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# Simple Experimental and Analytical Method to Estimate the Power Coupling Efficiency in Plasma Discharges

L. Colina Delacqua<sup>1</sup>, K. Ouaras<sup>1,2,\*</sup>, M. Redolfi<sup>1</sup>, J.-M. Orlac'H<sup>2,3</sup>, F. Silva<sup>2</sup>, X. Bonnin<sup>1,4</sup>, K. Hassouni<sup>1</sup>, G. Lombardi<sup>1</sup>

<sup>1</sup>LSPM, CNRS, Université Paris 13 Sorbonne Paris Cité, 99 Av. J. B. Clément, 93430 Villetaneuse, France

<sup>2</sup>LPICM, CNRS, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau 91128, France

<sup>3</sup>Present adress: ONERA, DAAA-CLEF, 92320, Châtillon, France

<sup>4</sup>Present adress: ITER Organization, Route de Vinon-sur-Verdon, 13067 St-Paul-lez-Durance, France

\* Corresponding author: karim.ouaras@polytechnique.edu

## ABSTRACT

A simple experimental method to estimate the power effectively absorbed by a plasma is presented. It relies on a thermal management study applied to the whole discharge system. This provides the energy released by the plasma and lost by convection and radiation at the reactor walls. The methodology is illustrated in the case of H<sub>2</sub> Electron Cyclotron Resonance microwave plasma. Nevertheless, this method can be extended to a variety of electrical discharge or feed gases. Using this method, an experimental coupling efficiency of  $\sim 22 \pm \sim 8$  % was derived. In comparison, an analytical balance of the plasma power absorption yields a theoretical coupling efficiency of  $\sim 28 \pm \sim 9$  %.

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**Keywords:** *effective absorbed plasma power, power coupling efficiency, microwave plasma*

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## I. Introduction

Plasma processes are usually quite complex and a coupled approach between modeling and experiments is often required to shed light on phenomena that take place in the electrical discharge. In order to develop self-consistent plasma discharge models, input data are needed such as feed gas composition, pressure or the power actually absorbed by the plasma [1]. The latter is a key parameter that can be easily over-estimated since it is most of the time taken equal to the difference between input and reflected power displayed on power generator. Such an approximation does not take into account potential power losses in the electromagnetic circuit between the power supply and the discharge chamber, which often leads to discrepancies between models and experiments. In addition, eventual modifications of the discharge system (geometry, materials...) may impact the power coupled to the plasma while using the same input power. For example, Ju Ho Kim *et al.* have recently shown that the positioning of the powered antenna and the passive resonant antenna in radiofrequency inductively coupled plasma strongly modifies the ion density which is 2.4 times to 9 times higher than that at non-resonance [2]. They have attributed this to the reduction in power loss in the powered antenna (including the matching circuits) and by the way the increase in power is absorbed by the plasma discharge.

In the literature devoted to RF discharges, several groups have reported methods to measure the power actually transferred to the plasma for several discharge systems. These includes inductive

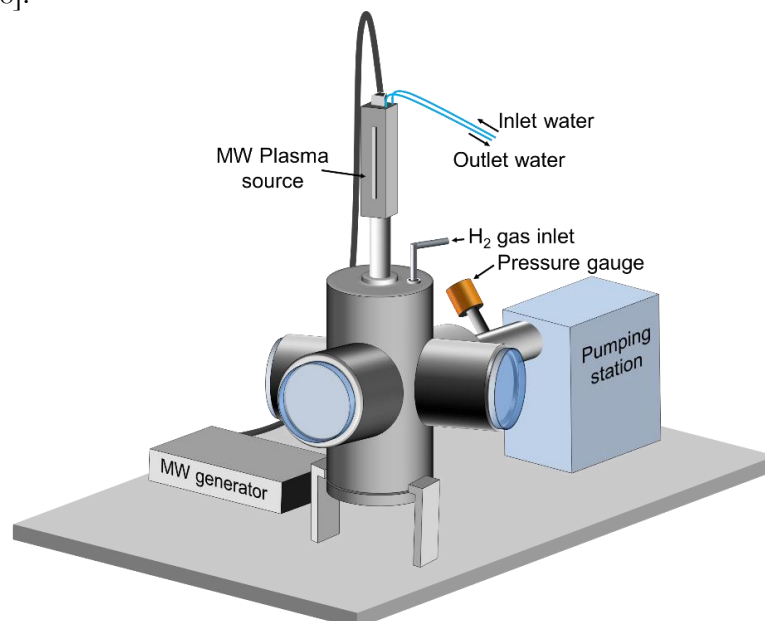
plasma discharge systems [3–5], IV probe in RF discharge [6], radio-frequency glow discharges used as optical sources [7–9], resonant RF network antennas where the driven antenna can be approximated by a parallel resonance equivalent circuit whose input impedance can be measured to interpret the power dissipation in the plasma [10–13]. These methods are mainly based on direct or indirect measurements of the plasma current. For example, Rauner *et al* have quantified the power transfer efficiency by using a subtractive method that relies on the measurement of the delivered RF power and of the RF current through the plasma coil both with and without discharge operation [5]. They have resorted to an analytical approach based on the measured plasma parameters to compare the above mentioned quantification. They found that more than 90% of the input power are absorbed by the plasma. On the contrary, in another work where RF ICP ions sources operating at 1MHz had been investigated, Zielke *et al* have shown that power transfer efficiency has been found to be surprisingly low, *i.e.* between 45% and 65%, under hydrogen atmosphere [14].

