Video Article

How to Ignite an Atmospheric Pressure Microwave Plasma Torch without Any Additional Igniters

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Abstract

This movie shows how an atmospheric pressure plasma torch can be ignited by microwave power with no additional igniters. After ignition of the plasma, a stable and continuous operation of the plasma is possible and the plasma torch can be used for many different applications. On one hand, the hot (3,600 K gas temperature) plasma can be used for chemical processes and on the other hand the cold afterglow (temperatures down to almost RT) can be applied for surface processes. For example chemical syntheses are interesting volume processes. Here the microwave plasma torch can be used for the decomposition of waste gases which are harmful and contribute to the global warming but are needed as etching gases in growing industry sectors like the semiconductor branch. Another application is the dissociation of CO_2. Surplus electrical energy from renewable energy sources can be used to dissociate CO_2 to CO and O_2. The CO can be further processed to gaseous or liquid higher hydrocarbons thereby providing chemical storage of the energy, synthetic fuels or platform chemicals for the chemical industry. Applications of the afterglow of the plasma torch are the treatment of surfaces to increase the adhesion of lacquer, glue or paint, and the sterilization or decontamination of different kind of surfaces. The movie will explain how to ignite the plasma solely by microwave power without any additional igniters, *e.g.*, electric sparks. The microwave plasma torch is based on a combination of two resonators — a coaxial one which provides the ignition of the plasma and a cylindrical one which guarantees a continuous and stable operation of the plasma after ignition. The plasma can be operated in a long microwave transparent tube for volume processes or shaped by orifices for surface treatment purposes.

Video Link

The video component of this article can be found at http://www.jove.com/video/52816/

Introduction

Atmospheric pressure microwave plasma torches offer a variety of different applications. On one hand they can be used for chemical volume processes and on the other hand their afterglow plasma can be applied for the treatment of surfaces. As surface treatment processes the treatment to increase the adhesion of glue, paint or lacquer or the decontamination or sterilization of surfaces can be named. The hot and reactive plasma itself can be used for volume processes like the decomposition of waste gases [1–7]. These waste gases are harmful, contribute to the global warming and can hardly be degraded conventionally. However, they are needed in growing industrial sectors such as the semiconductor branch. Other applications are chemical synthesis like the dissociation of CO_2 to CO and O_2 or CH_4 to carbon and hydrogen [8,9]. Surplus electrical energy from renewable energy sources can be used to dissociate CO_2 into CO and O_2. The CO can be processed further to higher hydrocarbons which can be used as synthetic fuels for transportation, as platform chemicals for the chemical industry or as chemical storage.

There are some microwave plasma torches but most of them have disadvantages: They only have very small plasma volumes, need additional igniters, need cooling of the plasma reactor or can only be operated in pulsed mode [10–18]. The microwave plasma torch presented in this movie offers an ignition of the plasma solely with the provided microwave power with no additional igniters as well as a stable and continuous operation without any cooling of the plasma reactor for a broad range of operation parameters and can be used for all of the above mentioned applications. The microwave plasma torch is based on a combination of two resonators: a coaxial one and a cylindrical one. The cylindrical resonator has a low quality and is operated in the well-known E_{010}-mode with the highest electrical field in its center. The coaxial resonator is located below the cylindrical resonator and consists of a movable metallic nozzle in combination with a tangential gas supply. The high quality of the coaxial resonator exhibits a very narrow but deep resonance curve. Due to the high quality of the coaxial resonator a high electrical field can be reached which is required for the ignition of the plasma. However, the high quality of the coaxial resonator is associated with a very narrow resonance curve and therefore the resonance frequency has to perfectly match the frequency of the supplied microwave. Since the resonance frequency shifts after ignition of the plasma due to the permittivity of the plasma, the microwave can no longer penetrate into the coaxial resonator. For the continuous operation of the plasma the cylindrical resonator with a low quality and a broad resonance curve is needed.

