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# RADIOFREQUENCY INDUCED PLASMA IN LARGE-SCALE PLASMA REACTOR

## RADIOFREKVENČNO INDUCIRANA PLAZMA V REAKTORJU VELIKIH DIMENZIJ

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In this contribution we describe the characteristics of an electrical discharge in rarified gas created by dual-excitation coil. By using two parallel and overlapping excitation coils we can achieve a better transfer of the electromagnetic power from the radiofrequency (RF) generator to gaseous plasma. Dual-excitation coil is connected via a matching unit and a high frequency cable to the RF generator. Such special assembly (coupling of plasma with RF generator) has several advantages in comparison with normally used set-up. These advantages are the following: power transfer to plasma is increased, plasma is more homogeneous, the voltage necessary for generating plasma is lower, and many side-effects which are due to capacitive coupling of the plasma system are reduced.

Keywords: radiofrequency discharge, gaseous plasma, large plasma reactor, matching network

V prispevku opisujemo meritve karakteristik plinske razelektritve, inducirane z dvojno vzbujevalno tuljavo. Z uporabo dveh vzporedno vezanih prekrivajočih se in zamaknjenih vzbujevalnih tuljav dosežemo boljši prenos elektromagnetne moči od radiofrekvenčnega generatorja v plinsko plazmo. Tuljavi sta vezani zaporedno v sklopu: tuljava-uskladitveni člen-visokofrekvenčni kabel-generator. Tovrstna vezava tuljav ima pred doslej opisanimi sklopi več prednosti, med drugim naslednje: izkoristek moči generatorja se poveča, plazma v razelektritveni posodi je bolj homogena, napetost na generatorju, ki je potrebna za generiranje plazme, je manjša, obenem pa so bistveno zmanjšani stranski pojavi, ki so posledica kapacitivnih sklopitev v plazemskem sistemu.

Ključne besede: radiofrekvenčna razelektritev, plinska plazma, sklopitveni člen, veliki plazemski reaktorji

## 1 INTRODUCTION

In last few decades, plasma has become an important medium for treatment of materials in many modern technologies like surface cleaning,[1–4] sterilization,[5–6] surface functionalization,[7–16] selective etching[17–20] and surface (nano)modification.[21–25] Plasma can be divided to thermodynamically thermal and nonthermal plasma. Thermal plasma, where the gas particles are in thermodynamic equilibrium, is used for plasma cutting and welding, for synthesis of ceramics, for the degradation of hazardous chemical waste, for the plasma spraying etc.[26–28] A request for ecologically suitable technologies has led to the development of new types of technologies like thermodynamically nonequilibrium plasma for processing of materials. Examples of application are: vacuum deposition of thin films, laser industry, microelectronics, macroelectronics (e.g. plasma displays), silicon micromachining (e.g. production of silicon pressure sensors) etc.[29] Numerous examples have been used in the automotive, optical and military industry and in biomedicine.

For processing of materials we can use different types of thermodynamic nonequilibrium plasmas, which are excited in different gases. Plasma can be created by passing the gas through an electric field. Such gas is partially ionized, which means that it contains not just neutral particles but also free electrons and ions. Free electrons are accelerated in the electric field and make collision with the atoms or molecules. At collisions atoms and molecules are excited from the ground state into different excited states.

Electrical discharges are further divided according to the frequency of the electric field needed for excitation of plasma to: DC discharge, corona discharge 50–450 kHz, radiofrequency (RF) discharge 5–100 MHz, microwave (MW) discharge 2.45 GHz and ECR (electron cyclotron resonance) discharge 2.45 GHz with magnetic field.[30–31]

Radiofrequency (RF) plasma usually works at two different frequencies 27.12 MHz or 13.56 MHz. RF plasma can be divided into capacitive and inductive coupled plasma, depending on the method used for creation of electric field. In the case of capacitive coupling the electric field is established between two electrodes (i.e. a capacitor) while for inductive coupling we need an excitation coil or a spiral.[30–31]

Inductively coupled plasma is not perfectly inductive but we can also have a contribution of capacitive component. Therefore, inductively coupled plasma can operate in two different operating modes: E- and H-mode.[32–38] At low RF powers the inductively coupled plasma is characterized by weak light emission intensity, low electrons density and relatively high electron temperature. This mode is called E-mode and here capacitive coupling prevails. With increasing RF power we can observe a transition to H-mode which is characterized by sudden increase of light intensity and electron density, while electron temperature is slightly reduced. In this mode, the inductive component prevails and plasma is concentrated in a small volume inside the excitation coil or in the vicinity of the excitation coil.