Taking into account the variety of both plasma discharge systems excitation and geometry that actually exist, it seems of interest to develop a simple and alternative experimental method to determine the power absorbed by the plasma that can be used in a variety of plasma systems. More specifically, it is of special interest for microwave (MW) discharges where large differences may exist between the input power and the power actually absorbed by the plasma, so that the uncertainty on the power transfer efficiency might be even larger than in RF discharges. It makes use of a global power balance that relies on the measurement of the power released by the plasma and lost at the reactor walls.

In the first part of the article, we present the experimental set-up and the experimental procedure used to estimate the absorbed power and the corresponding results. In the second part, a simple plasma model is used to determine the power absorbed by the plasma. The accuracy of the power value is evaluated by comparing experimental measurements and model predictions.

## II. Experimental setup and methodology

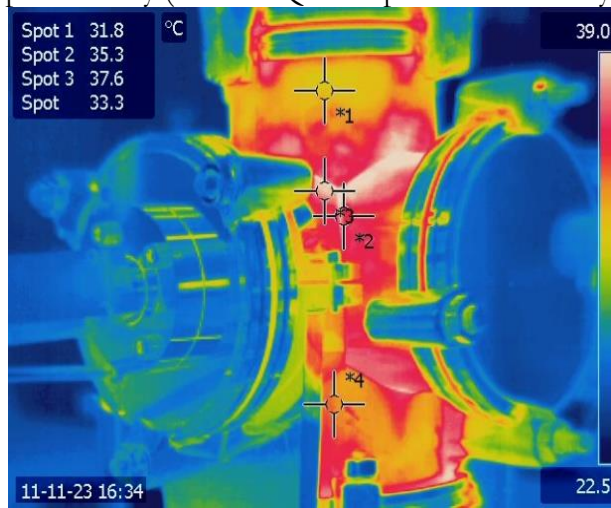
A schematic of the experimental set-up is shown in **Figure 1**. The six-flange vacuum chamber (100 mm diameter) is made of stainless steel. Its volume is about 5.12 l. The plasma is generated and sustained using a single cylindrical MW applicator (plasma source) terminated by a permanent magnet (Electron Cyclotron Resonance (ECR) dipolar source [15,16]). The ionization zone is located at the 875 Gauss magnetic induction line. Some applications of such plasma discharges can be found in [17,18].



**Figure 1.** Schematic of the plasma reactor set-up.

The plasma source is powered by a SAIREM microwave (2.45 GHz) generator GMP 12 KE/D. The wave is transmitted along a coaxial cable from the MW generator to the MW applicator. The operating conditions are the following: (i) H<sub>2</sub> gas (3 sccm), (ii) pressure of 0.1 Pa and (iii) input microwave power  $P_{MW}$  of 180 W, which is the upper value supported by the plasma source. In the thermal management experiments, we used an infrared (IR) lamp (with a known power) in order to determine the thermal conductance of the reactor walls under the same operating conditions as those used for plasma experiments. We used a IR camera (A320 - FLIR systems) equipped with uncooled Focal Plane Array (FPA) detector and suited for the 7.5-13  $\mu\text{m}$  spectral domain in order to monitor the temperature distribution on the reactor wall, see Figure 2. In addition, temperature measurements were also performed using thermocouples to check the accuracy of (i) the wall emissivity and (ii) the temperature measurements carried out with the IR camera.

