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GENERATION AND MODELING OF GASEOUS PLASMAS USING MICROWAVE POWER

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Introduction

In contrast to RF produced plasmas, in the case of microwave (MW) sustained plasmas the energy from the electromagnetic (EM) field is communicated only to electrons since ions, being a few thousand times much heavier than electrons, cannot respond to the periodic changes in the direction of the ***E***-field of microwaves (frequency range 300 MHz–300 GHz) and therefore cannot gain energy in the EM field. The energy thus acquired by electrons is essentially transferred to heavy particles either through collisional absorption (high enough gas pressures) or, in the presence of a static applied magnetic field, by collisionless (low-pressure: 10^{-4} – 10^{-3} mbar) absorption through electron-cyclotron resonance (ECR), providing in both cases excitation and ionization of the discharge gas. In order to analyze the power transfer from the EM ***E***-field, instead of the usual global power balance, it is much more direct and informative, as will be discussed, to turn to the concept of power per electron, more specifically of power absorbed per electron θ_A and of power loss in the plasma on a per electron basis θ_L.

This approach was initially based on the experimental results from Glaude et al. [1] who, when characterizing the properties of surface-wave sustained plasmas (at 300 MHz), noticed that electron density (under ambipolar diffusion regime) was proportional to absorbed microwave power. Another important step was later on contributed by Zakrzewski [2] and Ferreira [3] who, considering the global power balance, underlined that, under steady-state conditions, the level of MW power absorbed simply adjusts to compensate for plasma losses. Losses are finally mainly due to the recombination of charged particles (electrons, ions) on tube walls, which depend on operating conditions[1].

The properties of surface-wave discharges will be utilized in what follows to illustrate the discharge modelling developed, in the end suitable for MW discharges in general, and, also, to provide corresponding examples. Figure 1 displays a schematic representation of the surface-wave launcher with its EM field interstice (a 2–3 mm wide gap in the case of a surfatron), which is the essential part of the field applicators used to achieve tubular surface-wave discharges (SWDs). The EM field emerging from this interstice allows generating a plasma column sustained ultimately by an EM surface wave in both directions from the gap[2]. However, the SWDs do not start at the wave launcher immediate exit, but at some distance from it [4].

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[1] Operating conditions are: nature and pressure of discharge gas, EM field frequency, and discharge tube inner and outer diameters as well as permittivity. Absorbed MW power is excluded.

[2] The back column emerging from the surfatron interstice is much shorter in length than the forward column as a result of the presence of the surfatron body, a tight conducting enclosure surrounding the discharge tube.

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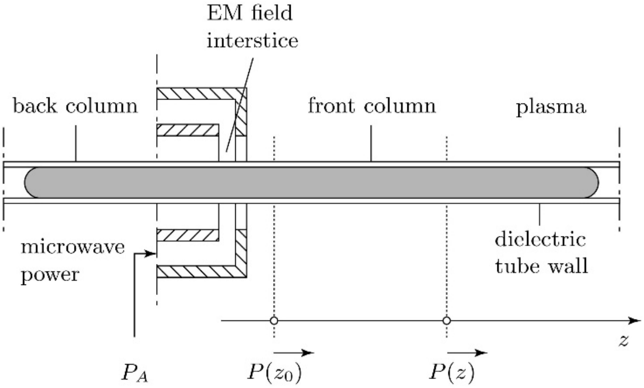

Figure 1. Schematic representation of an EM field applicator with a circular aperture (of the type developed in Montréal) used for achieving a tubular SW discharge, highlighting its essential part, namely the EM field radiating interstice, typically here a 2–3 mm wide gap. As a result of the EM field emerging from the interstice, a SW is launched in both directions (past the $P(z_0)$ point for the front wave), sustaining a plasma column enclosed in a dielectric tube. The impedance matching system of the feed line with the power generator is not represented.

