is given by $E,H \sim G(x,y)e^{i(\omega t-\beta_g z)}e^{-\alpha z}$ where α is the sought after wave absorption coefficient, and the propagation constant is β_g. For TE and TM types of waves, the $G(x,y)$ function for each field component is well known [3]. The time-averaged Joule dissipation per particle may be expressed in the general form

$$P_\Omega \equiv \left\langle \frac{\tilde{\vec{E}}\cdot\tilde{\vec{J}}^*}{2} \right\rangle_{\text{vol}} = \left\langle \frac{\tilde{\vec{J}}\cdot\tilde{\vec{J}}^*}{2\sigma} \right\rangle_{\text{vol}} = F(a,\sigma,\delta)\frac{\vec{H}\cdot\vec{H}^*}{2} \quad . \tag{1}$$

where F is the particle "form factor." Its value depends on the particle size, shape, electrical conductivity, and resistive skin depth $\delta = (\mu_0 \pi f \sigma)^{-1/2}$. A general expression for the absorption coefficient is found to be $\alpha = n_c \sigma_\alpha$ where the absorption cross section is [2]

$$\sigma_\alpha = \frac{F}{2}\frac{\int \vec{H}\cdot\vec{H}^* dxdy}{\int \hat{z}\cdot(\vec{E}\times\vec{H}^*)dxdy} = \frac{F}{2Z_0}\left(\frac{\kappa}{\mu}\right)^{1/2}\frac{1}{\left(1-\omega_{\text{cut}}^2/\omega^2\right)^{1/2}} \quad . \tag{2}$$

with $Z_0 = (\mu_0/\varepsilon_0)^{1/2} = 377\ \Omega$. The second expression pertains to square cross-section waveguide fields. For a cube-shaped pellet with edge length d, the angular cutoff frequency is $\omega_{\text{cut}}^2 = c^2\pi^2(m^2+n^2)/\mu\varepsilon d^2$, where m, n are the mode numbers. For a sphere of radius a we obtain [2]

$$F_{\text{sph}} = \frac{6\pi a^2}{\sigma\delta}\Phi(a/\delta) = V_s\omega\mu_0 Q(a/\delta) \quad , \quad \Phi(a/\delta) = \frac{\sinh(2a/\delta)+\sin(2a/\delta)}{\cosh(2a/\delta)-\cos(2a/\delta)} - \frac{\delta}{a} \quad . \tag{3}$$

In the limit $\delta/a \to 0$, $\Phi \to 1$, so that F_{sph} assumes the anticipated expression deduced by approximating the perturbed magnetic field surrounding the sphere as though the sphere were a perfect conductor.

In order to limit impurity contamination by the fueling system, it would be desirable to minimize the volume filling factor, represented by $f_v = V_{sph} n_{c,sph}$. In the case of two-pass wave absorption this is

$$f_v = \frac{\left(1 - \omega_{cut}^2/\omega^2\right)^{1/2}}{2 k_0 L_0 Q(a/\delta)} \left(\frac{\mu}{\kappa}\right)^{1/2} \qquad (k_0 = \omega/c) \quad , \tag{4}$$

where L_0 is the initial length of the pusher medium. In this formula, the essential controlling variable is the ratio $\zeta = a/\delta$ entering the quality factor Q, which has a maximum $Q_{max} = 0.533$ at $\zeta = 2.41$. Hence, irrespective of the specimen's properties, $f_{v,min}$ =1.3%, for ITER parameters: $L_0 = 0.012$ m, d = 6 mm, f =170 GHz, m = 4, $\mu = 1$, $\kappa = 1.33$. Accordingly, the ratio of Li atoms to D atoms injected along with the spent pusher gas is fortunately minimal, only 1%.

III. Gas Dynamics of Acceleration

A one-dimensional expansion model is presented here with a microwave heat source. The ideal gas energy equation becomes

$$\frac{\rho_0}{\rho}\frac{\partial p}{\partial t} + \gamma p \frac{\partial v}{\partial \xi} = -(\gamma - 1)\frac{\partial P_{wave}}{A \partial \xi} \quad , \qquad \left(A = d^2\right) \quad . \tag{5}$$