The power coupling efficiency is determined using two alternative methods, one is experimental and one is analytical. The experimental method consists in a power balance accounting for the energy losses from the reactor to the surrounding environment: room air, supporting structure, flow. The analytical method estimates the power coupling efficiency as the power density require to maintain the degree of ionization and electron temperature measured experimentally. The latter model requires the knowledge of the electron density and temperature,  $n_e$  and  $T_e$  respectively. These were measured using a Langmuir probe (Smartprobe, Scientific System). The ion population was determined using mass spectrometry (Hiden EQP 500 plasma monitor system).



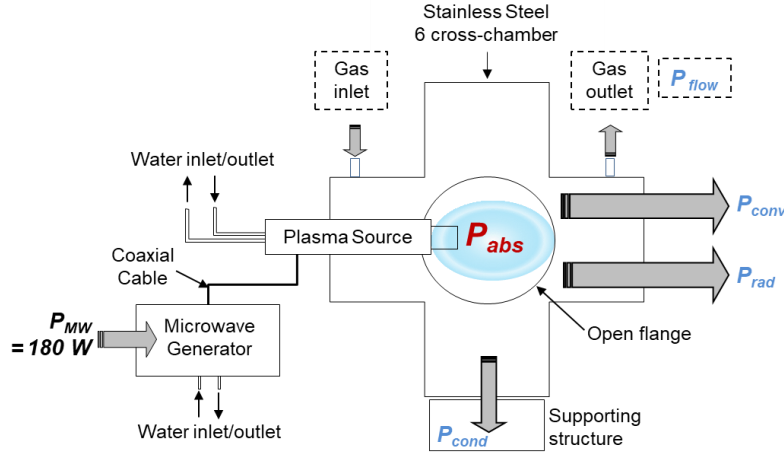
**Figure 2.** Example of a picture of the reactor recorded by the IR thermal camera during plasma experiment showing wall temperature values (colour online).

### III. Experimental determination of the power coupling efficiency

The reactor power balance is illustrated in **Figure 4**. The plasma induces a series of collisional processes, species and energy transport mechanisms and surface reactions that result in energy transfers between the plasma, the flow and the surrounding surfaces [19]. We consider that the power absorbed by the plasma is equal to the power dissipated by energy transfer from the plasma to the reactor wall through convection and radiation, plus the change in flow enthalpy between the reactor input and output. We neglect the potential wall heating induced by surface processes. On the other hand, the power received by the reactor walls from the plasma or from the EM source through Ohmic heating is transferred to the surrounding air by natural convection and radiation, as well as to the structure sustaining the reactor by conduction.

The potential contribution of the Ohmic heating of the metallic walls that are submitted to the high frequency current in the presence of the microwaves can be estimated. For this purpose, a high frequency electromagnetic (EM) simulation was performed using CST Microwave Studio® software package [20]. An empty reactor configuration (without plasma) was simulated. Therefore, the results obtained do not take into account the power fraction absorbed by the plasma and would

likely yield an upper limit of the power dissipated in the reactor wall by Ohmic effect for conditions where the plasma is ignited. The numerical EM modelling was undertaken using a transient solver. The presence of a symmetry plane was used to reduce the size of the problem geometry to model, thus leading to a mesh with  $3.8 \times 10^6$  cells. The boundary conditions on all walls were set to be metallic (*i.e.* imposing a zero electric field tangential component) except for the MW coupling port where a coaxial opening of waveguide EM field type was set at the MW coupling port (TEM propagation mode).



**Figure 3.** Representation of the power balance:  $P_{abs}$  is the power absorbed by the plasma.  $P_{conv}$ ,  $P_{rad}$  and  $P_{cond}$  are the power dissipated by convection, radiation, and conduction respectively.  $P_{flow}$  the power lost in the gas flow.

The material components and the geometry of the complete plasma reactor system (the MW applicator plus the stainless steel vacuum chamber) used in this model are presented in **Table 1** and in **Figure 4** (see insert), respectively. To determine the microwave power reflected back to the generator in our configuration, we calculate the S-parameter  $S_{11}$ , also known as the reflection coefficient or return loss [21], which represents the power fraction reflected from the MW antenna. We find that the S11 parameter is lower than 3% in the frequency range 2.4-2.5 GHz. This means that the reflected power is less than  $\sim 5$ W out of the 180 W input power. Therefore, we consider that microwave heating only affects the gas phase.

