A TRIBUTE TO THE WORK ACHIEVED BY PROFESSOR ZENON ZAKRZEWSKI AT THE UNIVERSITÉ DE MONTRÉAL

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Zenon Zakrzewski was born on September 22 1935 in Święte (Pomerania) Poland. He received the M.Sc. degree in radio engineering from the Technical University of Gdansk (Poland) in 1958 and the Ph.D. degree from the same university in 1967 for a dissertation on plasma diagnostics with microwaves. Subsequently (1968-1969), he was Postdoctoral Fellow of the National Research Council of Canada in the Groupe de physique des plasmas at the Université de Montréal. In 1986, he joined the Polish Academy of Sciences with the national title of Professor. He passed away on November 20 2014.

Starting in 1975, Professor Zakrzewski came to work, as an invited scientist/ invited professor, in the Groupe de Physique des plasmas at the Université de Montréal, as a rule on the occasion of summer stays for almost 30 years. His exceptional collaboration and involvement were a key factor in the development of our research team. The current paper illustrates his specific and original contributions over a cumulated period of time of more than 7 years.

1. INTRODUCTION

It is on his second stay in Montréal (August 1975-October 1976) that Zenon Zakrzewski and I began working together. At that time, the surfatron (a surface-wave launching device allowing sustaining long plasma columns) had already been well optimized. Zenon utilized it to characterize the properties of both the electromagnetic (EM) surface wave sustaining plasma and the plasma column itself. This work led to our first common paper [1]. Besides participating in ongoing researches, Zenon initiated in our laboratory a series of topics of his own: i) the use of the equivalent circuit concept to model the RF and microwave field applicators sustaining plasma successively developed in our lab; ii) the design of the TIAGO microwave-plasma torch; iii) the lowering down from microwaves to RF frequencies of surface-wave launchers (Ro-box); iv) the linear trough-guide microwave field applicator for surface coatings (industrial request). As a result of our efficient and concerted collaborative work, Zenon and I co-authored (with students and post-docs) 9 families of patents and 31 full papers among which 5 are cited more than 100 times, one of them reaching up to 325 citations [2].

2. THE CONCEPT OF EQUIVALENT CIRCUIT FOR DESCRIBING AND ANALYZING HIGH-FREQUENCY (HF) SUSTAINED PLASMA SOURCES

Representing a HF sustained plasma source by an equivalent circuit is a simple approach to allow determining and analyzing the HF power transfer within the plasma source and optimizing its efficiency. Such a circuit includes the plasma itself (represented by a complex impedance) and all the different components involved in impedance matching with the power transmission line. Experimentally, power transfer is examined through measurements, at the plasma-source *entrance port* (where it connects with the transmission line feeding power into it), of the reflected power (expressed in percentage of the incident power) as a function of one of the tuning means under varying operating conditions. Such a scheme yields the *tuning characteristics*, which are related to the input impedance at the entrance port. The objective is to ensure that the incoming power carried by the (coaxial or waveguide) transmission line from the HF generator is fully absorbed by the discharge.

In the process of designing a HF plasma source and optimizing its efficiency, examination of the tuning characteristics permits identifying the specific role of each plasma-source elements and, therefore, enables one to optimize its features. In a more advanced step of design, it is even possible to render the tuning characteristics less sensitive to changes in operating conditions.

Modeling the tuning characteristics of a plasma source through its equivalent circuit is much more straightforward than resorting to solving simultaneously Maxwell equations of the EM field and two or three hydrodynamic equations accounting for the discharge. However, the equivalent circuit approach is not self-consistent as far as the discharge is concerned, where plasma is represented by a complex impedance, the value of which is obtained by curve fitting on the tuning characteristics, as we will show. Nonetheless, it turns out that this procedure is reliable and surprisingly exact considering the relative simplicity of the equivalent-circuit modeling and calculations.

2.1 Equivalent circuit of the surfatron

In what follows, we consider the equivalent circuit of the surfatron, which was the first surface-wave plasma source that Zenon modeled. Figure 1 shows a schematized cross-sectional view of this device, which can be best used in the 200 to 2450 MHz range.

