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Parametric study of dielectric barrier discharge excimer UV lamps supplied with controlled square current pulses

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ABSTRACT

A parametric study of a system dedicated to non-coherent UV emission, by means of DBD excilamps, supplied by a controlled square shape current source is proposed. The presentation highlights on the one hand the performances experimentally obtained by combining together a set of 20 different bulbs with different diameters, gap and wall thicknesses (all the bulbs have the same length and are filled with the same Xe-Cl gas mixture), with different electrical power supplying conditions: magnitude, frequency (in the 30 kHz – 200 kHz range) and duty cycle of the square shape current pulses injected into the bulb. The performances concern the average UV power, the efficiency of the bulb conversion (electrical power to UV) and the adjustability of the power. On the second hand, we present design considerations of the power supply which has been especially developed for the purpose of these experiments.

1. INTRODUCTION

UV lamps of Dielectric Barrier Discharge (DBD) structure are environmentally friendly (mercury free) UV sources used for various applications: health, disinfection, surface treatments [1]. The applicability of these DBD excilamps has been demonstrated; today, studies are oriented toward the improvement of their performance. This can be achieved by means of the bulb design (geometry, filling mixture, pressure and materials) [2], [3] and also by selecting the most performing electrical operating conditions [4],[5].These both optimization paths are the purpose of this paper: the characteristics of the candidate bulbs, which performances will be experimentally compared, are presented in §2 and an estimation of the parameters of their equivalent circuit model is displayed. Associated to this set of lamps, the selected power supply, by means of a square shape current source generator is presented in §3: the operating principles of this topology, together with its performances are presented; elements for the design of the actual generator, specifically developed for this study are also proposed. Each bulb under test is connected to this power supply and the operation of the whole system is controlled and monitored by means of a test bench which is described in §0. The measurements achieved on the bench are used for several purposes: firstly, to measure the characteristics of each bulb (§5). Secondly, (§0), the performances obtained with each bulb, under similar supplying conditions, are compared in order to select the lamp and its operating conditions which offer the best results. Comparisons are focused on the efficiencies of: the conversion from electrical power to UV emission, the power supply (input and output powers ratio) and the whole system (energetic efficiency).

2. BULB CHARACTERISTICS AND PARAMETERS

The structure of the DBD excimer lamps is reminded on Figure 1-a: two sealed quartz tubes define a volume filled with a Xe-Cl gas mixture [1][2]. Metallic electrodes are disposed outside and connected to the power supply. In our parametric approach, this mechanical layout is parameterized with the T, the thickness of the quartz walls, as well as a and b, the respective diameters of the inner and outer sealed tubes (samples are shown on Figure 1-b); l is the length of the metallic mesh which is disposed on the outer tube. All the bulbs are filled with the same Xe-Cl mixture, with the same pressure. According to the classical model [5], based on the electrical equivalent circuit (Figure 1-c), the electrical properties of each bulb can be derived: the parameters of this model are: Cg and Cd, the capacitances of the gas gap and of the quartz walls (series connected), and Vth, the threshold voltage, i.e. the minimum value of the gas voltage required to turn on the plasma.
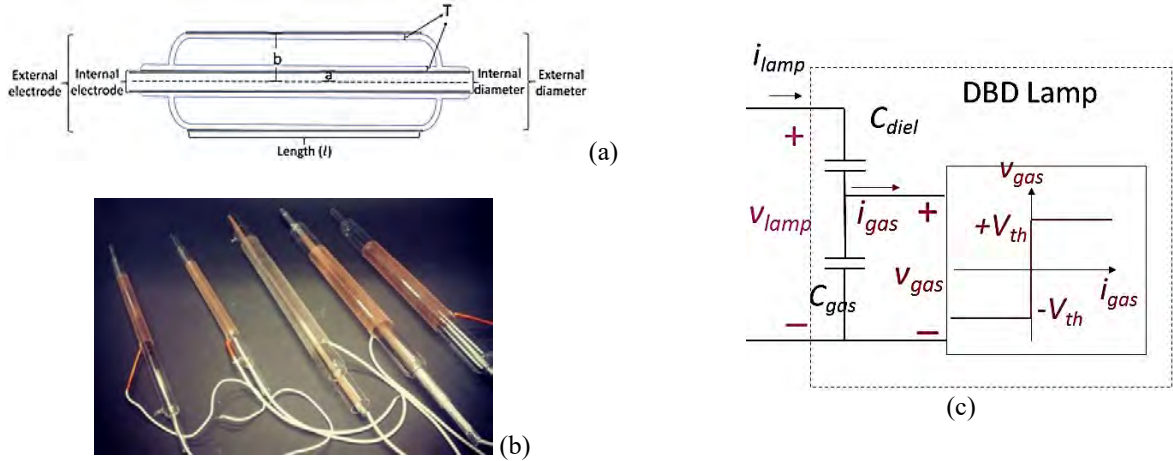