Thus, when considering the whole “plasma plus reactor envelope” system, the power balance at steady state should express the equality between the microwave power absorbed by the plasma  $P_{abs}$  on one hand and on the other hand, the power lost by the envelope through convection to the surrounding atmosphere  $P_{conv}$ , the power lost by conduction  $P_{cond}$  to the structure sustaining the reactor, and the power transferred to the gas flow  $P_{flow}$ . We should mention that due to the fairly moderate envelope temperature level, we did not take into account the power lost by radiation. As a matter of fact, for temperature lower than 350 K, the estimated radiated power is around 2 W so less than 1% of total power injected in the system.

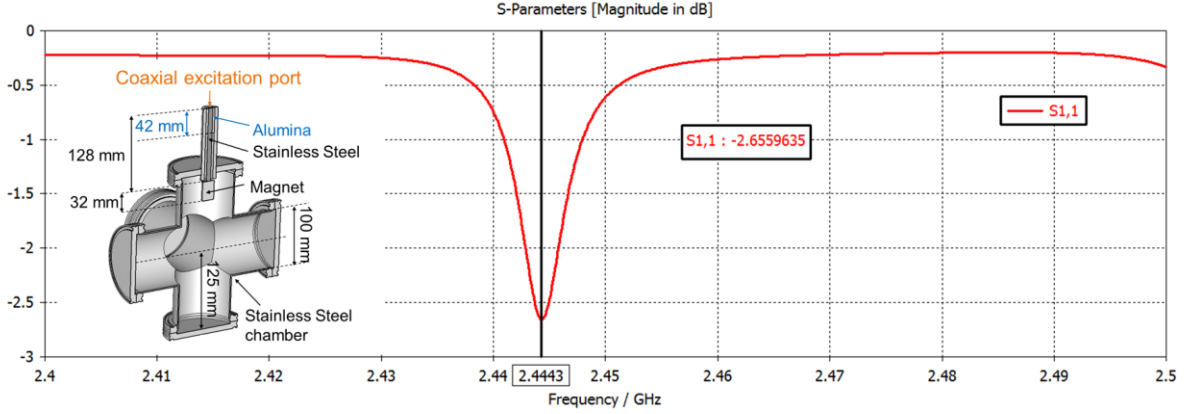
The power balance may be written as (the power balance is schematically presented in Figure 3:

$$P_{abs} = \overbrace{G_{conv}^{w/air} \times (T_w - T_{RT})}^{P_{conv}} + \overbrace{\frac{\lambda}{l} (T_w - T_{RT})}^{P_{cond}} + P_{flow} \quad (1)$$

where  $G_{conv}^{w/air}$  is the thermal conductance related to power lost by convection at wall/air interface.  $T_w$  is the measured average external wall temperature and  $T_{RT}$  the room temperature (298 K), and  $l$  is a characteristic conduction length.

Material	Relative permeability $\mu_r = \frac{\mu}{\mu_0}$ $\mu$ = material permeability $\mu_0$ = vacuum permeability	Electric conductivity $\sigma$ (S.m <sup>-1</sup> )	Relative permittivity $\epsilon_r = \frac{\epsilon}{\epsilon_0}$ $\epsilon$ = material permeability $\epsilon_0$ = vacuum permeability
Stainless Steel	1.02	$1.3 \times 10^6$	-
Alumina	1	-	9.4
Vacuum	1	-	1

**Table 1.** Parameters used for CST simulation.



**Figure 4.** (Color online)  $S_{11}$  parameter as a function of frequency. Insert showing scheme of the plasma chamber geometry used for the CST simulation showing the materials and dimensions of the system.

Actually, given the relatively high conductivity of the wall material,  $\lambda$ , i.e.  $\sim 50 \text{ W.m}^{-1}\text{.K}^{-1}$  and its 2mm thickness, we assume the external wall equal to the internal wall temperature.