An example of a SW sustained plasma column

Figure 2 shows photographs of the plasma column generated at atmospheric pressure in argon with a 915 MHz surfatron in a 6/8 mm id/od fused silica tube. The plasma column extends away from the ***E***-field applicator as a result of an EM SW using the plasma column and its dielectric medium as the propagating medium. In a), there is no surrounding Faraday cage (FC) at all while in b) and c), the discharge is enclosed in a 22.5 mm radius FC ensuring wave cut-off in a circular waveguide[3]. The cage length in b) is 30 mm, which was found to be the minimum FC length averting space-wave radiation in the room (see further) from affecting much our measurements; the axial slot in the FC allows making field intensity and spectroscopic measurements along the plasma column. In c), the FC length is longer than the plasma column. Absorbed power being 300 W in each photo, clearly, the plasma column length is the longest with the full length FC: this is because the power loss due to space-wave radiation generated by the ***E***-field applicator has been confined within the FC, giving rise to additional electrons [6].

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[3] A circular waveguide enclosing (coaxially) at cut-off (on its fundamental mode) the plasma tube prevents waves from propagating within this conducting cage (but not the SW, which uses the discharge tube and the plasma as its propagating medium). The fundamental mode of a circular waveguide (i.e., the lowest frequency at which a wave can propagate within it) is the TE_{11} mode. The minimum FC radius to achieve cut-off is given by $R_{Fc(co)} = 1.841\lambda_o/2\pi$, where λ_o is the free-space wavelength. At 915 MHz, a circular waveguide (acting as a Faraday cage) with a radius smaller than $R_{Fc(co)} = 96.1$ mm is at cut-off, i.e., no wave can propagate within it. At 2450 MHz, $R_{Fc(co)}$ is 35.9 mm [5].

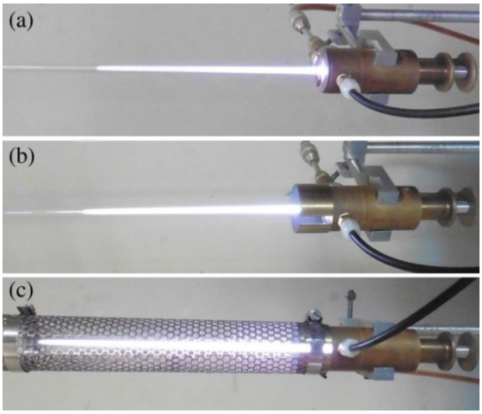

Figure 2. Photographs showing the plasma column obtained with a 915 MHz surfatron: a) with no surrounding Faraday cage at all; b) and c) when enclosed in a 22.5 mm radius FC corresponding to wave cut-off in a circular waveguide. In b), the cage length is 30 mm while in c) it is 305 mm long, extending beyond the present plasma column length. The MW power coupled to the surfatron is 300 W in each photo [6].

Defining the power absorbed per electron by considering the decrease of power flow along a SW sustained plasma column

Figure 3 shows the axial distribution of electron density along a SWD at reduced-gas pressure and at different applied-field frequencies. The arrows in the figure point at the value of the power flowing out from the surfatron interstice: at 100 MHz, it indicates that raising the MW power from 36 to 58 W simply increases the plasma column length without affecting the properties of the plasma column pre-existing at 36 W, and thus that the added power all went into the extension of the previously created plasma column. From this, we infer that any increase in wave power from $P_{\mathrm{a}}(z)$ to $P_{\mathrm{a}}\left(z+\mathrm{d}z\right)$ is absorbed in the differential segment of plasma column z, z + dz. It thus means that the amount of power taken away from the wave power flow sustaining the discharge is equal to the power absorbed in the additional plasma slab dz generated at z, hence experimentally the following relationship:

$$\mathrm{d}P_{\mathrm{a}}(z)/\,\mathrm{d}z=\theta_{\mathrm{A}}\,\overline{n}_{\mathrm{e}}(z)\,S \qquad (1)$$

where we define θ_{A} as the power absorbed per electron averaged over the plasma column cross-section S at z with a corresponding average electron density $\overline{n}_{\mathrm{e}}(z)$.