Figure 1 Coaxial DBD excimer lamp: (a) geometrical layout – (b) experimental samples – (c) equivalent electrical circuit

An initial guess of these 3 parameters can be obtained from equations derived from electrostatic calculations - equations (1) and (2), and approximation of the Paschen law [7] – equation (3)

$$C_g = \frac{2\pi \cdot \varepsilon_g.l}{In\left(\frac{b}{a}\right)} \approx \frac{K_g.l}{In\left(\frac{b}{a}\right)} \tag{1}$$

$$C_d = \frac{2\pi \cdot \varepsilon_d.l}{ln\left(\frac{(a+T).(b+T)}{a \cdot b}\right)} \approx \frac{K_d \cdot l}{ln\left(\frac{(a+T).(b+T)}{a \cdot b}\right)} \tag{2}$$

$$V_{th} = \frac{C \cdot p_{gas} \cdot d}{In(A \cdot p_{gas} \cdot d) - ln\left(ln\left(1+\frac{1}{\gamma}\right)\right)} \approx K_{th}\frac{d}{K' + In(d)} \tag{3}$$

	Theoretical Range	Exp. Range
Gas capacitance (C_g)	C_g 63pF - 1nF	C_g 50pF - 247nF
Dielectric capacitance (C_d)	C_d 94pF – 475pF	C_d 51pF – 360pF
Threshold voltage (V_{th})	V_{th} 1167 V – 2579 V	V_{th} 1026 V – 2574 V

Each one of the bulbs is characterized, according to these formulas, as presented in the previous table; experimentally found out parameters are also presented. They are required in order to design the power supply used to test the bulbs [10].

3. SQUARE SHAPE PULSED CURRENT SUPPLY

3.1 Topology, Principle and Properties

The power supply which has been selected to carry out the experiments is a square shape current source (the topology is presented on Figure 2[5], together with the main equations), already detailed in [5]: it presents a cascaded structure, associating a DC current source with a current inverter, aimed at controlling the shape of the square current pulses. Its main advantage is the availability of 3 independent degrees of freedom (DOF) to control the i_{lamp} current pulses injected into the bulb: their magnitude I, their frequency f, and their duty cycle D, or their duration $D/2f$, as shown on 4.

$$P_{lamp} = I.D.V_{th}. -4.f.C_g.V_{th}^2 \tag{4}$$

$$\widehat{V_{lamp}} = V_{th}.\left(1+\frac{C_g}{C_d}\right) + \frac{P_{lamp}}{4.f.C_d.V_{th}} \tag{5}$$
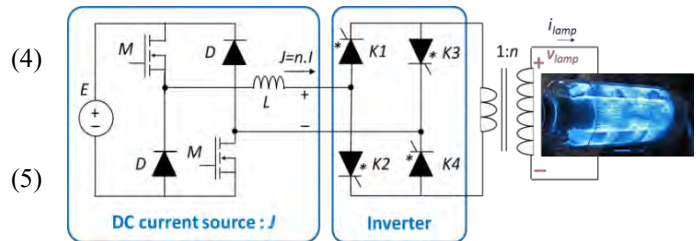

Figure 2 square shape current source generator: circuit and main equations

Keeping in mind the fact that the power supply needs to be able to set, for each one of the 19 bulbs, a number of various operating points, we describe now the main steps of the design [10] of this equipment.