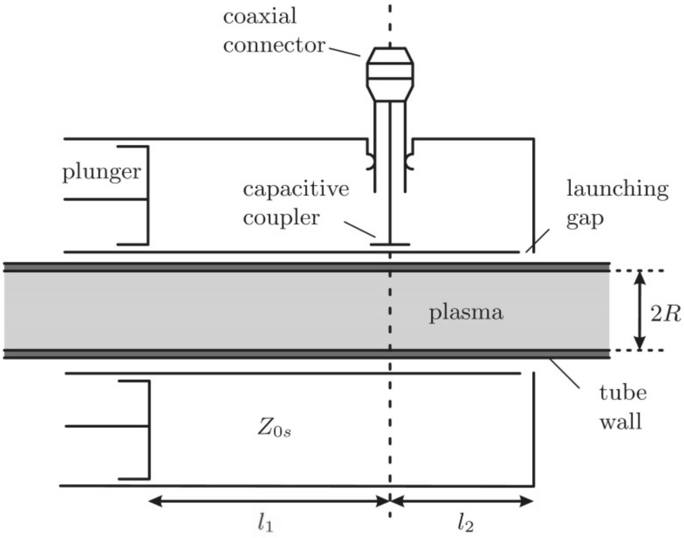

Figure 1. Schematized axial cross-section of a surfatron

The surfatron is a surface-wave launcher that integrates the EM field shaping interstice (gap) and two means of impedance matching (the capacitive coupler and the plunger, both adjustable). The surfatron body consists of two conducting cylinders forming a section of coaxial line (with ambient air as the dielectric) of length l_1 and l_2 and characteristic impedance Z_{0s} terminated by a short-circuit on one end and by a circular aperture surrounding the discharge tube on the other end. The l_2 length corresponds to the segment of the (intrinsic) coaxial line extending from the capacitive coupler plane, called the *reference plane,* to the *launching gap*. The capacitive coupler is based on a segment of semi-rigid coaxial cable, terminated on one end by a coaxial cable connector to match the feeding transmission line while at the other end its outer conductor (and dielectric) has been removed over a few mm length and soldered to a few mm diameter copper plate shaped such that it matches the curvature of the smaller diameter coaxial-cylinder of the intrinsic coaxial line, aluminum anodized on its outside: the distance between the copper plate and the cylinder defines the capacitance, which can be varied by moving in and out the coupler. The movable plunger terminating the intrinsic coaxial line sets the length l_1 required for impedance matching when the surfatron is not operated at a fixed field frequency.

Figure 2 shows the equivalent circuit of the plasma source schematized in Figure 1. All the displayed elements in this figure are actually physical components of this plasma source and are represented as lumped elements even though they can be distributed elements (e.g. transmission line).

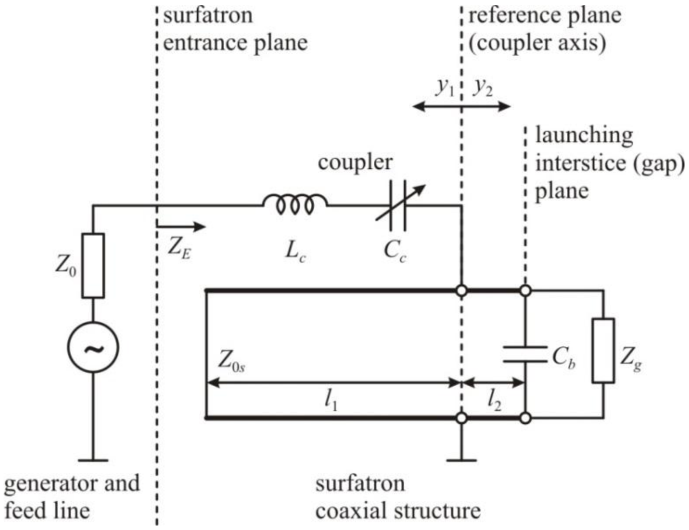

Figure 2. Equivalent circuit of the surfatron plasma source presented in Figure 1.

