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Effect of ICRF Heating on Single Particle Confinement in Tokamaks

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ABSTRACT

The simultaneous effect of ion heating and spatial diffusion due to ICRF heating in tokamak geometry is investigated from the single particle viewpoint. Transitions between passing and trapped trajectories are taken into account in the mapping equations. Specific results are given for typical experimental devices.

The heating of plasma ions by fast Alfven waves of frequency ω in the neighborhood of the ion cyclotron frequency Ω_i (ICRF) is presently considered to be an attractive scheme for achieving thermonuclear temperatures in Tokamak confinement devices. Previous theoretical studies[1,2] of this topic have dealt with important questions related to the efficiency of the heating mechanisms (fundamental, harmonic, minority), and the associated evolution of the ion distribution function in velocity space. However, such studies have not considered the intrinsic diffusion in configuration space which must always accompany the velocity space changes produced by the waves. In an actual experiment if the spatial diffusion rate is relatively fast compared to the heating rate, then the effect of the heating scheme can be quite deleterious to plasma confinement either due to the direct escape of single particles (i.e., a density loss) or because of the indirect recycling of wall impurities. The degrading of plasma confinement during ICRF heating has been documented experimentally in the ST[3], ATC[4], and Macrotor[5] Tokamaks. Recent experiments in PLT[6] have not shown any deleterious effects of the RF on confinement, as expected, because of the large current and size of this device and the low RF power levels applied thus far.

The present study is concerned with the calculation of the simultaneous change in the energy and radial position produced by resonant heating ($\omega - k_\parallel v_\parallel = n\Omega_i$, n = 1,2...) of single ions confined in a Tokamak. Specifically, this work yields the self-consistent heating and spatial diffusion rates in the absence of collisions. The role of collisions will be treated in a separate study. An important feature retained in the present calculation, and generic of Tokamaks, is the continuous transition between passing and trapped particle orbits produced by the preferential increase in perpendicular energy due to cyclotron absorption.

The physical model behind the present calculation hinges on the existence of a finite resonance layer inside the plasma where the condition $\omega - k_{\parallel}v_{\parallel} = n\,\Omega_i$ is satisfied for a wave of parallel wavenumber $k_{\parallel}$ and a parallel particle velocity $v_{\parallel}$. This arises from the R^{-1} dependence of the toroidal field, i.e., $\Omega_i \sim R^{-1}$ where R is the major radius. For simplicity, we take the layer to pass through the center of the plasma minor cross section. Because of the rotational transform, a given ion spends only a finite time inside the layer. During this time the ion magnetic moment μ experiences a net change $\Delta\mu$ due to the RF. After leaving the layer, the ion is no longer in resonance with the wave and proceeds to follow a Tokamak orbit dependent upon the single particle invariants, i.e., the energy, μ, and the toroidal canonical angular momentum P_{ϕ}. After the particle circulates half way around the magnetic surface, it encounters the resonance layer again. At this point the strength of the RF kick received by the particle depends on the phase difference experienced by the wave while the particle has been circulating. The repeated random scattering in μ and the associated orbit changes are responsible for the simultaneous heating and spatial diffusion of the particle.

Using a local orthogonal coordinate system $(x_{\parallel}, x_{\perp}, x_3)$ aligned with the total magnetic field $\vec{B}$, the Lorentz force equation can be averaged over the particle gyro-angle to yield the evolution equations.

$$\frac{d}{dt}\,\mu^{1/2} = eE_+\,(2mB)^{-1/2}\cos(k_{\perp}x_{\perp})\cos\delta \tag{1}$$

$$\frac{d}{dt}\,\delta = \omega - k_{\parallel}v_{\parallel} - \Omega_i - eE_+\,(2mB\mu)^{-1/2}\cos(k_{\perp}x_{\perp})\sin\delta \tag{2}$$

$$\frac{d}{dt} v_{\parallel} = -(\mu/m) \frac{\partial B}{\partial x_{\parallel}} \tag{3}$$

where e, m refer to the ion charge, and mass, and E_+ is the amplitude of the left-hand polarized component (resonant) of the wave having perpendicular wave number $k_\perp$; $\delta \equiv \theta - (k_\parallel x_\parallel - \omega t)$ where θ is the gyroangle between $\vec{v}_\perp$ and the normal to $\vec{B}$.