3.2 Step-by-step design of the square shape current supply

1. **Design specifications and constraints**: in order to design the power supply, a maximum power value of 500W and a 30kHz – 200kHz frequency range are chosen; the full 0 – 1 range is a priori selected for the D duty ratio. According to the electrical model of each lamp, the values of the required I amplitude of the (i_{lamp}) lamp current as well as the peak voltages, are calculated with equations (4) and (5). This set of values defines the specifications to be fulfilled by the electrical quantities related to the various lamps.

2. **Semiconductors selection**: The current inverter controls the frequency and the duration of the current pulses. It requires the use of thyristor-like switching functions: according to the selected frequency range, this feature is synthesized thanks to series connection of MosFets with diodes, driven with specific control [9] rules. The n turn ratio of the transformer, which can be seen on Figure 2, is a very useful mean to adapt the electrical constraints defined at the lamp level (step 1) with respect to the ratings of the available semi-conductors (the voltage rating is the lamp peak voltage divided by n, whilst the current rating is the $n.I$ product). The semiconductor devices selection is in this scope a matter of maximizing the number of realizable operating points, at the lowest cost.

3. **Transformer:** the design of the latter is then achieved with the selected n turn ratio (step 2), taking great care of the minimization of the parasitic parallel capacitance, which disturbs the actual control of the i_{lamp} current [8]: for this reason, single layer windings are selected for both primary and secondary.

4. **DC current source:** this stage controls the magnitude of the ilamp current pulses. According to the values of the I (obtained at step 1) and n (step 2) parameters values, a DC current source supplying a J=n.I current is needed. The latter is implemented using a modular architecture: DC-DC modules with unidirectional current, full-bridge topology are parallelized and synchronized [10], in order to minimize the J current ripple.

Table 1- power supply parameters

step	Parameter	Value(s)
1	Max output power	500W
	i_{lamp} frequency range	30kHz – 200kHz
	i_{lamp} magnitude I range	0 – 1.4A
	i_{lamp} duty cycle range	5% – 100%
	v_{lamp} peak voltage	7 kV, limited to 7 kV
2	Transformer turn ratio n	10
	Current inverter power MosFets	C4D10120D Wolfspeed / Cree
	Current inverter power diodes	C2M0080120D Wolfspeed / Cree
4	J current source: nb of modules	2
	$J/2$ module operating frequency	200 kHz
	Nb. of realizable operating points (19 bulbs)	2532

Table 1 summarizes the key parameters and properties of the square shape pulse current supply – one should keep in mind that these performances are obtained together with the parameter values of the 19 bulbs set to be tested.

4. EXPERIMENTAL TEST BENCH

A cumbersome number of operating points have to be visited; to enable a good reproducibility of each one of these experiments, and a complete record of all conditions and results, a test bench has been setup (Figure 3). Under the supervision of a program developed with Labview, for each operating point, the conditions are selected:
*   the characteristics of the i_{lamp} current pulses: I current magnitude, f operating frequency and D duty cycle;
and the obtained performances are recorded:
*   waveforms of lamp current and voltage, as well as UV instantaneous emission – the measurements are achieved using voltage probe TESTEC, mod. TT-SI 9110, current probes Lecroy, mod. AP015, Thorlabs mod. PDA-25k UV photodetector and are captured with a LECROY HDO4024 oscilloscope;
*   temperature, average UV power density (Gigahertz Optik P9710 Optometer);
*   electrical power injected into the bulb, and taken by the current source on its supply are calculated by the scope.
The supervision program scans all realizable operating points and stores the captured results for offline use.
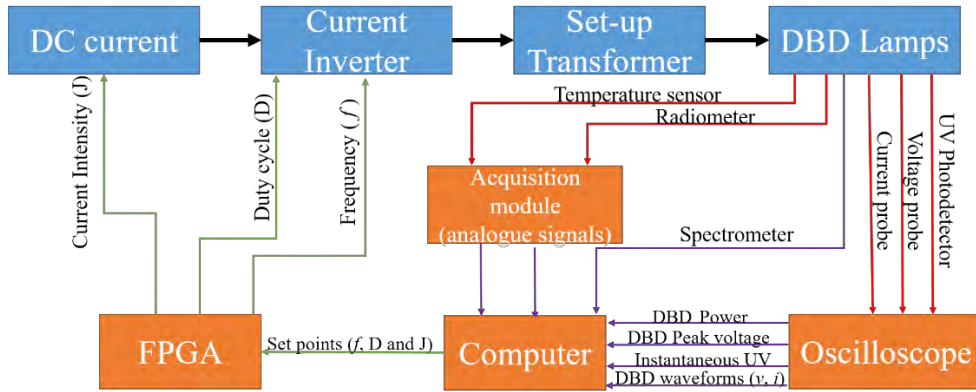
Figure 3 experimental test bench