2.2 Calculated input impedance Z_E

Since we are going to add impedances that are in parallel in the reference plane, we turn to admittances rather than impedances. Moreover, we employ normalized admittances of the form $y = Z_0/Z = g + jb$ where g is the conductance and b the susceptance, j being the imaginary operator. The normalized admittance y_1 seen at the reference plane of the intrinsic coaxial transmission line, because it is assumed lossless, is purely imaginary, thus $y_1 = jb_1$ where $b_1=Z_0\,[Z_{0s}\tan(2\pi\, l_1/\lambda_0)]^{-1}$ since the line is short-circuited at its other end. The admittance contribution on the right-hand side of the reference plane (see Figure 2), labelled y_2, ignores the influence of the transmission line of length l_2 since as a rule $l_2 << \lambda_0$, the EM field wavelength in free space. Designating the plasma normalized admittance by $y_g = b_g + jb_g$ and the normalized susceptance of the "gap capacity" C_b by $b_c = Z_0\,\omega\, C_b$ (ω is the EM wave angular frequency), then the sum of these two admittances, seen at the reference plane, is $y_2 = g_g + j\,(b_g + Z_0\,\omega\, C_b) \equiv g_2 + jb_2$. Finally, the total admittance at the reference plane, $y_R \equiv y_1 + y_2$, is $g_2 + j\,(b_2 + b_1)$. The corresponding normalized impedance $(y_1 + y_2)^{-1}$ is given by:

$$z_R = \frac{g_2}{g_2^2 + \left(b_2 + b_1\right)^2} - j\,\frac{\left(b_2 + b_1\right)}{g_2^2 + \left(b_2 + b_1\right)^2}. \tag{1}$$

Lastly, the total impedance brought back to the entrance plane is the sum of all the impedances set out in series:

$$\frac{Z_E}{Z_0} \equiv \frac{R_E}{Z_0} + j\,\frac{X_E}{Z_0} = \frac{g_2}{g_2^2 + \left(b_2 + b_1\right)^2} + j\left(\frac{\omega L_c}{Z_0} - \frac{1}{\omega C_c Z_0} - \frac{\left(b_2 + b_1\right)}{g_2^2 + \left(b_2 + b_1\right)^2}\right). \tag{2}$$

2.3 Impedance matching conditions

Impedance matching at the entrance plane is achieved provided $Z_E = Z_0$, which requires that $R_E/Z_0 = 1$ and $X_E = 0$[1]. To get $R_E = Z_0$, from (2) we need:

$$\left(b_2 + b_1\right)^2 = g_2 - g_2^2 \tag{3}$$

while $X_E = 0$, because of (3), imposes that :

$$\frac{1}{Z_0}\left(\omega L_c - \frac{1}{\omega C_c}\right) = \pm\left(\frac{1}{g_2} - 1\right)^{\frac{1}{2}}. \tag{4}$$

The value of g_2, the conductance of the plasma, and that of b_2 are determined by the operating conditions while the value of the inductance L_c, is set by the coupler design and dimensions. To achieve conditions (3) and (4), the two tuning means of the surfatron are needed, namely the length l_1 of the intrinsic transmission line, which allows varying b_1 (real part of Z_E in (2)) as required by (3), and the penetration depth of the coupler, which acts on C_c (imaginary part of Z_E) allowing complying with (4).

2.4 Corresponding tuning characteristics

Having obtained the surfatron input impedance, it is possible to determine the corresponding tuning characteristics since the ratio of reflected power to incident power is given by:

$$\frac{P_r}{P_{\text{in}}} = \left|\frac{Z_E - Z_0}{Z_E + Z_0}\right|^2. \tag{5}$$

In what follows, tuning characteristics are plotted as functions of the plunger position l_1 of the surfatron intrinsic coaxial line length.