The power absorbed per electron: an insightful and far-reaching parameter

Power consumption along the SW plasma column

Figure 4 shows measured values of θ_{A}/p as functions of the axial distance from the end of the SW plasma column sustained at 200 MHz, for three different gas pressures p. For a given gas pressure, θ_{A} is observed not to vary with axial position except close to the column very end [4]. Introducing θ_{A} in relation (1) is thus really insightful as it shows that the power cost for maintaining an electron in the discharge is almost the same all along the plasma column, hence that it is independent of electron density. This behavior is characteristic of plasmas operated under ambipolar diffusion regime[4] (as opposed to that of volume recombination of

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[4] This is the usual regime describing the movement of charged particles in low-pressure rare-gas discharges (0.5–10 Torrs, 65–1300 Pa).

charged particles occurring at higher discharge gas pressures), the simplest regime to deal with when investigating the features of the power balance per electron.

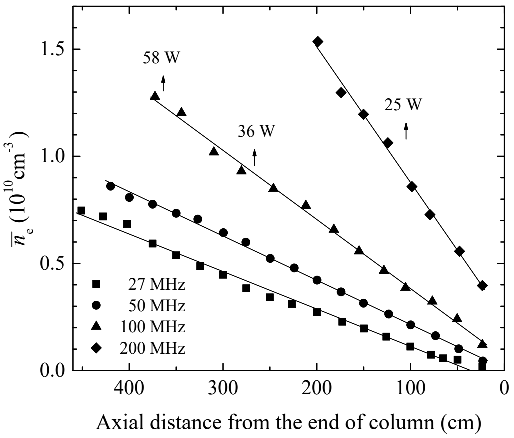

Figure 3. Measured axial variation of the electron density averaged over the radial cross-section of the plasma column sustained by the propagation of the electromagnetic surface wave at four different field frequencies, in argon gas at a pressure of 30 mTorr (≈ 4 Pa) in a tube of 64 mm inner diameter [7].

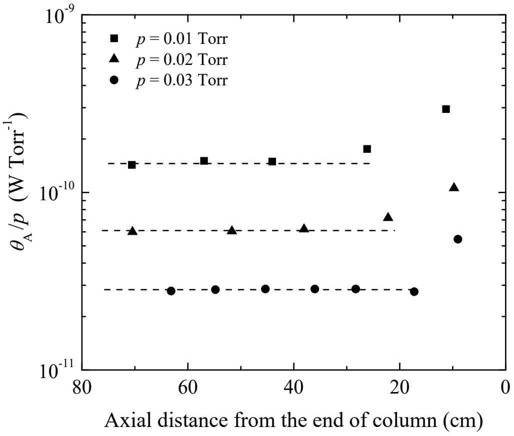

Figure 4. Measured values of θ_A/p as functions of the axial distance from the end of the SW plasma column sustained at 200 MHz, for three different gas pressures p. For a given gas pressure, θ_A is observed not to vary with axial position except very close to the column end [8].

Expression for the absorbed power θ_A (case of collisional absorption)
The value of θ_A, the average power (over a MW field period) absorbed per electron in the discharge, is given by [9]:

$$\theta_A(E) = e^2\,\overline{E^2}\,\nu \Big/ \left[m_e(\nu^2+\omega^2) \right], \qquad (2)$$

where ν is the electron-heavy particle collision frequency for momentum transfer, ω, the wave angular frequency, e/m_e, the electron charge to mass ratio, and $\overline{E^2}$, the mean squared value of the EM $\boldsymbol{E}$-field. Collisional absorption implies that ν/ω is not much smaller than unity.