An additional axial gas supply via the metallic nozzle of the coaxial resonator is possible. The plasma is ignited and confined in a microwave-transparent tube, for example a quartz tube. The permittivity of the quartz tube also affects the resonance frequency. Since the quartz has a

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permittivity of > 1, the volume of the cylindrical resonator is virtually enlarged which leads to a lower resonance frequency. This phenomenon has to be considered when the dimensions of the cylindrical resonator are designed. A detailed discussion about how the resonance frequency is affected by the inserted quartz tube can be found in Reference 23. If a long and extended quartz tube is used, this can also act as the reaction chamber for the volume processes. However, for surface treatments the plasma can also be shaped differently by different kind of orifices. The microwave is supplied via a rectangular waveguide from the magnetron. To avoid noise nuisance the use of a low ripple magnetron is recommended. The magnetron which is used in the movie is a low ripple one.

For the ignition of the plasma the high quality coaxial resonator is used while a stable and continuous operation is provided by the cylindrical resonator. To achieve the ignition of the plasma by the high quality coaxial resonator the resonance frequency of this resonator has to perfectly match the frequency of the microwave provided by the used magnetron. Since all magnetrons do not emit their microwave frequency at exactly the nominal frequency and since the frequency is dependent on the output power, the magnetron has to be measured with a spectrum analyzer. The resonance frequency of the coaxial resonator can be adjusted by moving the metallic nozzle up and down. This resonance frequency can be measured and thereby also adjusted to the sending frequency of the used magnetron with a network analyzer. To reach the high electrical field at the tip of the nozzle, required for the ignition of the plasma, a three stub tuner is needed in addition. This three stub tuner is a commonly used microwave component. The three stub tuner is mounted between the microwave plasma torch and the magnetron. After the resonance frequency of the coaxial resonator is adjusted, the forward power is maximized and the reflected power minimized by iteratively adjusting the stubs of the three stub tuner.

After having adjusted the resonance frequency of the coaxial resonator as well as having maximized the forward powers by means of the three stub tuner, the plasma of the microwave plasma torch can be ignited when the microwave plasma torch is connected to a magnetron. For the ignition of the plasma a minimum microwave power of about 0.3 to 1 kW is sufficient. The plasma ignites in the coaxial resonator. After the ignition of the plasma the resonance frequency of the coaxial resonator is shifted due to the dielectric permittivity of the plasma and the microwave can no longer penetrate into the coaxial resonator. Thus, the plasma switches from the coaxial mode into its much more extended cylindrical mode burning freely-standing above the metallic nozzle in the center of the cylindrical resonator. Since the quality of the cylindrical mode is very low and therefore exhibits a broad resonance curve, the microwave can still penetrate into the cylindrical resonator despite of the shift of the resonance frequency due to the dielectric permittivity of the plasma. Thus, a continuous and stable operation of the plasma in the cylindrical mode is provided by the microwave plasma torch. However, to reach a complete absorption of the supplied microwave power, the stubs of the three stub tuner have to be readjusted. Otherwise the supplied microwave power is not completely absorbed by the plasma but some percentage of the provided microwave is reflected and absorbed by the water load.

To examine the ignition of the plasma in the coaxial mode and then its transition into the extended cylindrical mode, the plasma ignition is observed by a high speed camera.

The presented movie will show how the frequency dependence of the magnetron is measured, the resonance frequency of the coaxial resonator is adjusted, how the forward power is maximized and how the plasma is ignited by the supplied microwave power. The high speed camera recording is shown as well.

Protocol

1. Measurement of the Magnetron

Note: The schematic of the experimental setup for measuring the magnetron is depicted in **Figure 1A**.