H-mode is fairly easy to create in a small plasma reactor,[39–49] but on the other hand it can be a big problem in large-scale plasma reactors. In large plasma reactor it is very difficult to create uniform inductive plasma in H-mode. In this paper we present characteristics of large plasma reactor, where plasma is excited with special dual-excitation coil, which is connected to RF generator via a special matching unit. Electrical characteristics and light emission was measured and compared to plasma created by normal excitation coil.

## 2 EXPERIMENTAL

### 2.1 Construction of plasma reactor

Schematic of the plasma system is shown in **Figure 1**. Plasma was created in a large quartz discharge tube with a length of 200 cm and a diameter of 20 cm. The discharge tube was pumped by rotary pump with a nominal pumping speed of 15 $m^3 h^{-1}$. The pressure was measured with an absolute vacuum gauge. The base pressure in the system was about 1 Pa. Oxygen was leaked into the discharge chamber through a precise leak valve and was set to two different pressures: 10 Pa and 40 Pa.

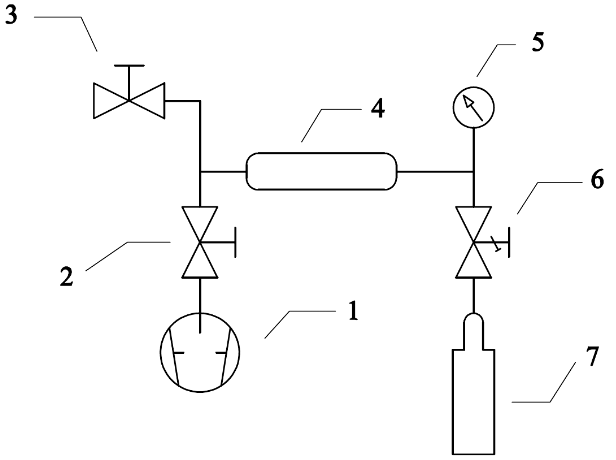

**Figure 1:** Schematic of the vacuum system: 1 – vacuum pump, 2 – valve, 3 – air-inlet valve, 4 – quartz discharge tube, 5 – absolute vacuum gauge, 6 – leak valve, 7 – gas

**Slika 1:** Shema vakuumskega sistema: 1 – vakuumska črpalka, 2 – ventil, 3 – ventil za vpust zraka, 4 – razelektritvena kremenova cev, 5 – merilnik absolutnega tlaka, 6 – precizni dozirni ventil in 7 – plinska jeklenka

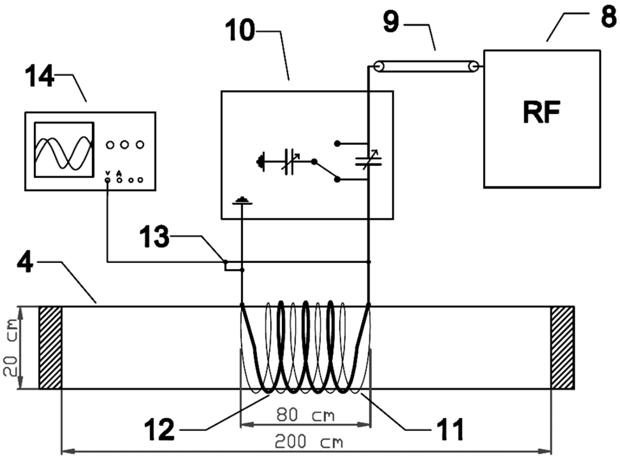

**Figure 2:** Excitation coil and matching network of plasma system: 8 – RF generator (8 kW), 9 – high frequency cable, 10 – matching unit, 11, 12 – normal or dual-excitation coil, 13 – high-voltage probe, 14 – oscilloscope

**Slika 2:** Vzbujevalni in sklopitveni člen vakuumskega sistema: 8 – RF generator, 9 – visokofrekvenčni kabel, 10 – uskladitveni člen, 11, 12 – navadna ali dvojna vzbujevalna tuljava, 13 – visokonapetostna sonda, 14 – osciloskop

For plasma excitation special dual-excitation coil was constructed. This coil was connected to the RF generator via a special matching unit (**Figure 2**). The RF generator is working at a frequency of 27.12 MHz and a maximum nominal power of 8 kW. Matching unit consist of two high-frequency, high voltage, vacuum variable capacitors, whose capacitance can be adjusted with the servo motors that are controlled by the RF generator. This matching unit is used to match the output impedance of the power supply and the impedance of the plasma system (load) to maximize the power transfer to plasma.[31]

### 2.2 Electrical characterization

Voltage on the excitation coils was measured with high voltage probe Tektronix P6015a connected to oscilloscope Tektronix TDS3024B. We measured root mean square-RMS voltage. Forwarded power measurement of the radiofrequency generator was taken from the generator display.