The important changes described by Eqs. (1) - (3) occur at the crossing of the resonant layer, where abiabaticity is broken; outside the layer these equations predict small oscillations which are neglected in this calculation. To extract the jump $\Delta\mu$ at the layer, Eqs. (1) and (2) are combined into the exact expression

$$\frac{d}{dt}\left\{ \mu^{1/2}\exp[i(\delta - \int dt' \ (\omega - k_\parallel v_\parallel - \Omega))] \right\}$$

$$= eE_+ \ (2mB)^{-1/2}\cos(k_\perp x_\perp)\exp[-i\int dt'(\omega - k_\parallel v_\parallel - \Omega)] \tag{4}$$

Observing that the left side of Eq. (4) is of the form $g(t)\exp[if(t)]$, where $g(t)$ varies slowly in time, the method of stationary phase can be used to obtain the value of $\mu = \mu(t)$ after passage through the n-th harmonic resonance.

$$\mu(t) = \left| \ \mu^{1/2}(o) \pm eE_+(2mB)^{-1/2}(\Delta t)\exp\left\{ i[\pm \pi/4 - \psi] \right\} \right|^2 \tag{5}$$

where, $\Delta t = \cos(k_\perp x_o)T$ for n odd, and $\Delta t = \sin(k_\perp x_o)T$ for n even, and

$$T = J_{n-1}(k_\perp\rho)(\pi/2)^{1/2} \ [(d\Omega/dx_\parallel)(nv_\parallel - ck_\parallel\mu/e)]^{-1/2} \tag{6}$$

$$\psi = \int_{-\infty}^{t} dt' \ (\omega - k_\parallel v_\parallel - n\Omega) \tag{7}$$

J_n is the Bessel function of order n, x_o the guiding-center position, ρ the gyro radius, c the speed of light. All the spatially dependent terms, B, x_o in Eq. (5), $\rho, v_{\parallel}, \mu$ in Eq. (6) and t in Eq. (7) are evaluated at the resonance point. In Eq. (5) the (+) refers to n odd, (-) to n even. Physically, Δt represents the effective time spent by the ion inside the resonant layer.

To calculate the phase change $\Delta\psi$ between resonances, one uses the small inverse aspect ratio $\varepsilon = r/R$ expansion for the toroidal field, $B_t = B_o\,(1 - \varepsilon\cos\alpha)$.

$$\Delta\psi = 2(\varepsilon\omega Rq/v_{\parallel}a)(1+a)^{1/2}\,[E(\alpha_2/2,\kappa) - E(\alpha_1/2,\kappa) - (F(\alpha_2/2,\kappa) - F(\alpha_1/2,\kappa))/(1+a)] - k_{\parallel}R\,q\,(\alpha_2 - \alpha_1) \tag{8}$$

where $a = 2\varepsilon B_o\mu/mv_{\parallel}^2$, $\kappa^2 = 2a/(1+a)$, q is the safety factor, and $F(\alpha,\kappa)$, $E(\alpha,\kappa)$ are the incomplete elliptic integral of the 1st and 2nd kind.

In Eq. (8) $v_{\parallel}$ is evaluated at the resonant point $(\alpha=\alpha_1)$. A passing particle has $a<1$ and thus $\kappa<1$. The appropriate expression of $\Delta\psi$ for the trapped particle can be found[7] from the continuation formula of the elliptic integral from $\kappa>1$ to $\kappa<1$.

Having found analytic expression for the changes in (μ,ψ), an appropriate set of mapping equations can be found. Because in Tokamak geometry $dB/dx_{\parallel}$ changes sign upon successive passages through the resonant layer, two different sets of difference equations must be used. In addition, because the RF can induce changes between passing and trapped orbits, different expressions must be used as an ion crosses the trapping boundary.

