Electron heating mode transitions in dual frequency capacitive discharges

M. M. Turner*

School of Physical Sciences and National Centre for Plasma Science and Technology,
Dublin City University, Dublin 9, Ireland

P. Chabert

Laboratoire de Physique et Technologie des Plasmas,
Ecole Polytechnique, 91128 Palaiseau, France

Abstract

We consider electron heating in the sheath regions of capacitive discharges excited by a combination of two frequencies, one much higher than the other. There is a common supposition that in such discharges the higher frequency is the dominant source of electron heating. In this letter, we discuss closed analytic expressions quantifying the Ohmic and collisionless electron heating in a dual frequency discharge. In both cases, we show that the lower frequency parameters strongly influence the heating effect. Moreover, this influence is parametrically different, so that the dominant heating mechanism may be changed by varying the low frequency current density.

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*Electronic address: `miles.turner@dcu.ie`

Dual frequency capacitive discharges are a topic of intense interest because of their adoption as a processing tool by the semiconductor industry. The compelling practical advantage of these discharges is that they permit a degree of independent control of two critical process parameters, namely the flux and energy of ions impacting on the surface being processed [1]. Such control is impossible in a single frequency discharge. This background makes an enquiry into the physics of dual frequency discharges desirable, with the aim of establishing simple models based on an understanding of the dominant physical effects. These are not a trivial superposition of the effects of the two frequencies acting separately, as has already been shown [2–6]. In this Letter we discuss the relative importance of two important electron heating mechanisms, Ohmic heating and collisionless or stochastic heating. We consider a discharge excited by two frequency components, with angular frequencies, $\omega_{l,h}$ and current density amplitudes $\tilde{J}_{l,h}$, where the subscripts l and h denote the lower and higher frequencies. We recently developed a compact expression for the collisionless heating component in this case [6] (see [7] for a different perspective on this issue), showing that there is a strong dependence of the collisionless heating power on both the low and high frequency current densities, contrary to a simple expectation that power coupling to electrons is independent of the low frequency parameters because the low-frequency current density is comparatively small [1]. Below, we develop a similarly compact expression for the Ohmic heating component. We go on to discuss the dependence of this result on the low frequency parameters, and the relative importance of the Ohmic and collisionless heating components.

The discharge can be divided into two regions—the bulk, where the plasma is quasi-neutral at all times, and the sheaths, where positive space charge is present for part of each low frequency period. In a low pressure discharge, electron heating occurs predominantly in sheath regions, and collisionless heating is in any event essentially absent from the bulk. Moreover, the calculation of Ohmic heating in the bulk is straightforward [8]. We therefore shall not discuss heating in the bulk. Our discussion of the sheath is simplified by the assumption that, at any given time, an electron sheath edge can be defined as a point, with a position denoted by $s(t)$, where quasi-neutral plasma ends and space-charge sheath begins. The path described by $s(t)$ in dual frequency discharges is complex [2], but bounded between the electrode and another point that we define as the ion sheath edge, which is the origin for $s(t)$. We will consider heating effects occurring in the region between the electron and ion sheath edges. This calculation is complicated, because we must deal in effect with a moving boundary problem. In [6] we showed that the time-averaged collisionless heating in this region can be expressed as:

$$\bar{S}_{\text{stoch}} = 2Q_b\left[\delta_l^2 F_0(\alpha,\beta,H_{\text{eff}}) + \delta_h^2 F_1(\alpha,\beta,H_{\text{eff}})\right] \tag{1}$$

where F_0 and F_1 are functions approximated by $F_0 \approx 36H_{\text{eff}}/(55+H_{\text{eff}})$ and $F_1 \approx 1.1F_0$, $\alpha = \omega_h/\omega_l$, $\beta = \tilde{J}_h/\tilde{J}_l$, $H_{\text{eff}}^2 = H_l^2 + H_h^2$, $H_{h,l} = \tilde{J}_{h,l}^2/\pi T_b \omega_{h,l}^2 n_0$, T_b is the effective bulk electron temperature in joules, n_0 is the plasma density at the ion sheath edge, $\delta_{l,h} = \tilde{J}_{l,h}/en_0\bar{v}_b$ and $Q_b = \frac{1}{4}n_0\bar{v}_b T_b$ is the electron heat flux incident on the sheath, with $\bar{v}_b = \sqrt{8T_b/\pi m_e}$. We note that $H_{\text{eff}}^2 = H_l^2\left[1+(\beta/\alpha)^4\right] \approx H_l^2$ in most cases. This result shows that the collisionless heating power is a strong function of the low frequency parameters ω_l and $\tilde{J}_l$, because these parameters control the spatial structure of the sheath [2, 6, 9].