5. MEASUREMENTS AND VALIDATION OF THE THEORETICAL PARAMETERS

Using the recorded waveforms (Figure 4), the Manley diagram (Figure 6) is built after each measurement: the electrical charges are calculated (integration of the experimental i_{lamp} current) and plotted versus the measured v_{lamp} voltage.
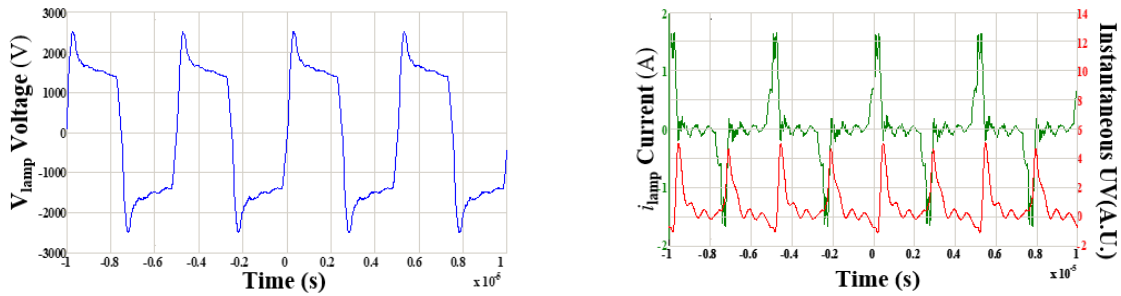

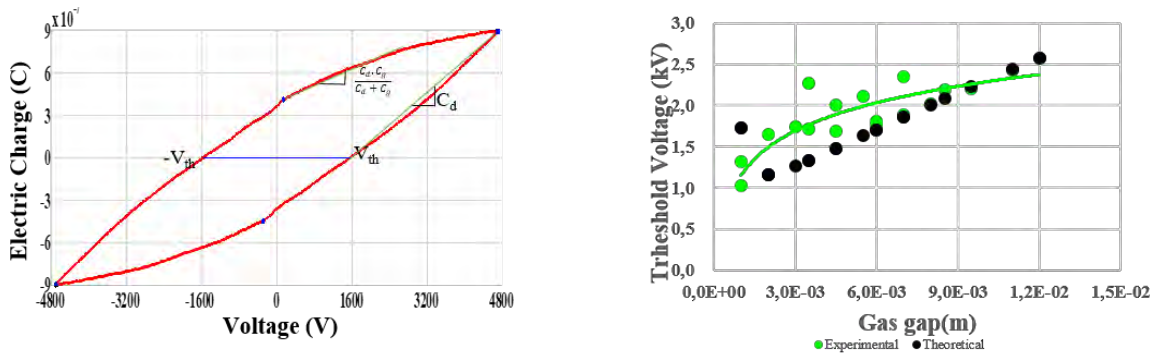Figure 4 experimental waveforms: v_{lamp} (blue) and i_{lamp} (green), UV (red)

Figure 5 experimental determination of the bulb parameters : Manley diagram and gas threshold voltage V_{th}