The change of the ion orbit[8] can be found from the conservation of the total energy, μ and P_ϕ between resonances, i.e.,

$$P_\phi = \sigma m R v_{\parallel} \left(1 + \frac{2\varepsilon\mu B_o}{m v_{\parallel}^2} \cos\alpha\right)^{1/2} \cos\beta - e\,\Psi(r)/c \qquad (9)$$

where $\sigma = \pm 1$ refer to co-flowing and counter-flowing particles, $\tan\beta = B_p/B_t$. From Eqn. (9), $r(\alpha,\mu)$ can be found for given values of P_ϕ, $v_{\parallel}$ and the functional form of the poloidal flux function $\Psi(r)$. After updating $\mu \rightarrow \mu + \Delta\mu$ using Eqs. (5), (8), the orbit change can be obtained from Eq. (9).

In a sample numerical calculation one considers several protons having equal μ initially and distributed uniformly over the phase $(0, 2\pi)$. Then Eqs. (5), (8), (9) are iterated by a computer for each particle and the results are averaged over the initial phases. For simplicity a cylinder having a parabolic current profile is used to obtain $\Psi(r)$. Fig. (1) shows an example of successive changes in the averaged total energy, while Fig. (2) demonstrates the corresponding change of guiding center minor radius Δr as the ion passes through the equatorial plane ($\alpha = 0$). The machine parameters correspond to the UCLA Macrotor for 3 different RF power levels. (The relationship between E_+ and RF power can be found with the aid of Ref. (9).) The linear dependence of $(\Delta r)^2$ on the transit number seen in Fig. (2) demonstrates that the radial motion is diffusive. The heating rate and diffusion coefficient can be obtained from the slope of these figures. The radially averaged values for Macrotor and PLT are shown in Figs. (3) and (4). The idealized parameters used to generate these results are shown in Table I. All the other parameters are fixed in such a way that Fig. (3) and (4) represent first harmonic ($n = 1$) heating of protons (minority) in a deuterium (majority) plasma. The single particle confinement time and maximum attainable energy can be found by examining such figures. For instance, in high current PLT at 300 kw RF power it takes a proton 45msec to attain a perpendicular energy of 37.5 KeV while it walks out radially 5cm. Similar studies have been made for second harmonic heating. Since this process is proportional to $(k_{\perp}\rho)^2$, as shown in Eq. (6), the corresponding heating rate and diffusion coefficient are smaller than the fundamental case at least by an order of magnitude.

In summary, a scheme has been developed which permits the calculation of the simultaneous ion cyclotron resonance heating rate and the associated real space diffusion coefficient in Tokamak geometry. The diffusive nature of the heating and radial excursion have been demonstrated, and its magnitude found to scale as $|E_+|^2$. The preferential transfer of perpendicular energy due to cyclotron resonance produces an enhanced banana diffusion rate which limits the maximum energy attainable by single particles. Such an effect can be quite severe for small and/or low current machines and should be included in sophisticated codes that attempt to explain experimental heating result.

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Table 1. Idealized parameters used in generating Figs. (3) and (4). $T_{\parallel}$ is the initial parallel energy at the resonance layer.

Machine	Major Radius (cm)	Minor Radius (cm)	B_o (kG)	I (KA)	Cavity Q	$T_{\parallel}$ (eV)
Macrotor	100	30	2	60	30	100
PLT	130	40	30	600	30	500

Figure Captions

Fig. 1 Secular increase in the average ion energy due to transits through the fundamental resonance ($n = 1$) for different RF power levels. Parameters correspond to protons in the Macrotor tokamak.

Fig. 2 Secular change in the guiding center minor radius Δr as the ion passes through the equatorial plane. This radial diffusion is obtained self-consistently with the heating shown in Fig. 1.

Fig. 3 Radial and phase averaged heating rate (solid curve) and spatial diffusion coefficient (dashed curve) for minority protons in Macrotor.