We now turn to the calculation of the Ohmic heating component. In general, the instantaneous Ohmic heating power per unit volume dissipated in a plasma with density n and electron collision frequency ν_e is

$$P_{\text{ohmic}} = \frac{m_e \nu_e J^2(t)}{ne^2} \tag{2}$$

where J is the current density, and we have assumed that any ionic contribution to the heating effect is negligible. The Ohmic power dissipation per unit area within the sheath is now found by integrating from the ion sheath edge to the electron sheath edge at $s(t)$:

$$\begin{aligned} S_{\text{ohmic}}(t) &= \frac{m_e\nu_e J^2(t)}{e^2}\int_0^{s(t)} \frac{dx}{n(x)} & (3)\\ &= J^2(t)\frac{m_e\nu_e}{e^2}\int_0^{\phi(t)} \frac{d\phi'}{n(\phi')}\frac{dx}{d\phi'} & (4)\end{aligned}$$

where $\phi = \omega_l t$ is the independent variable of the Lieberman [9] and Robiche [2] sheath models. These expressions hold for any sheath model. If we assume that the sheath structure is adequately described by the analytical dual frequency sheath model of [2], then we have closed, albeit complex, expressions for $dx/d\phi$ and $n(\phi)$. The problem of calculating the time-averaged Ohmic heating thus becomes a double quadrature that can be written:

$$\bar{S}_{\text{ohmic}} = \frac{32}{\pi} Q_b \delta_l^3 \left(\frac{\nu_e}{\omega_l}\right) F_2(\alpha,\beta,H_l). \tag{5}$$

The integrations entailed in the function F_2 can be carried out formally, but the resulting expressions are not useful [2]. A compact and convenient approximation can however be obtained by considering the limit $\alpha \gg 1$, in which case the high frequency terms can be substituted by constants. This is possible because the low-frequency current can be considered nearly constant over a period of the high-frequency current. The remaining integrations can then be carried out without further approximation to find:

$$F_2 \approx A_2 = \left[\frac{1}{2}\left(1+\beta^2\right) + \frac{1}{\pi}\left(\frac{512}{675} + \frac{32}{27}\beta^2\right) H_l + \left(\frac{14912}{165375} + \frac{1336}{3375}\beta^2\right) H_l^2\right]. \qquad (6)$$

Fig. 1 shows that this approximation is good when $\beta/\alpha \ll 1$, rather independently of the value of H_l. Since this condition is required for the sheath model to be valid [2], eq. 6 is likely to be useful whenever the sheath model is useful. We note that the condition $\beta/\alpha \ll 1$ can be expressed less precisely but perhaps more helpfully as $\tilde{V}_h \ll \tilde{V}_l$, which will hold for most conditions of practical interest.

This result shows that Ohmic heating, like collisionless heating, is enhanced by the combination of two frequencies. The physical mechanism of the enhancement is similar—when the lower frequency is applied, the spatial structure of the sheath region is modified, the maximum sheath width is increased and the ion density near the boundary is greatly reduced. When the sheath is collapsed, and these regions are populated by electrons, the higher frequency current is conducted through a much more tenuous plasma than would be the case if the lower frequency was absent. As eq. 2 suggests, the Ohmic heating effect is thereby considerably enhanced. In fact, as inspection of eqs. 1 and 6 indicates, Ohmic heating is more effectively enhanced than collisionless heating by the influence of the low-frequency current. Indeed, fig. 2 shows that the dominant heating mode can be changed by application of the low-frequency current. In this example, we have taken $\nu_e/\omega_l = 30$, corresponding to a discharge in argon at a pressure of approximately 100 mTorr, with $n_0 = 5 \times 10^{15}$ m^{-3}, T =30000 K, $\omega_l/2\pi = 2$ MHz, $\omega_h/2\pi = 27$ MHz, and $\tilde{J}_h = 36$ A m^{-2}. These conditions are typical for contemporary experiments. In fig. 3 we show the ratio of the collisionless and Ohmic heating powers for a range of values of ν_e/ω_l spanning any likely experiments. These results show that dual-frequency discharges may in principle be dominated by either collisionless heating or Ohmic heating, but that typical experiments are likely to be in a mixed regime tending to Ohmically dominated.