The power θ_A and the casting of similarity law diagrams

Similarity laws, by definition, involve combined variables. It suffices to know the values of a limited number of these combined variables, obtained experimentally or theoretically from a given set of operating conditions, to span the full extent of these combined variables without the need for further measurements or calculations. It has long been known, for instance, that E/p vs. pR (where E is the intensity of the discharge maintenance field) constitutes a similarity law for the DC positive column. Ferreira [3] showed, by modeling under diffusion regime, that this similarity law could be extended to include SWDs, provided it then reads θ/p vs. pR. It is verified experimentally in figure 5, at a fixed wave frequency, for different values of the tube radius R.

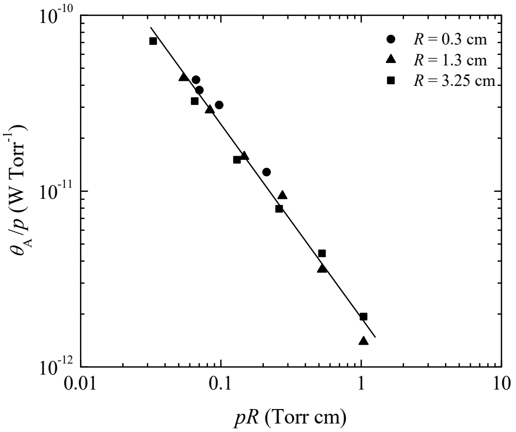

Figure 5. Measured θ_A/p values as functions of the pR product at 200 MHz, for three values of the discharge tube inner radius [3], establishing that θ_A/p vs. pR constitutes a similarity law.

Expression for the absorbed power θ_A (case of collisionless absorption at ECR)

MW power transfer at electron cyclotron resonance (ECR) requires a static magnetic field, of given intensity B, assumed in the present case to be parallel to the SW direction of propagation (z coordinate). Usual ECR conditions are two-fold: a) $\omega_{ce}/\omega = 1$ where $\omega_{ce} = |e|B/m_e$ is the electron cyclotron angular frequency; b) very low discharge gas pressure such that $\nu / \omega \ll 1$. Physically speaking it means that the EM electric field vector, which is oriented perpendicularly to $\boldsymbol{B}$ (y coordinate), is rotating around $\boldsymbol{B}$ field lines (z coordinate) at the same frequency as that of the electrons (characterized by ω_{ce}), hence the electron *sees* a constant $\boldsymbol{E}$-field! Therefore, the lower the collision frequency disrupting this process, the higher the power gained by electrons in the MW field during the time elapsed between successive collisions.

The expression for θ_A can be shown [9] to be given by:

$$\theta_{\mathrm{A}} \equiv \frac{P_{\mathrm{a}}}{n_{\mathrm{e}}} = -\frac{e}{2}\Re\left[v_y E_y^*\right] = \frac{e^2 E_0^2}{2\nu m_{\mathrm{e}}}\left[\frac{1}{2}\frac{\nu^2}{\left(\omega-\omega_{\mathrm{ce}}\right)^2+\nu^2}+\frac{1}{2}\frac{\nu^2}{\left(\omega+\omega_{\mathrm{ce}}\right)^2+\nu^2}\right], \tag{3}$$

where it is assumed that a plane EM wave is propagating along the z axis (parallel to the static $\boldsymbol{B}$-field) with the electric field component $\boldsymbol{E}=\boldsymbol{E}\exp(\mathrm{i}\omega t)$ taken along y, of intensity E_0^2; v_y is the electron velocity along the $\boldsymbol{E}$-field while n_e is the electron density, assumed uniform; (3) clearly reduces to (2) for ω_{ce}=0. Expression (3) in a condensed form:

$$\theta_{\mathrm{A}} \equiv \frac{P_{\mathrm{a}}}{n_{\mathrm{e}}} = \frac{1}{2n_{\mathrm{e}}}\Re\left(\sigma_{yy}E_0^2\right) \tag{4}$$

or equivalently:

$$\theta_{\mathrm{A}} = \frac{E_0^2}{2n_{\mathrm{e}}}\Re(\sigma_{yy}), \tag{5}$$

where $\Re(\sigma_{yy})$ means the real part of the electron-conductivity tensor of component yy (recall that the y coordinate is directed along $\boldsymbol{E}$). The expression for $\Re(\sigma_{yy})$ is readily obtained from (5) by keeping only the ECR frequency-condition term ($\omega_{\mathrm{ce}} = \omega$), yielding [9]:

$$\Re\left(\sigma_{yy}\right) = \frac{n_{\mathrm{e}}e^2}{m_{\mathrm{e}}}\left[\frac{1}{2}\frac{\nu}{\left(\omega-\omega_{\mathrm{ce}}\right)^2+\nu^2}\right]. \tag{6}$$

Figure 6 shows experimentally that: i) the higher the value of ω_{ce}, i.e. the higher the static magnetic field intensity, the lower the charged particles losses as a result of their increased confinement; ii) there is no maximum of the θ_{A} value at $\omega_{\mathrm{ce}}/\omega = 1$ as the value of pressure p is decreased such as to meet gradually condition b) above (ν / ω □ 1).

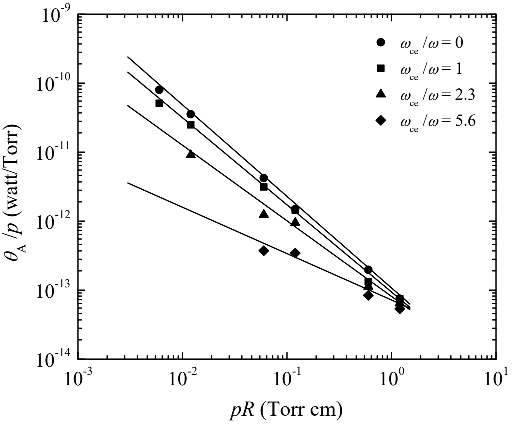

Figure 6. Measured absorbed power per electron as a function of the pR product in a SW sustained argon discharge immersed in a static magnetic field $\boldsymbol{B}$ directed along the plasma column (i.e. along the SW direction of propagation), considering different values of the ratio $\omega_{\mathrm{ce}}/\omega$ (including ECR frequency condition $\omega_{\mathrm{ce}}/\omega = 1$). The EM surface wave propagates on the HE_{01} fundamental mode (magnetized plasma case [10]) at the frequency $\omega/2\pi = 600$ MHz. The tube inner radius is $R = 13$ mm while the pressure domain is varied between 5×10^{-3} and 1 Torr (≈ 0.67–133 Pa) in order to achieve the pR values plotted in the figure [10].

The value of $\Re(\sigma_{yy})$ in (6) increases as ω tends toward $\omega_{\mathrm{ce}} = \omega$ (passing through a maximum at $\omega_{\mathrm{ce}}/\omega = 1$), but the value of θ_{A} goes on decreasing linearly as pressure is reduced (no maximum or minimum in θ_{A} : figure 6): it requires that the intensity of the EM electric field in (5) must decrease correspondingly to compensate for the increase in $\Re(\sigma_{yy})$ to ensure the observed behaviour of θ_{A}. It therefore can be concluded that there is no increase but rather a decrease in the intensity of the maintenance field at ECR in contrast to what has long been accepted [11]. The fact that there are no changes in the value of θ_{A} as the MW power absorption mechanism is varied proves once again that the plasma losses are controlling the discharge behavior and that the absorbed power necessarily adjusts to compensate these losses.

Using the properties of SWDs to develop and extend the power per electron concept to various microwave discharges

a) Case of homogeneous plasmas

By homogeneous plasmas, it is meant that the differential volume in which the wave power is absorbed is the same as the one in which this power is spent.