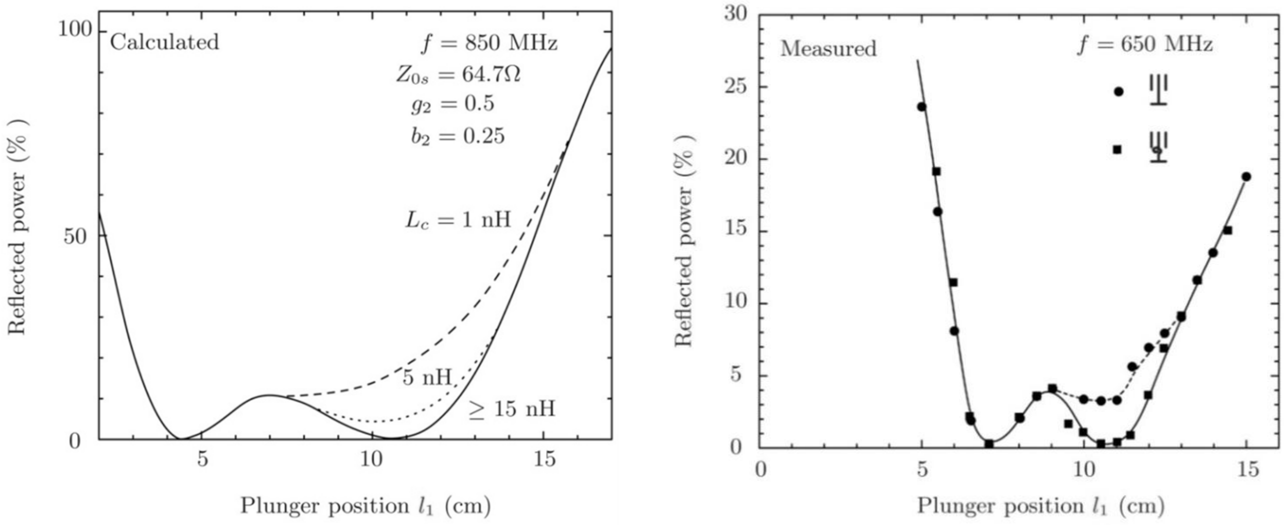

Figure 3 a) calculated tuning characteristics from (2) and (5), assuming g_2 and b_2 values for three values of L_c, the coupler inductance; b) measured tuning characteristics where the coupler bare conductor (determining L_c) is either a straight wire or a single turn wire, thus with a higher inductance value than the straight wire.

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[1] We are assuming that the operating frequency is high enough such that the characteristic impedance of the transmission line can be considered purely real.

Figure 3 (a) shows a calculated tuning characteristic at a given field frequency, assuming three values of the inductance of the bare part of the semi-rigid coaxial line of the coupler. Figure 3(b) displays two measured tuning characteristics, corresponding in one case to a straight bare wire while in the other case it is twisted in a single turn wire providing a higher inductance value than the straight wire. Clearly, the influence of the value of the coupler inductance is well accounted for in the calculated tuning characteristics, demonstrating the accurateness of the equivalent circuit!

Figure 4 shows the data points obtained from measurements of the tuning characteristic at 950 MHz. The full line is the tuning characteristic determined from a fit on the data points, yielding a set of g_2 (plasma conductance) and b_2 values. These fit the whole extent of the calculated tuning characteristic displayed (at higher percentages of reflected power, measurement accuracy can be lost due to the limited isolation of the bi-directional coupler ports).

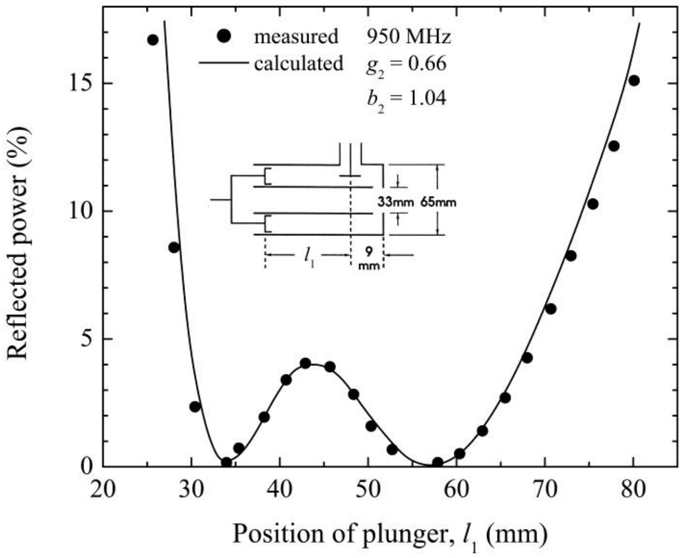

Figure 4. Data points obtained experimentally at 950 MHz with the corresponding fitted calculated tuning characteristic, yielding the g_2 and b_2 values

In summary, the concept of equivalent circuit applied to the surfatron has proven to be exceptionally simple and useful, but also accurate, where only actual elements of the device are included in its description (much more detailed calculations and experimental considerations can be found in [3]). All the various types of surface-wave launchers designed in our lab were in the end accompanied by their equivalent circuit [2].