The diagram provides a good estimation of the bulb's equivalent model parameters (C_g, C_d, V_{th}). It offers the opportunity to adjust the theoretical equations (1), (2) and (3) used to calculate the (C_g, C_d, V_{th}) parameters needed for the supply's design, which will be used in the future for system level optimization.
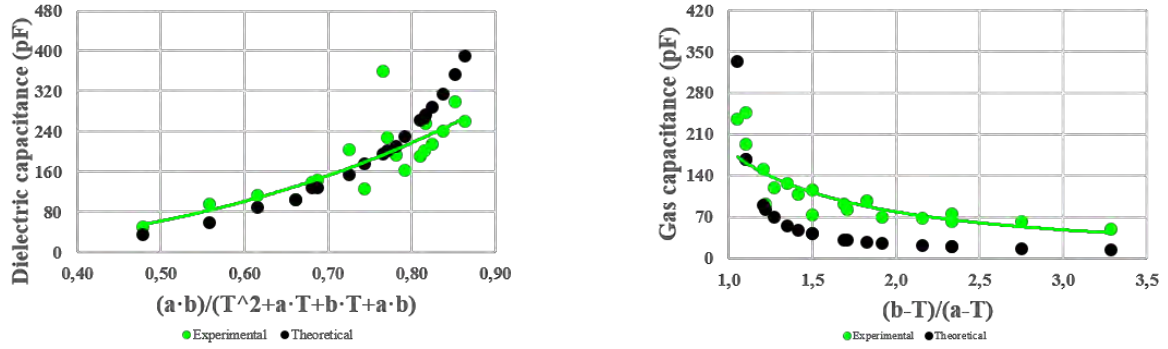
Figure 6 experimental determination of the bulb parameters : C_d and C_g

6. BEST SYSTEM'S PERFORMANCES

All the bulbs have been tested in the planned operating range (overall: 2532 experiments). The following diagrams summarize the most relevant conclusion concerning the UV emission performances.

6.1 Bulb dimensions

According to equations (1) and (3), the gas gap value has an impact on the C_g and V_{th} parameters; as shown on Figure 7, the according variations of these parameters show a trend on the UV power emission, as well as on the lamps efficiency (UV power with respect to the electrical power injected into the bulbs): relatively to these both criteria, the bulbs with the largest gas gap present the highest performances.
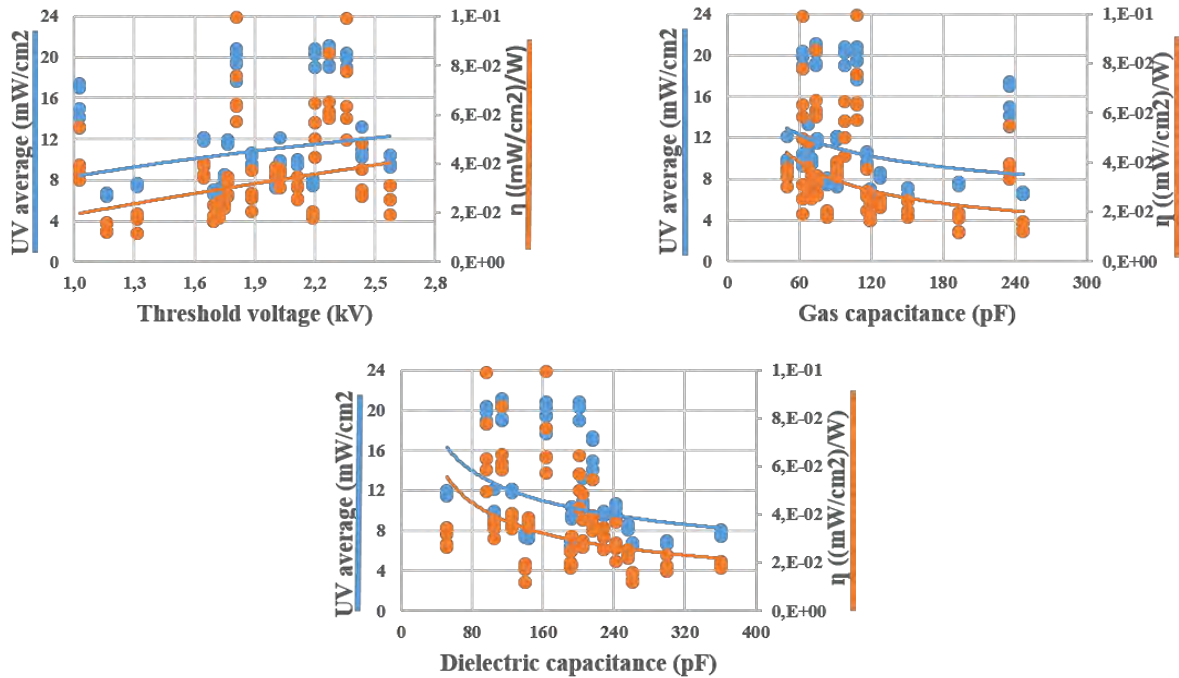

Figure 7 UV power emission and efficiency – impact of the gap value (through C_g and V_{th} parameters variations), top and of C_d bulb parameter (controlled by the quartz walls thickness), bottom.