Fig. 4 Radial and phase averaged heating rate (solid curve) and spatial diffusion coefficient (dashed curve) for minority protons in PLT.

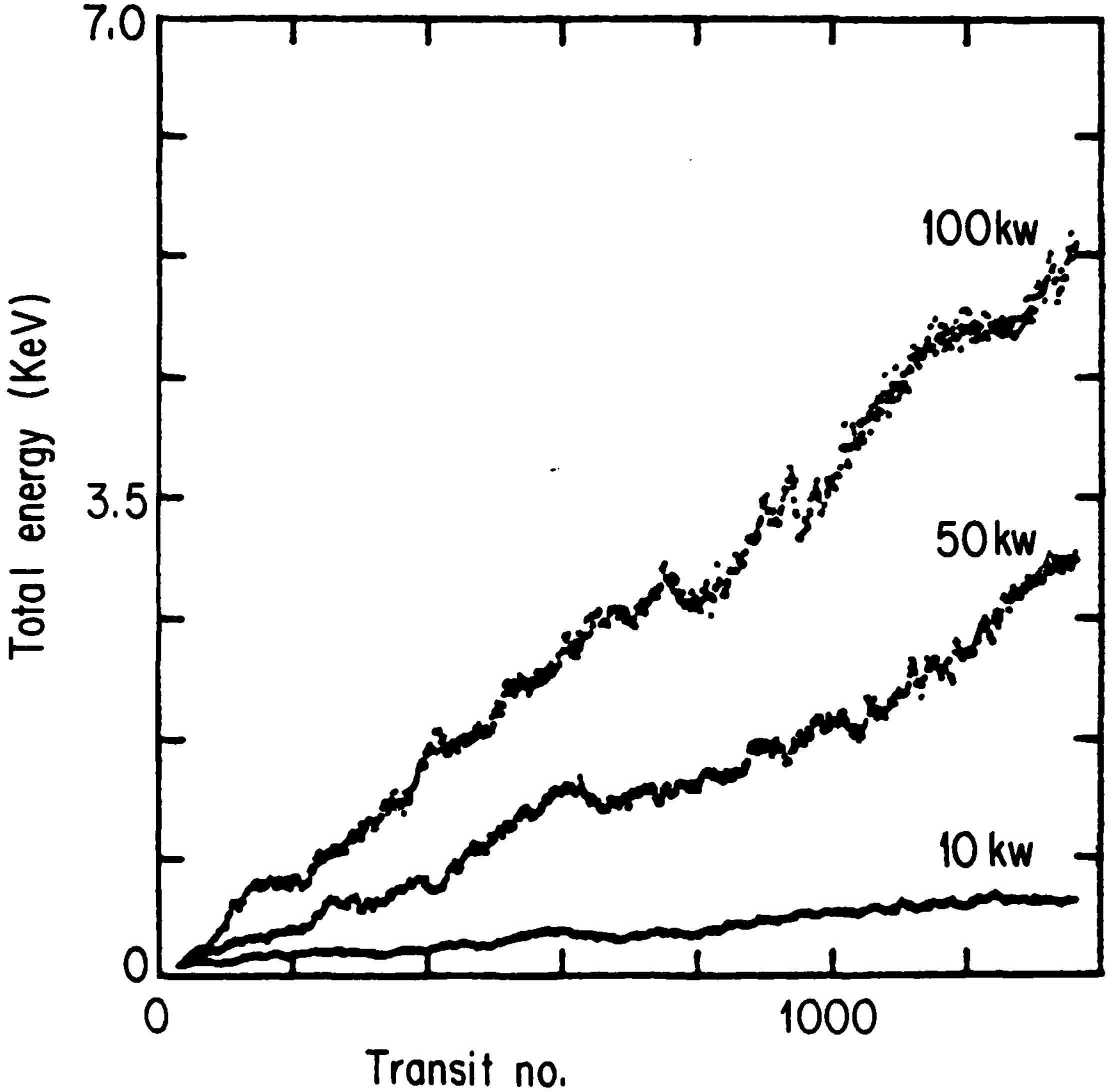

Fig.1

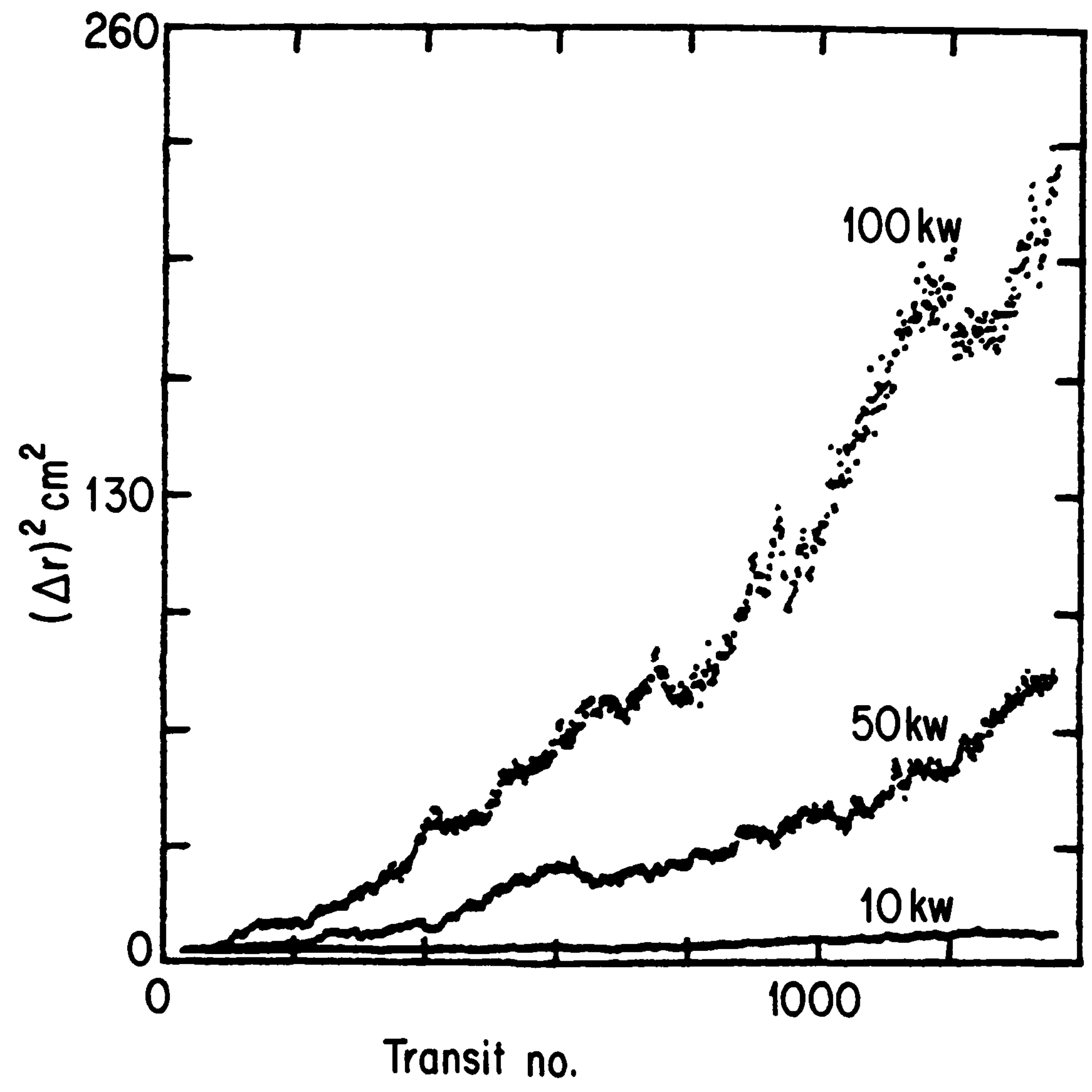

Fig.2

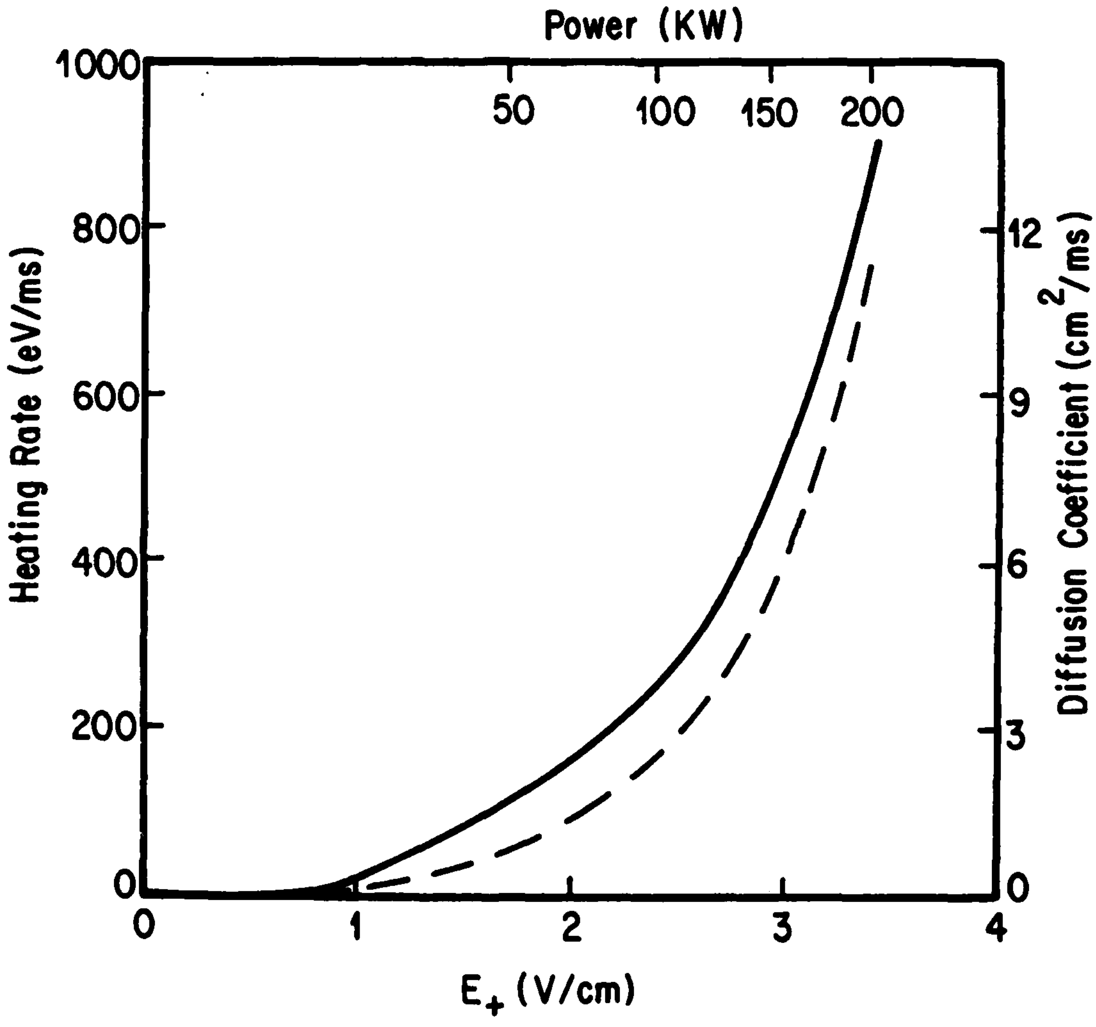
Power (KW)
50
100
150
200
1000
800
600
400
200
0
Heating Rate (eV/ms)
12
9
6
3
0
Diffusion Coefficient (cm^2/ms)
0
1
2
3
4
E_+ (V/cm)