3. THE TIAGO MICROWAVE PLASMA-TORCH

A microwave plasma-torch is a device in which a microwave sustained discharge is induced in open space, usually in a stream of gas directly surrounded by air, at the tip of the field applicator. Achieving the discharge rather within a dielectric tube can create problems at atmospheric pressure when large power densities are deposited in the plasma, resulting in erosion of the tube and subsequent contamination of the carrier gas.

The TIAGO[2] torch is an illustration of Zenon's simplified (and aesthetic) approach to a previously comparatively cumbersome and more complicated torch design, the TIA [4]. Figure 5(a) is a schematic

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[2] TIAGO = Torche à Injection Axiale sur Guide d'Onde in French

side-view of the TIAGO torch showing its implementation in the reduced-height part of a surfaguide [2]. The body of the nozzle is held in place by a screw-nut resting on the external wall of the bottom part of the surfaguide (gas inlet side). Figure 5(b) is a later version of the TIAGO, where the nozzle is adjustable in height with respect to the plane of the launching gap of the surfaguide, allowing maximizing the power absorbed in the flame at the nozzle tip.

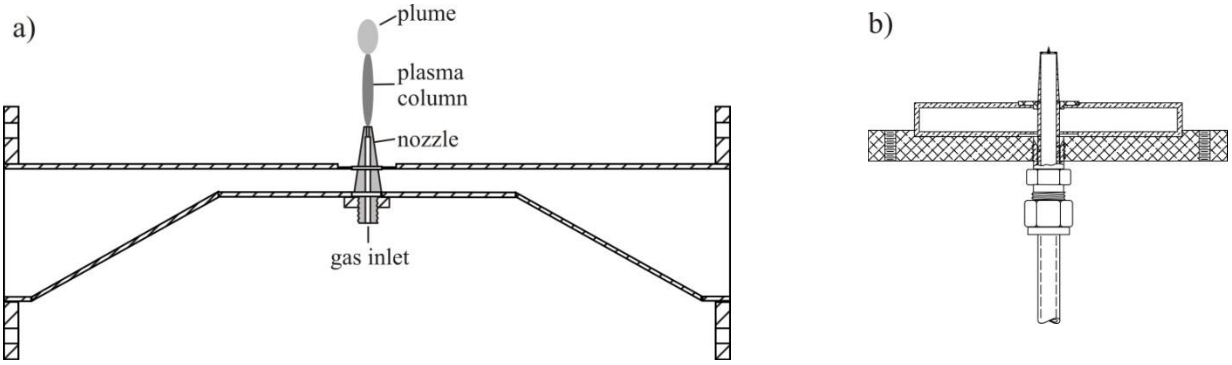

Figure 5. a) The TIAGO initial nozzle-gap design, with the microwave power coming in from one side of the surfaguide while the other side is terminated by a moving (contactless) short-circuit (plunger), not shown; b) a 90° cut-view with respect to figure 5(a) of a later version of the TIAGO where the height of the nozzle tube is readily adjustable with a screw-nut such that the distance from its tip with respect to the surfaguide gap plane can be varied.

Figure 6 shows the data points obtained from measurements of the tuning characteristic of the TIAGO torch at 2450 MHz [5]. The full line is the tuning characteristic resulting from a fit of the data points, yielding the set of g_2 (plasma conductance) and b_2 values.