The power lost by conduction to the structure that sustains the reactor is described by the term  $\frac{\lambda}{l} (T_w - T_{RT})$ . The characteristic conduction length  $l$  is difficult to estimate. To circumvent this difficulty, we define an effective thermal conductance  $G^{eff}$  that accounts for both convective and conductive losses from the envelope to the structure that holds the reactor. Equation (1) can be rewritten as below:

$$P_{abs} = G^{eff} \times (T_w - T_{RT}) + P_{flow} \quad (2)$$

To determine  $G^{eff}$ , we introduced an IR lamp with a known output power  $P_L$  of 60 W in one of the available flange, while keeping identical the usual working conditions in terms of pressure, flows and gas composition without igniting the plasma. It is worthy to mention here that the thermal conductance of the reactor walls to the surrounding medium (surrounding air and the structure sustaining the envelope) is not affected by the presence of the plasma and only depends on the reactor structure and ambient air conditions. We use the following equation to determine the value of  $G^{eff}$ :

$$P_L = G^{eff} (T_w^L - T_{RT}) \quad (3)$$

The steady state wall temperature,  $T_w^L$ , obtained when the wall is heated by the IR lamp was inferred from the infrared radiation of the wall monitored by the IR camera. The wall emissivity required for this purpose was evaluated by calibration experiments where the monitored IR image of the reactor was compared with simulated images obtained for the wall temperature value measured by

a thermocouple. The emissivity value was adjusted so as to minimize the difference between measured and simulated IR images. This procedure assumes that the wall emissivity is spatially constant which is fairly reasonable assumption, taking into account the homogeneity of the reactor wall material and the moderate level of thermal heating, i.e., less than 200 K. For further details about temperature measurements using IR camera in plasma system, the reader can refer to the detailed study of Mazouffre *et al* [22].

The steady state wall temperature value was  $309 \pm 3$  K. The conductance  $G^{eff}$  ( $5.1 \pm \sim 1$  W.K<sup>-1</sup>) is obtained from the steady state power balance on the reactor wall when it is heated by the IR lamp (using equation (3)).

The remaining part of the power balance of equation (2) that has to be determined is the power transported in the gas flow  $P_{flow}$  which was estimated using the following equation:

$$P_{flow} = \rho \cdot Q_v \cdot (h_{out} - h_{in}) \quad (4)$$

where  $\rho \approx 0.0899$  kg.m<sup>-3</sup> is the mass density of hydrogen gas,  $Q_v = 8.3 \times 10^{-8}$  l.s<sup>-1</sup> the flow rate,  $h_{in}$  and  $h_{out}$  the specific enthalpies of the gas flows entering and leaving the reactor, respectively. In principle, the enthalpy of the gas flow exiting the reactor includes a thermal component and a chemical component due to the presence of high formation enthalpy active species, mainly H-atom and to a much lesser extent, hydrogen ions. However, for a H<sub>2</sub> dissociation yield of 10%, and plasma density, *i.e.*, 10<sup>10</sup> cm<sup>-3</sup>, we estimated an upper limit of approximately 0.1 W for the chemical enthalpy of the flow exiting the reactor. This value is negligible with respect to the enthalpy flow corresponding to the thermal component. Therefore, the thermal enthalpy variation can be estimated as:

$$(h_{out} - h_{in}) = c_p \cdot \Delta T \quad (5)$$

where  $c_p = 14300$  J.K<sup>-1</sup>.kg<sup>-1</sup> is the specific heat of hydrogen gas.

As the temperature difference  $\Delta T$  is less than 150 K, the power lost by gas flow  $P_{flow}$  was estimated to be less than 0.1 W, hence negligible. We should mention that it is likely to be negligible in low-pressure where relatively small flow rates are involved. However, for higher pressure discharges such as plasma jet or DBD that involves flow rates that can be sometime ten to hundred times higher, it can no longer be negligible along with the fact that those discharges might deliver a different dissociation rate of the main gas precursors and substantially larger gas heating.

Finally, using equation (2) we could estimate the power absorbed by the plasma value as at the steady state, when H<sub>2</sub> plasma is running, the wall temperature value  $T_w$  in that case was  $305 \pm 3$  K. We found that  $P_{abs} \approx 36 \pm \sim 14$  W. This indicates that the power absorbed by the plasma is in the range 22 W-52 W and therefore only represents between 12% and 30% of the input power ( $P_{MW} = 180$  W). It appears therefore that a large fraction of the input power is necessarily lost before the wave reach the applicator. This loss may take place through different channels and in particular (i) reflection to the power generator and (ii) dissipation by thermal heating in the microwave circuit. In any case, in order to assess the validity of the experimental method based on the above macroscopic energy balance, the power absorbed by the plasma was estimated directly from the discharge characteristics using an analytical plasma model.