In summary, we have presented simple and useful expressions for the collisionless and Ohmic heating powers in dual-frequency discharges. These results will be of value in simple models of this type of discharge. Our expressions show that both the collisionless and

Ohmic heating mechanisms are strongly influenced by the low frequency current density under typical experimental conditions, contrary to elementary ideas about dual-frequency discharge operation. This influence is exerted by modification of the spatial structure of the sheath: In particular, the relatively large voltage associated with the lower frequency greatly affects the ion density in the sheath region. Our results also controvert the generally accepted view that capacitive discharges used for semi-conductor processing are dominantly heated by collisionless processes. In dual-frequency discharges, Ohmic processes can be of comparable or greater significance.

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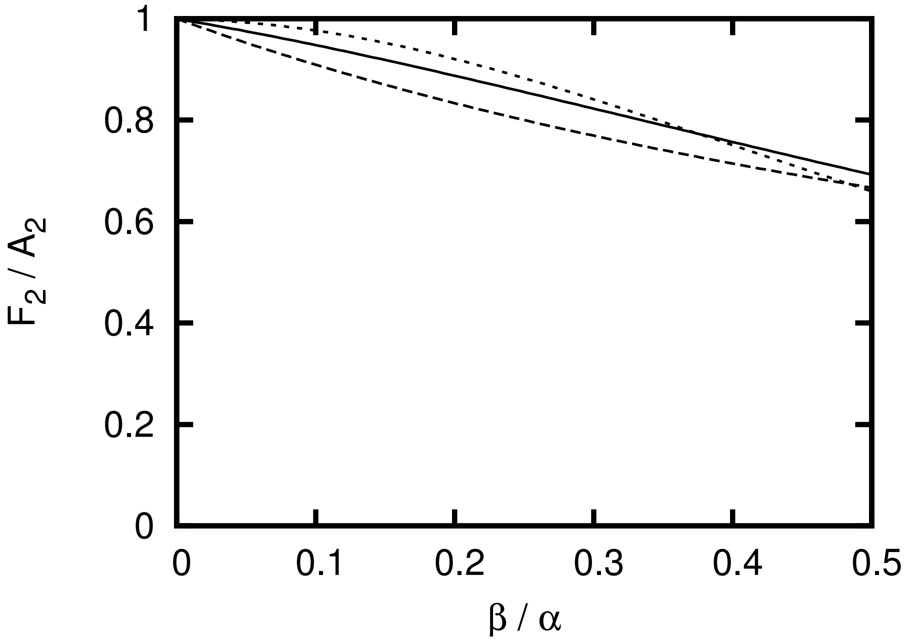

FIG. 1: The approximation given by eqn. 6 compared with numerical evaluation of the integral in eqn. 5, for various parameters. Solid line, $H_l = 1$, $\alpha = 100$; Long dashed line, $H_l = 0$, $\alpha = 10$; Short dashed line, $H_l = 11$, $\alpha = 20$