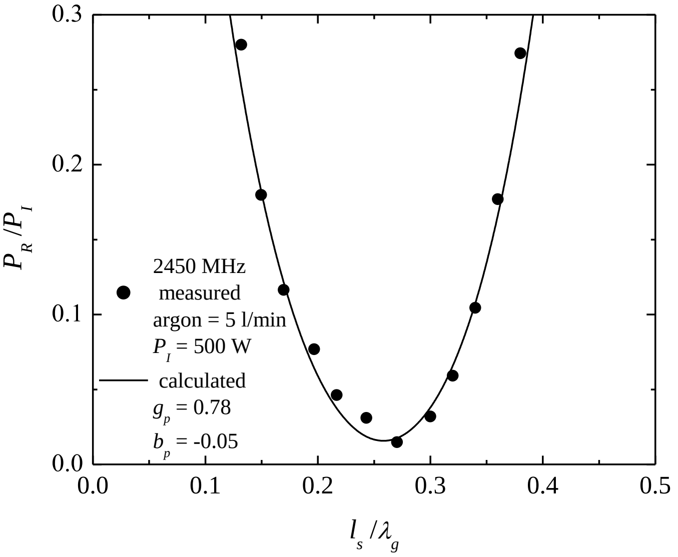

Figure 6. Measured and calculated tuning characteristic of a TIAGO single-torch system located on the waveguide center-line and where l_s is the relative position of the short-circuiting plunger and λ_g the wavelength in the waveguide [5].

4. THE RO-BOX SURFACE-WAVE LAUNCHERS

Operating the surfatron at frequencies as low as, for instance, 100 MHz would require l_1 values of the order of 1 m (to ensure the first zero (smaller l_1 length) of reflected power: see Figure 4) making this device cumbersome. Zenon came up with the two different, small-size, surface-wave launchers displayed in Figures 7 (a) and (b), further on named the LC Ro-Box and the stub Ro-Box, respectively. In the first case, the matching circuit comprises (one or two) continuously variable coils (inductors) and variable capacitors, which are set out, for example, in a Π or L configuration, and enclosed in a so-called *match-box*. In the second case, the Ro-Box is impedance-tuned like a surfatron with a capacitive coupler and with, this time, an "externalized" intrinsic transmission line in the form of a tuning stub, i.e. a variable coaxial line terminated at one end by a (movable) short-circuit.

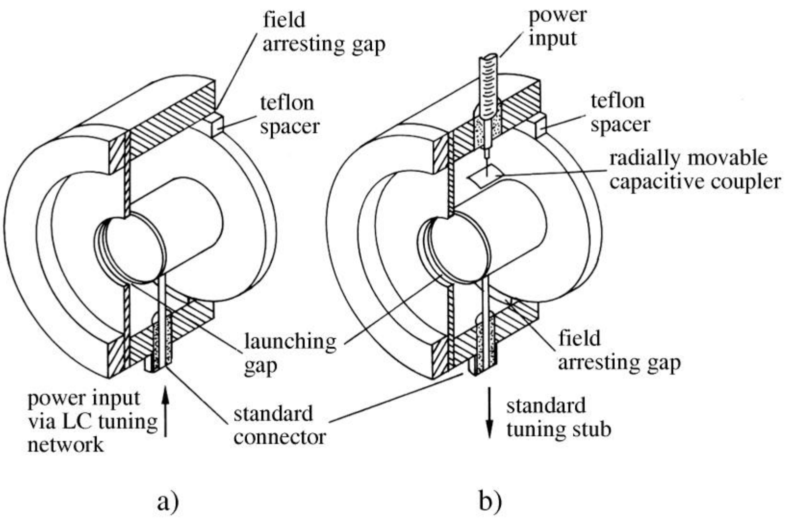

Figure 7. The Ro-Box surface-wave launchers; a) LC configuration; b) stub configuration [6].

These devices were operated to sustain argon discharges at gas pressures extending from a few 100 millitorr (≈ 13 Pa) up to atmospheric pressure and at frequencies ranging from 3.8 MHz to 200 MHz. The plasma column extended about evenly on both sides of the launcher. Figure 8 shows representative measurement results in a 6 mm i.d. Pyrex discharge tube at field frequencies from 27 to 100 MHz, with both types of Ro-Box [6].