#### IV. Analytical determination of the power absorbed by the plasma

To theoretically estimate the power coupling efficiency, we assume that the electromagnetic power coupled to the plasma may be directly inferred from the power density required to sustain an electron-ion pair in the whole volume of the plasma  $V$  (m<sup>-3</sup>) per time unit [23]. This is expressed as:



$$P_{abs} = r \cdot V \cdot e \cdot E_T \quad (6)$$

where  $r$  ( $\text{s}^{-1} \cdot \text{m}^{-3}$ ) is the number of electron-ion pairs created per time and volume units,  $e$  the electron charge and  $E_T$  (eV) the total collisional energy spent per electron-ion pair created per time and volume units. The parameter  $r$  is expressed as [23] :

$$r = k_i \cdot n_e \cdot n \quad (7)$$

where  $k_i$  is the ionization constant ( $\text{m}^3 \cdot \text{s}^{-1}$ ), and  $n$  the total particle density ( $\text{m}^{-3}$ ). The values of the electron density used to calculate  $r$  is the one obtained using Langmuir probe measurement ( $n_e \approx 5 \times 10^{15} \text{ m}^{-3}$ ).

The energy required to maintain the plasma  $E_T$  corresponds to the total collisional energy spent per electron-ion pair created per unit time and volume, expressed as in eq. (3.5.8) of reference [23]:

$$E_T = \sum_r \frac{k_r \mathcal{E}_r}{k_i} \quad (8)$$

where  $k_r$  ( $\text{m}^3 \text{ s}^{-1}$ ) and  $\mathcal{E}_r$  (eV) correspond to the reaction constant and the threshold energy of a given reaction  $r$ , respectively.  $k_i$  ( $\text{m}^3 \text{ s}^{-1}$ ) is the ionization constant.

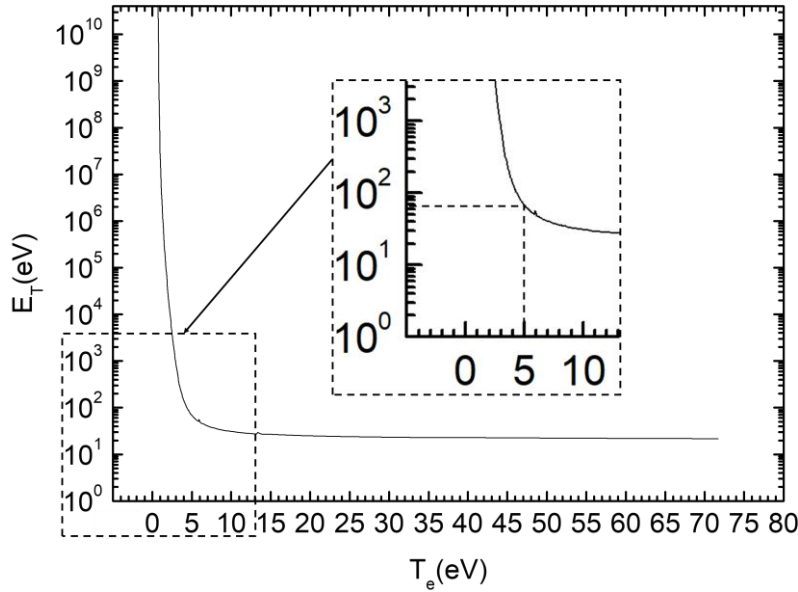
The energy required for sustaining an electron ion pair was estimated using the measured value of the electron temperature  $T_e = 5 \pm 0.5$  eV and the collisional model discussed in [24]. This collisional model assumes that the dissociation degree of the plasma remains fairly low and  $\text{H}_2$  ground state is the major neutral species. We did not consider all collisional processes occurring in the plasma, we only took into account the major electron energy dissipation channels, *i.e.*, vibrational excitation, electron-impact dissociation, singlet state excitation, dissociative excitation. Given the very low pressure in our discharge (0.1 Pa), *i.e.* a low collision frequency, heavy-heavy collisions are neglected and only electron-heavy (e- $\text{H}_2$ ) collisions were considered. The ionization, excitation and elastic processes considered for the calculation of the energy required to maintain the plasma  $E_T$  are given in **Table 2**. Knowing the cross-sections of each reaction as a function of the electron energy (Lxcat database [25]), the reaction constants  $k_r$  and ionization constants  $k_i$  are obtained by solving the Boltzmann equation. Once  $\mathcal{E}_r$  and  $k_{r,i}(T_e)$  of all reactions included in **Table 2** are known, we calculated the collisional energy lost by electron-ion pair created as a function of electron temperature  $T_e$  using (8). Thus, we found  $E_T$  for a given electron temperature using the graph in **Figure 5**. Note that  $E_T$  energy drastically increases for electron temperature below 5 eV. Indeed, only a few energetic electrons are sufficient to produce an electron-ion pairs while a large amount of energy is spent by low-energy electrons in exciting the molecules to intermediate states.