Of course, the limitation in the use of this trend relies in the cost of the V_{th} increase: at the system level, the growth of V_{th} leads to increase the secondary winding's turn number, thus the parasitic capacitance of the step-up transformer, as well as its price. The impact of the wall thickness is also evaluated on Figure 7 (bottom), through its impact on the C_d bulb parameter. The comparison of the obtained performances allows to filter the measurements cloud: the 4 most performing bulbs from the whole set are now considered for the following analysis, focused on the supplying conditions.

6.2 Supplying conditions

Considering again as performance criteria UV emission (average value measured with the photometer) and its ratio with respect to the electrical power injected into the bulb (i.e. the efficiency of the bulb), the cloud of operation points is filtered to consider the best five points of each bulb. The results are shown on Figure 8. Clearly, bulbs numbered 4, 5, 6 and 7 are much better, for both criteria. These are also the ones which have shown the best performances in §6.1
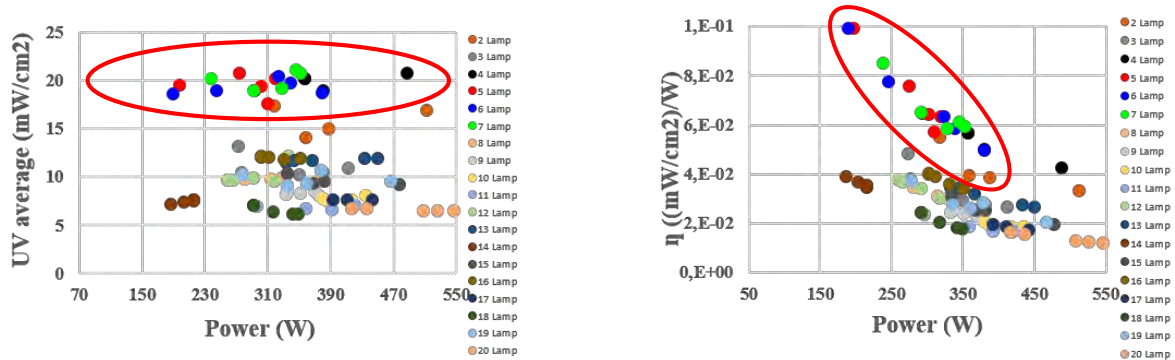

Figure 8 UV power emission and efficiency – selection of the most performing bulbs