### 2.3 Plasma characterization

Optical emission spectroscopy (OES) was applied as a method for measuring the difference in light emission intensity of normal and dual-excitation coil. Spectra were measured in the range from 200 nm to 1100 nm by an optical spectrometer (Avantes AvaSpec-3648-USB2). Spectral resolution was about 1 nm. Integration time was 100–200 ms.

## 3 RESULTS AND DISCUSSION

The matching unit is attached to a dual excitation coil, which consists of two parallel overlapping exci-

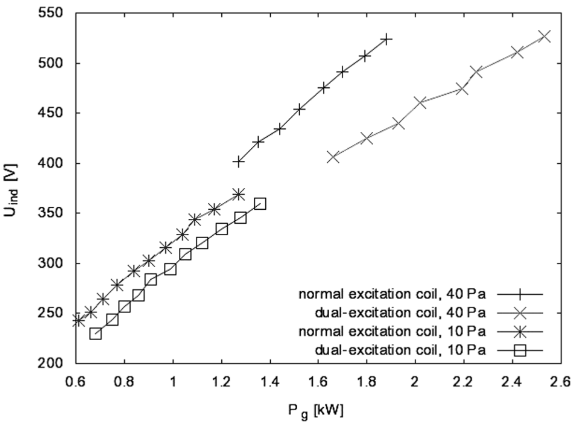

**Figure 3:** Voltage measured on normal excitation coil and dual-excitation coil versus RF power

**Slika 3:** Meritve napetosti na navadni vzbujevalni tuljavi in dvojni vzbujevalni tuljavi v odvisnosti od moči generatorja

tation coils. Excitation coils, which are of the same diameter, are overlapping in such a way that they have the same axis and are fixed together only at the beginning and the end, where they are linked to the matching unit. First excitation coils is shifted along the axis in comparison to the second excitation coil in such a way that turns of the second excitation coil are wound in the middle of the turns of the first excitation coil (**Figure 2**). Furthermore, both excitation coils are wound in the same direction, so that turns of the first excitation coils run parallel with the turns of the second excitation coil. Dual-excitation coil is made of 25 mm wide copper band with a thickness of 0.4 mm. The first excitation coil has five turns, while the second one has four turns. The entire length of the dual-excitation coil is 800 mm.

Comparison of measurements made in oxygen plasma generated by a normal excitation coil and measurements made with a dual-excitation coil is shown in **Figures 3–6**. Here we should also note that a length of the normal excitation coil is the same as a length of dual-excitation coil and has five turns. **Figure 3** shows the measured voltage of normal excitation coil and dual-excitation coil as a function of power of RF generator. From **Figure 3** we can conclude that in the case of dual-excitation coil lower voltage is required for the same power transfer than in the case of normal excitation coil. By using dual-excitation coil the applied voltage is reduced in comparison with the normal excitation coil and this is from the technological point of view very useful.

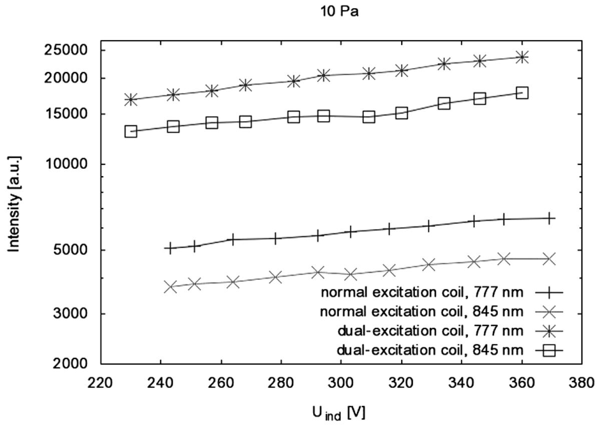

**Figure 4:** Light intensity measured in the centre of normal excitation coil and dual-excitation coil versus the applied voltage to the coil. The pressure was 10 Pa.

**Slika 4:** Meritve intenzitete izsevane svetlobe na sredini navadne vzbujevalne tuljave in dvojne vzbujevalne tuljave v odvisnosti od napetosti na vzbujevalni tuljavi pri tlaku 10 Pa

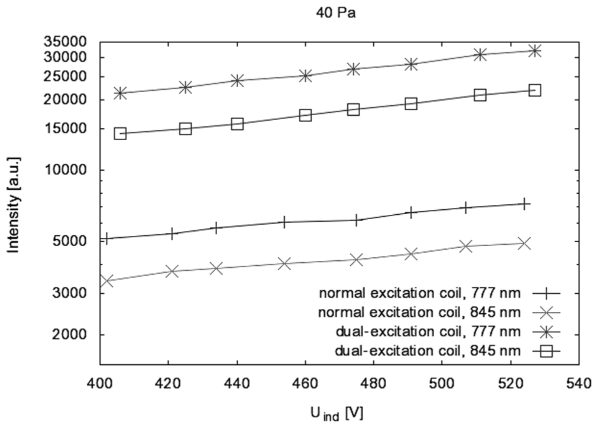

**Figure 5:** Light intensity measured in the centre of normal excitation coil and dual-excitation coil versus the applied voltage to the coil. The pressure was 40 Pa.