1. Connect the magnetron to an insulator consisting of a circulator and a water load with 10 screws.
2. Connect the insulator to a directional coupler with 10 screws.
3. Connect the directional coupler to a second water load with 10 screws.
4. Supply all water loads with water.
5. Calibrate the spectrum analyzer with its calibration function according to manufacturer's protocol.
6. Connect a 20 dB attenuator to the spectrum analyzer by plugging the 20 dB attenuator to the spectrum analyzer.
   Note: The 20 dB attenuator is used to protect the spectrum analyzer from too high powers above 1 W.
7. Connect the 20 dB attenuator equipped spectrum analyzer to the end of the coaxial cable equipped with a BNC connector by plugging the coaxial cable into the 20 dB attenuator.
8. Connect the end of the coaxial cable equipped with an N connector to the directional coupler by plugging the coaxial cable to the directional cable.
9. Switch on the magnetron via the power supply and the spectrum of the emitted microwave is displayed on the spectrum analyzer.
10. If necessary, adjust the displayed abscissa, ordinate and their resolution according to the manual of the spectrum analyzer.
11. To measure the frequency of the output microwave in dependence of the microwave power, increase the microwave power from 10% to the maximum of the output power in 5% to 10% steps and for every step determine the frequency of the maximal amplitude of the spectrum displayed by the spectrum analyzer.
    Note: Usually, the frequency spectrum of a magnetron below 10% of its maximum output power is very broad, exhibits many different peaks and therefore is not usable.

2. Adjustment of the Resonance Frequency

Note: The schematic of the experimental setup for measuring and adjusting the resonance frequency is depicted in **Figure 2A**.

1. Calibrate the network analyzer with the calibration kit for S11 operation (according to manufacturer's protocol).

2. Connect the coaxial cable via the N-connector to the coaxial part of a coaxial-to-rectangular-wave guide transition by plugging the coaxial cable to the coaxial-to-wave-guide-transition.
3. Connect the rectangular part of the coaxial-to-rectangular-wave guide transition to a three stub tuner with 10 screws.
4. Connect the three stub tuner to the microwave plasma torch assembly with 10 screws.
5. In the network analyzer menu switch to S11 operation.
6. In the network analyzer menu switch to VSWR mode or to log mode.
7. Iteratively adjust the resonance frequency of the microwave plasma torch assembly to the measured frequency of the magnetron at an output power of 25%– 60% of the maximum output power by moving the nozzle up and down. The resonance frequency of the microwave plasma torch assembly is given by the dip of the S11 parameter measurement as depicted in **Figure 2B**. Adjust this dip by moving the nozzle up and down to the recommended frequency.
8. When the resonance frequency is adjusted, lock the position of the nozzle with the locking nut.
9. Increase the forward microwave power iteratively by adjusting the three stubs of the three stub tuner by moving the stubs up and down. The microwave power absorbed by the microwave plasma torch assembly is given by the depth of the dip of the S11 parameter. Thus, maximize this dip by adjusting the stubs of the three stub tuner. Commonly, it is sufficient that two of the three stubs are used.

3. Ignition of the Plasma

1. Wear UV protection glasses since the plasma emits UV radiation. Operate the plasma torch under local gas ventilation since the plasma produces nitride oxides.
2. Connect the microwave plasma torch assembly with the adjusted coaxial resonator (nozzle is locked) and the adjusted three stub tuner to the magnetron equipped with an insulator consisting of a circulator connected to a water load.
3. Connect the gas supply to the microwave plasma torch.
4. Turn on the gas supply to 5 to 20 slm.
5. Since microwave radiation in higher doses is harmful especially for the eyes, check that there are no microwave leakages.
    1. To do so, turn on the microwave at a very low power of 10% to 12% and check all microwave connections with a microwave meter for leakages.
    2. If there are any leakages remove them completely before increasing the microwave power or operating the microwave plasma torch.
6. If there are no leakages turn on the microwave starting with low powers of 10% and increase the microwave power slowly within 10 to 60 sec until the plasma ignites in the quartz tube of the microwave plasma torch.
7. Carefully observe if and where the plasma ignites but be careful with possibly radiated microwaves. Preferably use a mirror for the observation of the plasma ignition.
8. If no plasma ignites, switch off the microwave power and carefully check if the microwave power is properly coupled into the coaxial resonator and not misguided to other components heating them up or even harming them. Check if some components are getting heated up.
    1. If any component gets heated up — *i.e.*, the microwave power is misguided — move all stubs of the three stub tuner out of the waveguide and adjust them to maximize the microwave coupling into the plasma torch assembly as described in step 2.9. Then start again with step 3.1.
    2. Adjust the resonance frequency of the coaxial resonator of the plasma torch to the sending frequency of the magnetron at a high enough microwave power output of 25% to 60% of the maximum output power with the network analyzer as described in step 2. To improve the ignition, adjust the resonance frequency of the coaxial resonator as described in step 2 to a higher output power. Then start again with step 3.1.
9. If the plasma ignites somewhere in the plasma torch and does not automatically switch to the coaxial or cylindrical mode, vary the supplied microwave power and gas flow until it burns in the cylindrical mode.
10. When the plasma burns in the cylindrical mode, iteratively adjust the stubs of the three stub tuner by moving them up and down so that all of the supplied microwave power is absorbed by the plasma and the reflected microwave power becomes zero.
    Note: If a microwave diode is connected to the water load and to the corresponding input of the control unit, the reflected microwave power is displayed at the control unit of the microwave power supply. How to do this is described in the manual of the microwave power supply.
11. When higher microwave powers of 1.5 kW or more and low gas flows of less than 15 slm are used, check carefully that the plasma does not touch the walls of the quartz tube. The quartz tube must not glow anywhere.
12. If the quartz tube glows red, decrease the microwave power or increase the gas flow until it vanishes completely.
13. Since microwaves can be radiated by the plasma due to the conductivity of the plasma, check with a microwave meter that the radiated microwave power is below the threshold.
14. If the radiated microwave power is above the threshold, shield the plasma with a metallic mesh where the mesh size is much smaller than half of the used microwave wave length.