Focusing on these 4 lamps, a refined parameters sweep is achieved to find out the current pulses characteristics which offer the best performances. Results are presented on Figure 9.
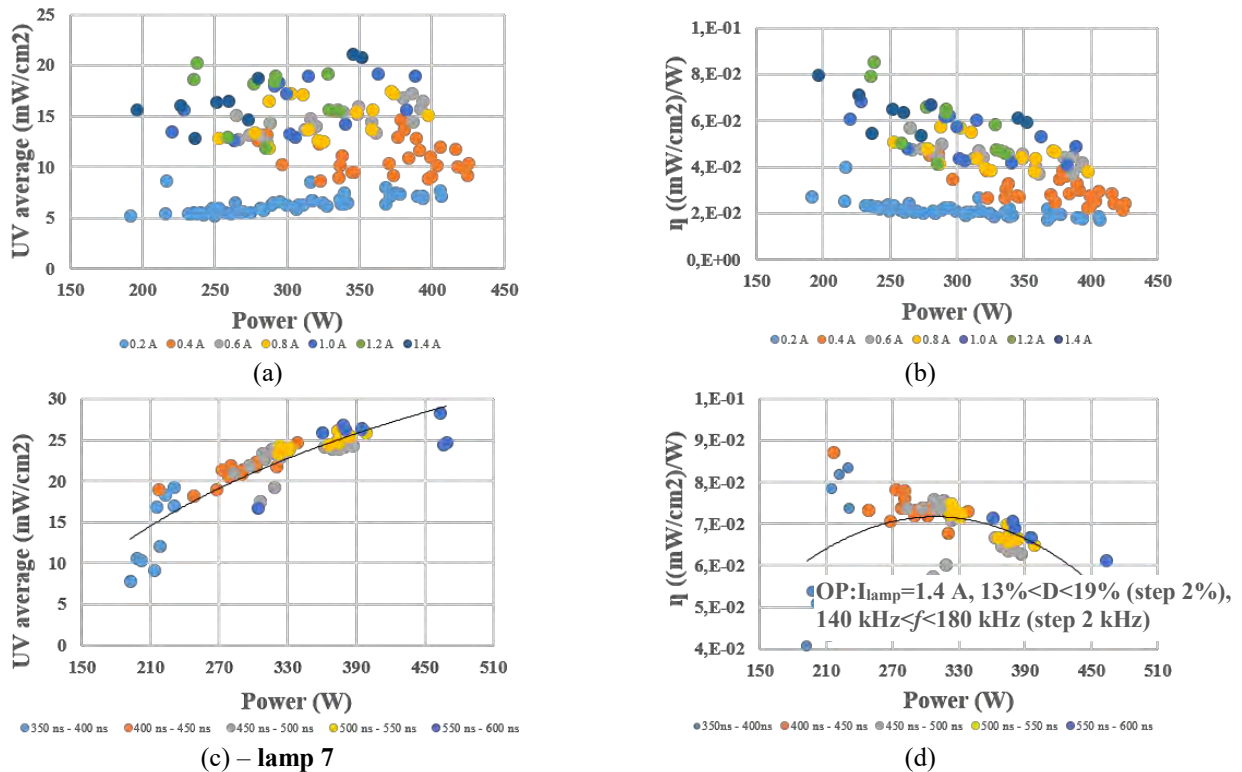

(a)

(b)

(c) – **lamp 7**

(d)

Figure 9 research of the "optimal" current pulses for the best 4 bulbs: sweep of current pulses magnitude:(a) and (b) – sweep of the current pulses duration (c) and (d)

As can be seen, on Figure 9 (a) and (b), a fine sweep of the *I* current pulse magnitude shows that the highest UV power as well as the best efficiency (electrical lamp power to UV power) are obtained with the highest available *I* values (1.2A and 1.4A in our case). Lamp 7, which is selected for the next steps, is the one which offers the best results.

Focusing from now on this bulb (7), and for the *I=1.4A* condition, which has shown the best results, Figure 9 (c) and (d) analyze the choice of the pulses duration : the highest UV level (average value measured with the photometer) is obtained

with the longest current pulses (range: 550ns – 600ns) – this confirms the correlation between the gas current and the UV emission already mentioned in [3], and also visible on Figure 4. With respect to the bulb efficiency, it nevertheless appears that current pulses with duration in the 400ns – 500ns offer the best performances.

7. CONCLUSION

The square shape pulsed current power supply with adjustable pulses parameters (magnitude, duration, frequency) shows in this study its ability for experimental comparison of the performances offered by DBD excimer lamps of various geometrical characteristics. This supply is controlled by a supervising tool which allows automatic parametric sweeps, considerably reducing the time of analysis and study and minimizing measurement errors. From these automated measurements, it is possible to state that the theoretical equations used to guess the bulbs model parameters (Cg, Cd and Vth) and their approximations are in good agreement with the experimental data. This validates the design of the power supply and the programming of the operating points through the test bench. Additionally, the capability of this test bench to achieve automatically any parametric sweep makes it easy to compare the performances of different candidate lamps to be used in a process; for the specific case studied in this paper, a subset of 4 lamps (4, 5, 6 and 7), from the 19 tested, appears to be much better than the others. These bulbs are the ones which present the largest gas gap and they have the best performances, considering the UV emission level, as well as considering the efficiency of the conversion from electrical power to UV power. Concerning the supplying conditions, it is possible to state that the lower the current amplitude (0.2 A and 0.4 A), the lower the UV production and the efficiency are. However, for the two highest current amplitudes (1.2A and 1.4A) no significant differences are found. Using the experimental bench and its parametric sweep tool, it is possible to find the optimal pulse width range, and specifically, for the performed experiments, a range between 400ns and 450ns is obtained.

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