Considering the plasma potential measured by Langmuir probes, it is shown that the plasma extends throughout the reactor volume (sphere-like of diameter  $\sim 10$  cm) which corresponds to a volume of  $4.2 \times 10^{-3} \text{ m}^3$ . The power absorbed by the plasma was therefore calculated for an average value of  $T_e \sim 5$  eV over the whole plasma volume. For  $T_e = 5$  eV, we obtained  $E_T = 65$  eV and using (6), we found that  $P_{abs} \sim 50$  W. This value depends on  $T_e$  value. Thus, we consider the error on electron temperature measurement which is around 10 %. Finally, we obtain an average value of  $P_{abs} \sim 50 \pm \sim 16$  W which would indicate that only  $\sim 28 \pm \sim 9$  % W out of the 180 W is effectively coupled to the plasma. Taking into account the simplicity of the approach, these values, although little higher, are in a fairly satisfactory agreement with those determined in the previous section through global power balance on the plasma reactor. In any case the two approaches show that the power absorbed by the plasma represents less than 40%, and may be as low as 15%, of the total input power.



Reactions	$\mathcal{E}_R$ (eV)
$e^- + H_2 \rightarrow 2e^- + H_2^+(b^2\Sigma_g^+)$	15.4
$e^- + H_2 \rightarrow e^- + H_2(b^3\Sigma_u^+)$	8.9
$e^- + H_2(v=4) \rightarrow H + H^-$	1.86
$e^- + H_2(v=5) \rightarrow H + H^-$	1.45
$e^- + H_2(v=6) \rightarrow H + H^-$	1.08
$e^- + H_2(v=7) \rightarrow H + H^-$	0.4
$e^- + H_2(v=0) \rightarrow H_2(v=1)$	0.516
$e^- + H_2(v=0) \rightarrow H_2(v=2)$	1
$e^- + H_2(v=0) \rightarrow H_2(v=3)$	1.5
$e^- + H_2(v=0) \rightarrow H_2(B^1\Sigma_u^+)$	11.3
$e^- + H_2(v=0) \rightarrow H_2(C^1\Pi_u^+)$	12.4
$e^- + H_2 \rightarrow e^- + H + H(n=2)$	15
$e^- + H_2 \rightarrow e^- + H + H(n=3)$	16.6

**Table 2.** Reactions considered to calculate  $E_T$ . Threshold energies were taken from [26].



**Figure 5.** Collisional energy lost by electron-ion pair created as a function of electron temperature. For  $T_e = 5$  eV, one obtains  $E_T = 65$  eV

## V. CONCLUSION

In this paper, a simple experimental method to estimate the plasma power absorption as well as an analytical analysis of the energy required to maintain the plasma is presented. The principle of the method is based on a simple energy balance of the reactor. This experimental method presents two main advantages: (i) it can be easily implemented for any type of discharge without modifying the configuration of the experimental setup, (ii) temperature measurements by thermal camera or are straightforward and not intrusive.

By using both experimental and analytical methods, a coupling efficiency of  $\sim 22 \pm \sim 8 \%$  and  $\sim 28 \pm 9 \%$  (the input power is 180 W) are obtained, respectively. The remaining power is most probably reflected to the power generator, and dissipated by thermal heating along the coaxial

cables that carry the microwave. Experimentally, we found that the main source of thermal dissipation at the wall is convection. The main outcome of this method is its ability to give a reasonable estimate of the power that is actually coupled in the plasma which is a key-input parameter for self-consistent plasma models. We especially showed that the assumption of full power absorption, i.e.,  $P_{input}=P_{abs}$ , may lead to a substantial error and prevent any validation of the predictive character of self-consistent plasma models.

## Acknowledgments

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## Availability of data

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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