4. High-speed Camera Movie of the Plasma Ignition

Note: Since the ignition of the plasma and its transition to the cylindrical mode is in the range of some hundred milliseconds, this process can best be investigated by means of a high speed camera. However, it is not necessary to observe the ignition process by means of a high speed camera each time the plasma is ignited.

1. Place the lens of the high speed camera in front of the microwave plasma torch looking through the diagnostic slit at the front of the plasma torch.
2. Adjust until the camera is pointing into the coaxial resonator at the tip of the metallic nozzle.
3. Focus the camera on the tip of the metallic nozzle.
4. Start the recording with 1,000 fps (frames per second) of the high speed camera.
5. Ignite the plasma as described in section 3.

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5. Stable and Continuous Plasma Operation

Note: When the plasma has been ignited in the cylindrical mode and the three stub tuner has been adjusted to maximize the absorption of the microwave power by the plasma a stable and continuous operation of the plasma torch is possible.

1. Adjust the dimension — the radial and axial extension — of the plasma to the desired dimension by varying the supplied microwave power between 10% and the maximum output power and the gas flow between 10 and 70 slm. Keep the radial dimension limited to the diameter of the quartz tube. The plasma must not touch the wall of the quartz tube which means that the quartz tube must not glow.
2. To shape the plasma to different shapes, use a short quartz tube which only confines the plasma inside of the cylindrical resonator and place one orifice on the top of the plasma torch assembly.
3. If necessary, fasten the orifices with some screws.

Representative Results

To provide a plasma ignition without any additional igniters as well as a stable and continuous plasma operation a high quality coaxial resonator with an adjustable resonance frequency was combined with a low quality cylindrical resonator to a microwave plasma torch. The schematic of this plasma torch is presented in **Figure 3**. The plasma is confined into a microwave-transparent tube, here a quartz tube. This tube can act as a reaction chamber for volume plasma processes or a plasma brush for surface treatments can be formed by an orifice. The microwave power is guided via a rectangular waveguide from the magnetron to the microwave plasma torch. Different kinds of gases can be supplied via either the tangential gas supply or axially through the metallic nozzle of the coaxial resonator. The microwave plasma torch is equipped with a frontal slit, so that the plasma inside the torch and the ignition can be investigated in detail.

To guarantee an ignition of the plasma solely by the supplied microwave power a high electrical field of about 3 to 6 MV/m is needed. To get a better understanding of the electrical field distribution, simulations of the electric field distribution as well as Eigenmode analysis with the commercially available simulation software COMSOL Multiphysics were conducted. Modeling and simulations of electrical field distributions of atmospheric pressure microwave plasma torches provided already detailed insights and led to further developments and improvements regarding for example their ignition or operation behavior [19–22].