Expression for the power loss on a per electron basis θ_{L}

The absorbed power θ_{A} gained by electrons is mainly lost through various collisions (elastic and inelastic) with heavy particles, designated θ_{Lc}, a possible form of which is:

$$\theta_{\mathrm{Lc}}(\langle U_{\mathrm{eV}}\rangle) = \frac{2m_{\mathrm{e}}}{M}\langle \nu(U_{\mathrm{eV}})U_{\mathrm{eV}}\rangle + \sum_j \langle \nu_j(U_{\mathrm{eV}})\rangle V_j + \langle \nu_i(U_{\mathrm{eV}})\rangle V_i \tag{7}$$

where m_{e}/M is the mass ratio of the electron to that of the atom (molecule), $\nu\left(U_{\mathrm{eV}}\right)$ representing the microscopic collision frequency for an electron of energy U_{eV}, which results in a transfer of momentum to heavy particles, while ν_j and ν_i are the microscopic collision frequencies generating atomic (molecular) excitation to level j (threshold energy V_j) or ionisation (threshold energy V_i), respectively; the symbol $\langle\ \rangle$ represents the average of the quantity within the brackets taken over the electron energy distribution function (EEDF). Expression (7) illustrates the case of excitation and ionisation by a single collision from the ground state ("direct collision"). In the case where the EEDF is Maxwellian, the average values in (7) are completely determined by the sole electron temperature T_{e} and gas pressure. In general, $\theta_{\mathrm{Lc}}\left(\langle U_{\mathrm{eV}}\rangle\right)$ is an increasing function of $\langle U_{\mathrm{eV}}\rangle$. When discharge- gas pressure is increased, direct collisions must be completed by multi-step excitation and ionisation processes. Although the power lost in collisions θ_{Lc} is the main loss mechanism, some of the power gained by electrons in the wave electric field is ultimately lost in the sheath[5] and in sustaining the ambipolar DC field, hence the total power loss needs to be expressed on a per electron basis designated as θ_{L}.

Ultimately, the power thus transferred from electrons to heavy particles is lost in ion-electron recombination (at the tube wall under diffusion regime or, at higher pressures, in volume recombination within the plasma), in light emission (photons) through de-excitation or recombining electron-ion emission, and in heating the discharge tube wall,…

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[5] The plasma sheath is that non-neutral region connecting the plasma with the discharge tube. In contrast to RF sheaths, it does not vary with the EM field and it is much smaller in width (because the electron density is higher).

Setting the per-electron power balance

In the case of homogenous plasmas, the power balance then simply reads:

$$\theta_A = \theta_L \quad (8)$$

and more explicitly as:

$$\theta_A(E) = \theta_L(U_{eV}) \quad (9)$$

Since the value of θ_A adjusts so as to compensate exactly for θ_L, as repeatedly mentioned, the intensity of the maintenance ***E***-field sustaining the discharge comes out as an *internal* parameter. It means that it is operator-independent, in contrast to what is commonly believed,[6] whatever the kind of ***E***-field sustained discharges.

b) Case of inhomogeneous plasmas

It means considering the possibility that MW power be absorbed in a smaller volume V_1 than the plasma volume V_2: in such a case, the smaller the volume in which power is absorbed with respect to the volume in which it is spent, the higher the intensity of the maintenance ***E***-field. This can be seen from the global power balance:

$$\theta_A n_{e1} V_1 = \theta_L n_{e2} V_2 \,, \quad (10)$$

where n_{e1} and n_{e2} are the electron density in the absorption and plasma volumes, respectively. Since the total number of electrons in volume V_1 must be equal to that in volume V_2, then:

$$\theta_A / \theta_L > n_{e2} / n_{e1} > 1. \quad (11)$$

A smaller absorption volume thus provides higher excitation and ionization rates (including molecular dissociation). In particular, it explains the very high ionization rate in micro-discharges [4].

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[6] For example, it is of no use to call on a resonant cavity with a high *Q*-factor (hence a very high local ***E***-field) to achieve a discharge with a higher maintenance ***E***-field. However, in such a case, starting the discharge is easier!