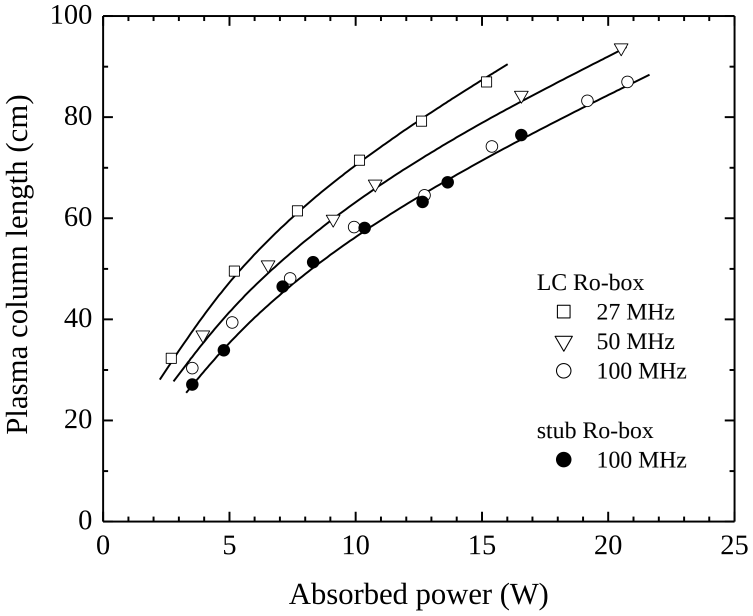

Figure 8. Measured surface-wave plasma column length as a function of the power absorbed in the plasma source in argon gas at 1 torr (≈ 130 Pa) [6].

The Ro-box surface-wave launcher is a compact surfatron surrogate for field frequencies below 100 MHz, furthermore less critical in terms of its dimensions, and thus less expensive to fabricate.

5. THE TROUGHGUIDE : A LINEAR FIELD APPLICATOR

The design of this device resulted from an industrial contract (Imperial Chemical Industries (ICI) UK) for a long, uniform, high density plasma for achieving thin film deposition using a roll-to-roll machine of the order of a meter in length, with the specific constraint of ensuring that the system was not already protected by a patent. In contrast to surface-wave discharges, the present field applicator runs parallel and adjacent to the discharge, the applicator being possibly many times longer than the free-space wavelength at the operating frequency. In this case, it requires generating a wave, either traveling or standing along the discharge vessel. Figure 9 shows schematically that the discharge is sustained in a transparent-to-microwave vessel by an EM wave leaking out from a wave-guiding structure, hence its designation as a *leaky-wave* field applicator. The wave properties are then determined by the waveguiding structure alone, which exhibits fast-wave characteristics and, in our case it is a traveling wave, hence the match load at the opposite end to the feeding line to avoid wave reflection [7].

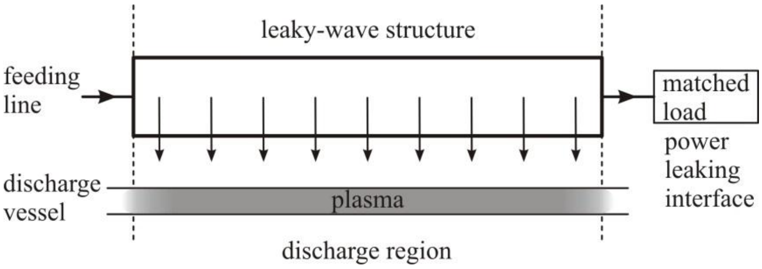

Figure 9. Schematic representation of a leaky-wave discharge sustained with a traveling wave [7].

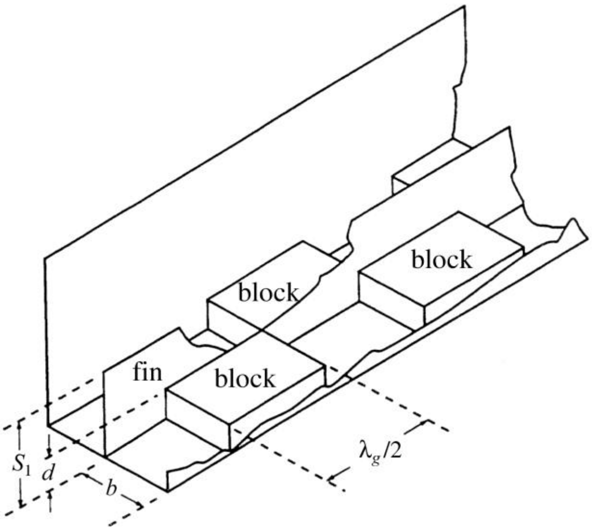

Figure 10. Schematic view of the EM wave attenuating blocks lying on the bottom of the trouhguide. They are distributed in a periodically asymmetric fashion with respect to the center fin (height S_1), the height of the blocks (d) increasing from the feeding line toward the match load to compensate for the loss of power that has already leaked out from the waveguiding structure.