The electrical field distribution of the coaxial mode as well as of the common cylindrical E_{010} mode is depicted in **Figure 4a** and **4b**, respectively. The electrical field is displayed in arbitrary units, since the electrical field in the coaxial resonator is many times higher compared to the electrical field in the cylindrical resonator. It can be seen that a high electrical field at the nozzle tip is reached with the coaxial resonator and the highest electrical field of the cylindrical resonator is in the center of the cylindrical resonator. The resonance frequency of the coaxial resonator can be varied by the position of the metallic nozzle. The simulation results for the resonance frequencies for different nozzle positions for a microwave plasma torch with a cylindrical resonator with a radius of 0.05 m and a height of 0.048 m are shown in the diagram in **Figure 4C**. It can be seen that the resonance frequency of the cylindrical mode is not affected by the position of the metallic nozzle. However, the resonance frequency of the coaxial mode is dependent on the nozzle position and decreases when the metallic nozzle is moved upwards into the cylindrical resonator.

To reach the required high electrical field in the coaxial resonator this resonance-frequency-adjustable coaxial resonator exhibits a high quality and a sharp and narrow resonance curve. However, a sharp and narrow resonance curve requires that the resonance frequency of the coaxial resonator matches perfectly the frequency of the supplied microwave. Since usually magnetrons do not emit the microwave at their nominal frequency and since the frequency of the microwave is dependent on the output power of the microwave, the frequency dependence of the magnetron has to be measured by means of a directional coupler and a spectrum analyzer. The experimental set-up to measure the frequency dependence of the magnetron with a spectrum analyzer is schematically given in **Figure 1a**. The measured frequency dependence of the utilized magnetron is shown in the diagram in **Figure 1B**. The center frequency was set to 2.45 GHz and the video bandwidth was 200 MHz. It can be seen that at a power of 200 W (10% of the maximum output power of the magnetron) the frequency of the microwave is at 2.44638 GHz and increases when the microwave power is increased. At the maximum output power of 2 kW the microwave frequency reaches a value of 2.45213 GHz.

The resonance frequency of the microwave plasma torch can be measured with a network analyzer and since the nozzle is movable the resonance frequency of the coaxial resonator can be adjusted. To do so, the microwave plasma torch assembly has to be connected to a network analyzer via a rectangular-to-coaxial waveguide transition as shown in the schematic in **Figure 2A**. By measuring the S11 parameter of the microwave plasma torch assembly the resonance frequency can be determined. The S11 parameter represents the ratio of the input power to the reflected power in dependence of the frequency. When a resonance is reached, an electrical field establishes in the resonator structure leading to a reduced reflected microwave power. However, the field strength inside the cavity is directly related to the fixed wave amplitude of the microwave provided by the network analyzer. A dip appears in the S11 spectrum which corresponds to the resonance frequency. A typical measurement of the S11 parameter is depicted in **Figure 2B**. Here a resonance is observed at a frequency of 2.846 GHz. By moving the metallic nozzle up and down, the resonance frequency of the coaxial resonator can be varied as the simulations depicted in **Figure 4C** showed. This dependence of the resonance frequency of the coaxial resonator on the metallic nozzle position can be measured by means of the S11 parameter. A measurement of the resonance frequency in dependence of the nozzle position and the appertaining simulation results are presented in the diagram in **Figure 2C**. This diagram shows that there is a good agreement between the simulation results and the measured values of the resonance frequency. The very small shift of the two curves can be explained by very small deviations of the geometry or dimension of the manufactured nozzle compared to the one used for the simulations. To adjust the resonance frequency of the coaxial resonator to the frequency of the supplied microwave, the metallic nozzle has to be iteratively moved up and down until the dip in the S11 parameter is located at the measured microwave frequency. Then the metallic nozzle has to be locked and the forward power can be maximized by iteratively adjusting the stubs of the three stub tuner so that the S11 parameter dip reaches its maximum depth. The high quality of the resonator and the maximized forward power lead to fewer microwave reflections and a high electrical field is established in the resonator which is why a deep dip in the S11 parameter results.