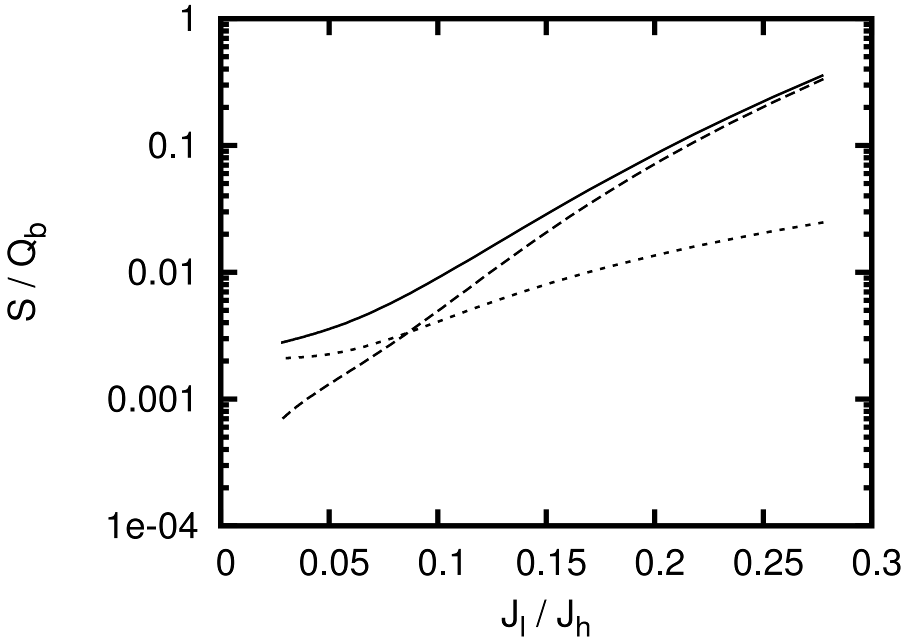

FIG. 2: The collisionless, Ohmic and total heating powers, shown as a function of the low frequency current density. Solid line—total; long dashed line—Ohmic; short dashed line—collisionless. The conditions are $\omega_l/2\pi = 2$ MHz, $\omega_h/2\pi = 26$ MHz, $\tilde{J}_h = 36$ A m^{-2}, $n_0 = 5\times10^{15}$ m^{-3}, $T_b = 30000$ K, and $\nu_e/\omega_l = 30$

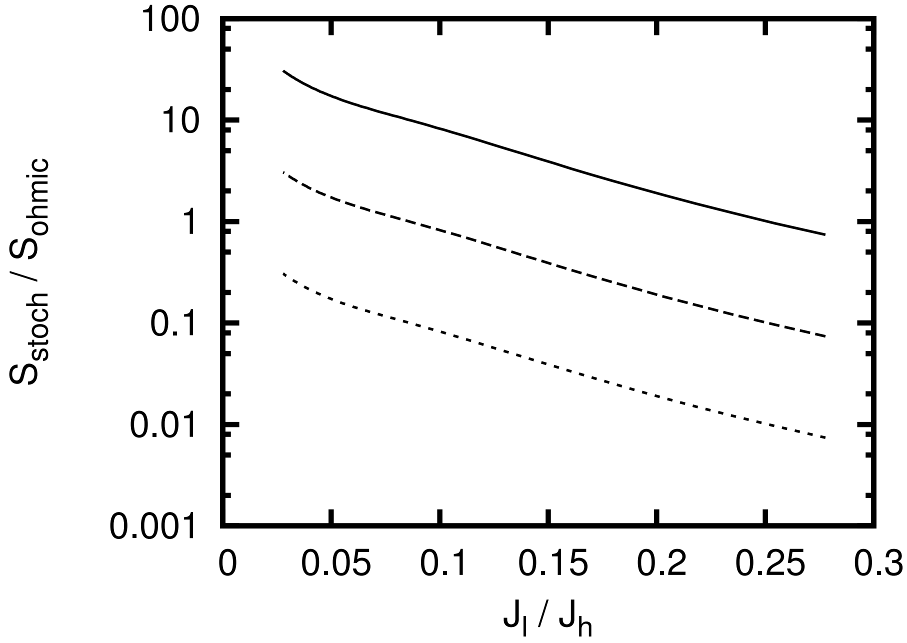

FIG. 3: The ratio of the collisionless and Ohmic heating powers for various electron collision frequencies, corresponding approximately to conditions in argon at pressures of 10 (solid line), 100 (long dashed line) and 1000 mTorr (short dashed line), corresponding to $\nu_e/\omega_l = 3, 30, 300$.