Figure 10 displays a series of blocks, of length $\lambda_g/2$, lying on the bottom of the waveguiding structure, which has the form of a drinking trough. The blocks are distributed alternately on each side of the fin (height S_1) that divides the trough into two parts. Alternating periodically the blocks leads to a broadside radiation pattern of the wave (the maximum of the wave power flow is perpendicular to the direction of wave propagation). This is a key issue since otherwise a surface wave is launched on the fused silica window (not shown) that isolates (under reduced pressure conditions) the troughguide from the discharge volume, and longitudinal uniformity of plasma is hindered. Figure 10 also shows that the height of the block is increasing from the feeding line toward the match load (Figure 9). This allows to achieve a continuously increasing attenuation coefficient of the wave to compensate for the power that has already leaked out to the discharge at this position, in the end ensuring that a uniform power flow leaks out all along the applicator.

Figure 11 displays the measured light intensity distribution along the discharge chamber (for more details see [7]).

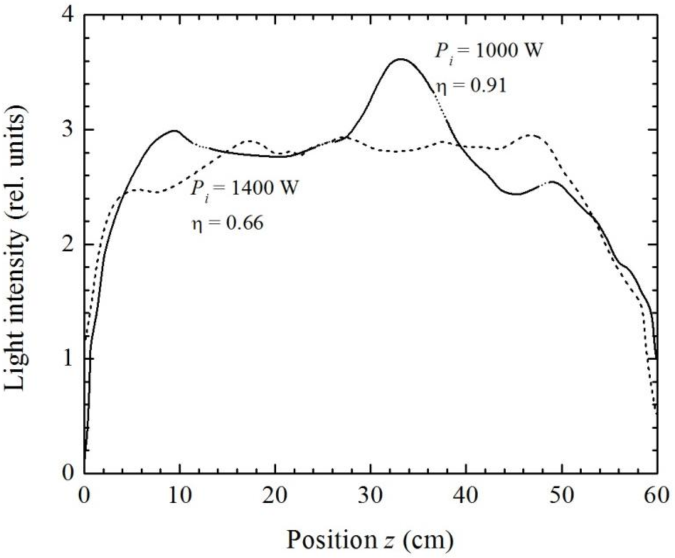

Figure 11. Emitted light intensity distribution recorded along the discharge chamber [7].

The troughguide manufactured for implementation in a testing web coating machine using the computer program had a total block length of 240 mm. This was retrofitted onto a system where a sputtering cathode had been replaced with a fused silica window. The uniformity of this source was determined by the plasma enhanced chemical vapor deposition (PECVD) of a thick transparent carbon coating, which was deposited onto a polymer substrate and the thickness profile determined from the interference fringes. This troughguide was tested using powers of up to 1 kW forward power with 100 W of reflected power at a system pressure in the range 10-35 Pa (75-260 mtorr). For a 240 mm long aperture, the uniformity was ±7% over a 200 mm span and ±5 % over a 180 mm span. It is typical that the uniformity drops off at the ends of the source; this is why sources are specified to be larger than the web width. For aluminum metallization, the uniformity is generally ±l0%; it is only with sputtering sources that uniformity of ±5% can be expected. Hence the troughguide system has a similar uniformity performance to the best of the roll to roll web coating techniques [7].

6. CONCLUSION

As we have illustrated with four selected (but heavily abridged) topics (equivalent circuit modeling, TIAGO torch, Ro-Box launchers and the troughguide field applicator), Professor Zakrzewski has brought original and innovative contributions to the work in which he participated in the Groupe de physique des plasmas at the Université de Montréal. We are therefore extremely grateful to him since without his assistance, the *scientific production* of our microwave-plasma team would have been of much less interest and, consequently, not as widely cited. It is also to be mentioned that many of the Groupe’s students, technicians and invited scientists benefitted from his knowledge and skill, and additionally enjoyed his humoristic comments.

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