Fig.3

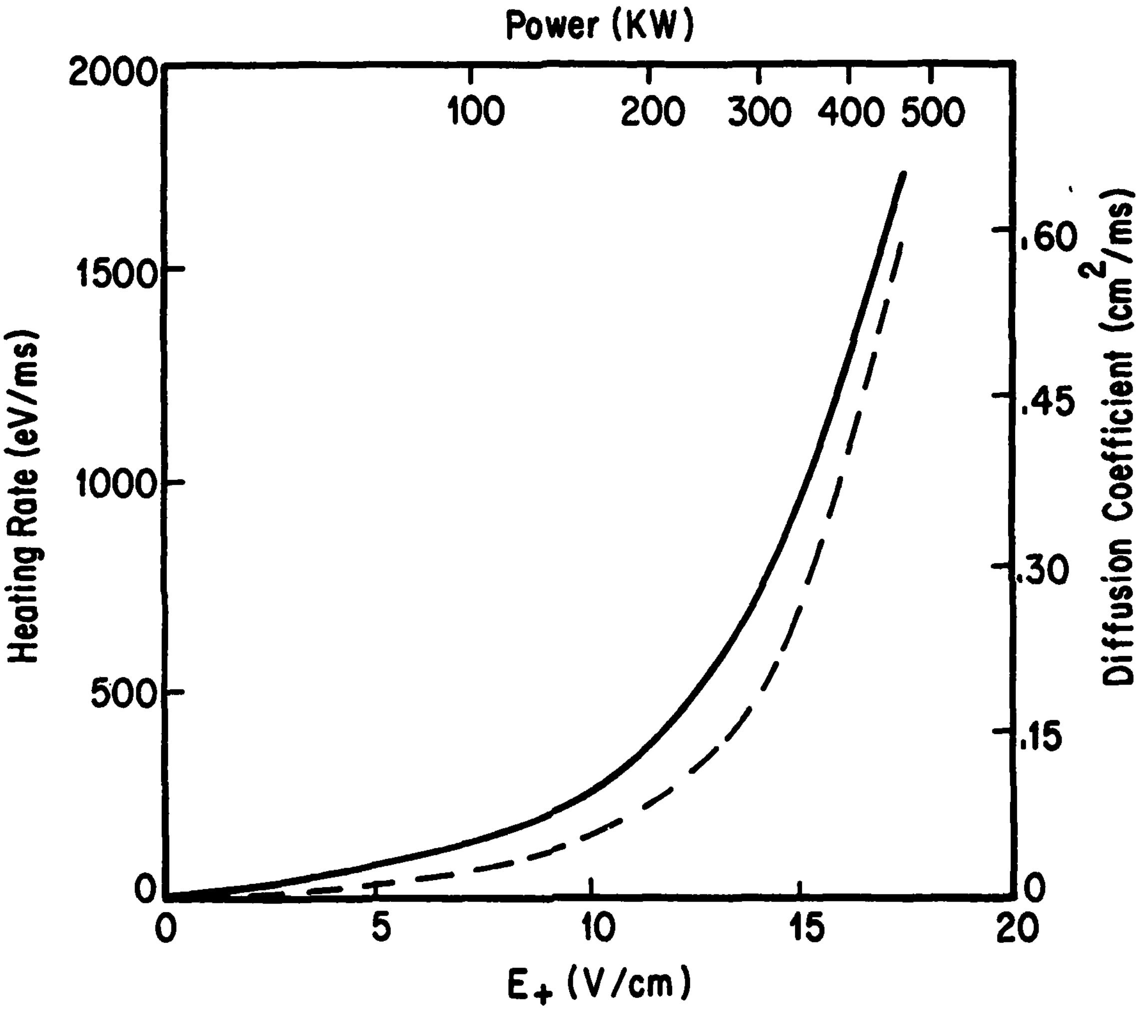
Power (KW)
100
200
300
400
500
2000
1500
1000
500
0
Heating Rate (eV/ms)
.60
.45
.30
.15
0
Diffusion Coefficient (cm^2/ms)
0
5
10
15
20
E_+ (V/cm)

Fig.4

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