Independent coordinates are time t and Lagrangian coordinate ξ, which labels the axial position of a fluid element at $t = 0$, and $0 < \xi < L_0$. Note also that the Lagrangian coordinate ξ and the physical distance coordinate z are related through the differential form of the continuity equation, $\rho dz = \rho_0 d\xi$, where ρ_0 denotes the initial gas density ρ $(\xi,0)$, i.e., the density of solid D_2. The wave power dependence, e.g., for a forward propagating wave only, can be written in the form $P_{wave} = P_0(t)\exp[-2\sigma_\alpha \int_0^z n_c(z',t)dz'] = P_0(t)\exp\left[-2\sigma_\alpha n_c(0)\xi\right]$ where initial particle concentration $n_c(0)$ was specified in Sec. II. We assume that the pressure remains nearly uniform in space i.e. $p(\xi,t) \cong p(t)$. By integrating Eq. (5) over ξ from $\xi = 0$ to $\xi = L(0) = L_0$ we obtain (dot $= \partial/\partial t$)

$$L\dot{p} + \gamma p \dot{L} = (\gamma - 1)\frac{P_{gyr}(t)}{A} \quad , \tag{6}$$

where $P_{gyr}(t) = P_0(t)\left\{1 - \exp\left[-2\sigma_\alpha n_c(0) L_0\right]\right\}$ is the total gyrotron power absorbed by the pusher gas. Now we have two coupled differential equations, Eq. (6) and $M_p \ddot{L} = Ap(t)$ describing the motion of pellet with mass M_p. Of the two dependent variables, L and p, we eliminate p, and with P_0 = const we obtain a third order differential equation $X\dddot{X} + \gamma \dot{X}\ddot{X} - 1 = 0$ for $X = L/L_0$, $(\text{dot} = \partial/\partial\tau), \tau = t/t_0$, $t_0 = [L_0^2 M_p/(\gamma - 1)P_{gyr}]^{1/3}$. The initial conditions are $X(0) = 1$, $\dot{X}(0) = 0$,

$\ddot{X}(0) = (M_{gas}/M_p)t_0^2(kT_0/m)/L_0^2 \lesssim 1$, where $M_{gas} = \rho_0 A L_0$ is the mass of the pusher medium. Of most practical interest is when the pusher gas has expanded to about $L \sim 5L_0$ or greater, whereupon the asymptotic solution at long times ($\tau >> 1$) becomes $X \approx [8/(9\gamma - 3)]^{1/2}\tau^{3/2}$. From this, scaling laws for the pellet velocity and gas temperature versus acceleration length L become

$$v_p = 3^{2/3}\left(\frac{\gamma-1}{3\gamma-1}\right)^{1/3}\left(\frac{P_{gyr}L}{M_p}\right)^{1/3} \qquad T = \frac{m}{3k}\frac{M_p}{M_{gas}}v_p^2 \qquad (7)$$

In Fig. 2 we plot the pellet velocity and temperature versus L given by Eq. (7) and compare it with the numerical solution. In both figures, the analytical and numerical solutions are in close agreement. A simple expression for the hydrodynamic efficiency was derived from this model, obtaining $\eta_{hydro} = (2 + M_{gas}/3M_p)^{-1}$ $\approx 45\%$ [2].

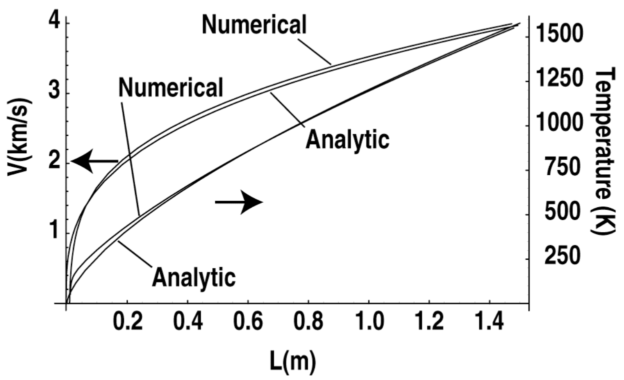

FIG. 2. Pellet velocity and pusher gas temperature as function of acceleration length obtained from numerical and analytic calculations

IV. Conclusions

The large size of ITER supports location of a novel pellet accelerator in the gaps between the blanket-shield modules. The proposed system projects a velocity scaling law given by Eq. (7) and has value of >3 km/s for ITER — an order of magnitude above the currently planned system.

This work was supported by the U.S. Department of Energy under DE-FG03-95ER5309.

References

[1] Baylor L.R., Maruyama S., Parks P.B., *et al.*, Phys. Plasmas **12**, 056103 (2005) (see reference therein).

[2] Parks, P. B., Perkins, F. W. Nuclear Fusion (in press 2006).

[3] Schwarz W.M., *Intermediate Electromagnetic Theory* (John Wiley & Sons, Inc, New York 1964) pp. 337-344.