**Slika 5:** Meritve intenzitete izsevane svetlobe na sredini navadne vzbujevalne tuljave in dvojne vzbujevalne tuljave v odvisnosti od napetosti na vzbujevalni tuljavi pri tlaku 40 Pa

The emission intensity of oxygen plasma measured in the middle of the excitation coil as a function of voltage or RF power shows that the plasma generated in a dual-excitation coil is much more intense than plasma, generated in the normal excitation coil (**Figures 4 and 5**). **Figure 4** presents the results of measurements of the intensity of oxygen emission lines 777 nm and 845 nm (transition O(3p$^5$P → 3s$^5$S) and O(3p$^3$P → 3s$^3$S))[50–52] in a

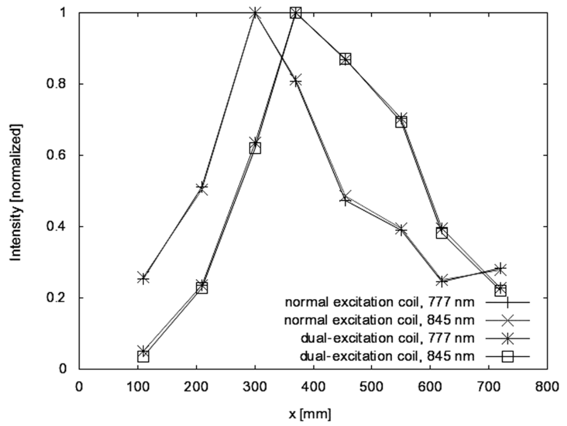

**Figure 6:** Light emission intensity of oxygen plasma measured along normal excitation coil and dual-excitation coil

**Slika 6:** Meritve intenzitete izsevane svetlobe vzdolž navadne vzbujevalne tuljave in dvojne vzbujevalne tuljave plasma at a pressure of 10 Pa. The integration time was 200 ms. We can see that the intensity of light in plasma generated in a normal excitation coil, is about three times lower than in the case of dual-excitation coil. In **Figure 5** are presented the same results for the pressure of 40 Pa. In this case the spectrometer integration time was 100 ms. The difference is even more evident than at a pressure of 10 Pa. The light emission intensity in a dual-excitation coil is at the same applied voltage up to 4-times bigger than in the case of normal excitation coil.

With OES method we have measured also the difference in homogeneity of the plasma in H-mode (**Figure 6**) for both coils (normal and dual). This was done by measuring the plasma emission in the range between 200 nm and 1100 nm at eight different points along the coil. **Figure 6** shows the normalized intensity of oxygen 777 nm and 845 nm emission lines as a function of position of spectrometer along the excitation coil. First position (point at $x$ = 100 mm in **Figure 6**) of the spectrometer was at the beginning of the excitation coil. The graph shows that the intensity of oxygen lines in the case of dual-excitation coil is at four measured points higher than a half of the maximum intensity, while in the case of normal excitation coil the intensity is higher at only two points. Furthermore, the width of the measured curve at half of the maximum intensity is for a factor of two wider for the case of a dual-excitation coil in comparison to the normal one. It can be concluded that the length of plasma column in H-mode is larger when we used dual-excitation coil, while in the case of normal excitation coil it is shorter.

At the end we should also mention, that instead of dual-excitation coil we can also use triple-excitation coil (or even multiple coils). The only limitation is that turns of individual excitation coil may not overlap turns of another excitation coil. So this means that another excitation coil must be shifted along the discharge tube in such a way that turns of the second (third …) coil run between turns of the first coil. From practical point of view, if we have dense coil windings around the discharge tube, we have limit space for further wrapping of additional coils between the turns of the first coil. So this means that too many coils are not useful.

## 4 CONCLUSION

In this paper we present characteristics of a large plasma reactor, where plasma is excited with a special dual-excitation coil, which is connected to RF generator via a matching unit. By this special set-up plasma is run in inductive mode without capacitive coupling. We have shown that in such configuration power transfer to plasma is optimized and plasma is homogenous. Measurements of voltage on the excitation coil show that in the case of dual-excitation coil lower voltage is required for the same transfer of power than in the case of normal excitation coil. Comparison of normal and dual-excitation coils which run at the same voltage shows that plasma is much more intense if it is generated in dual-excitation coil.

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