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After the microwave plasma torch assembly is mounted to the magnetron and the gas supply is connected, the plasma torch can be ignited and operated. The ignition of the plasma can be investigated best by observing the ignition with a high speed camera. The ignition of the plasma was recorded at 1,000 fps. The presented plasma ignition was conducted at a microwave power of 1 kW and a supplied gas flow of 15 slm air. Images of each phase of the ignition are summarized in **Figure 5**. The image in **Figure 5A** shows the view from above, looking down on the nozzle at an angle through the diagnostic slit at the front of the inoperational plasma torch. The bottom of the cylindrical resonator is in the front. In the mid plane you can see the beginning of the coaxial resonator. The tip of the nozzle can also be seen. The bottom of the cylindrical resonator is located in the background again. Since the focus is on the nozzle tip, the bottom of the cylindrical resonator is somewhat blurry. The other images show the phases of the plasma ignition. When the microwave power is turned on at t = 0 msec, the plasma ignites somewhere in the coaxial resonator as can be seen in **Figure 5B**. Then, during 64 msec, the plasma winds up the metallic nozzle to its tip and then burns straight at the nozzle tip in the coaxial mode as the **Figure 5C** to **5E** show. The intensity of the plasma grows for the following 692 msec as it is shown in **Figure 5F**. Then, due to the shift of the resonance frequency caused by the burning plasma in the coaxial resonator 1 msec later, the plasma starts to break away from the nozzle tip as shown in **Figure 5G** and **5H**. The complete break away of the plasma from the nozzle tip is reached after 58 msec as depicted in **Figure 5I**. The plasma is now burning freely above the metallic nozzle in the cylindrical mode. During the last second, the three stub tuner is readjusted to maximize the forward microwave power. This leads to an increase of the plasma as the image in **Figure 5J** shows. However, the plasma is still burning freely above the nozzle tip with no contact to it. Due to the low quality of the cylindrical resonator the plasma can be operated continuously and stably in this cylindrical resonator mode.

The dimension of the plasma depends on the supplied microwave power and the gas flow. Photos of the plasma for microwave powers of 1 and 2 kW and gas flows of 10, 30 and 70 slm are presented in **Figure 6**. The resonator with its diagnostic slit at its front is located in the lower part of the photos. The plasma is confined into a quartz tube within and above the cylindrical resonator. UV light couples into the quartz tube which is why the quartz tube exhibits a bluish glowing. It can be seen that the dimensions — radial and also the axial extension — of the plasma increase with an increase of the supplied microwave power while an increase of the gas flow leads to a smaller plasma flame. However, measurements of the gas and electron temperature show the maximum temperatures of T_g = 3,600 K and electron temperature T_e = 5,800 K are independent of the outer parameters, supplied microwave power and gas flows, as well as of the plasma volume [19]. The temperatures were obtained by means of optical emission spectroscopy. The $A^2\Sigma^+$ - $X^2\Pi_\gamma$-transition of the free OH radical was used for the determination of the gas temperature while a Boltzmann-plot of atomic oxygen lines was conducted for the estimate of the electron temperature. A detailed description on how the temperatures have been measured and the complete temperature distributions can be found in References 23 and 24.

To treat surfaces in the afterglow of the plasma, the plasma can be shaped with different kinds of orifices. **Figure 7** depicts photos of differently shaped plasmas. The layout is similar to the photos of the plasma confined to a long quartz tube: the cylindrical resonator is at the bottom of the image; its diagnostic slit illuminated by the plasma. Differently shaped plasmas can be seen burning above the top-opening. On the photo in **Figure 7A** the confining quartz tube does not extend outside of the resonator. The plasma can burn freely above the resonator. An extended plasma brush can be formed with as slit orifice as depicted in **Figure 7B**. A plasma needle can be achieved by using an orifice with a hole in its center. This is shown in **Figure 7C**. Very small and smooth afterglow plasmas are formed by orifices which have a narrow slit or some small holes arranged in a circle as the photos in **Figure 7D** and **7E** show.

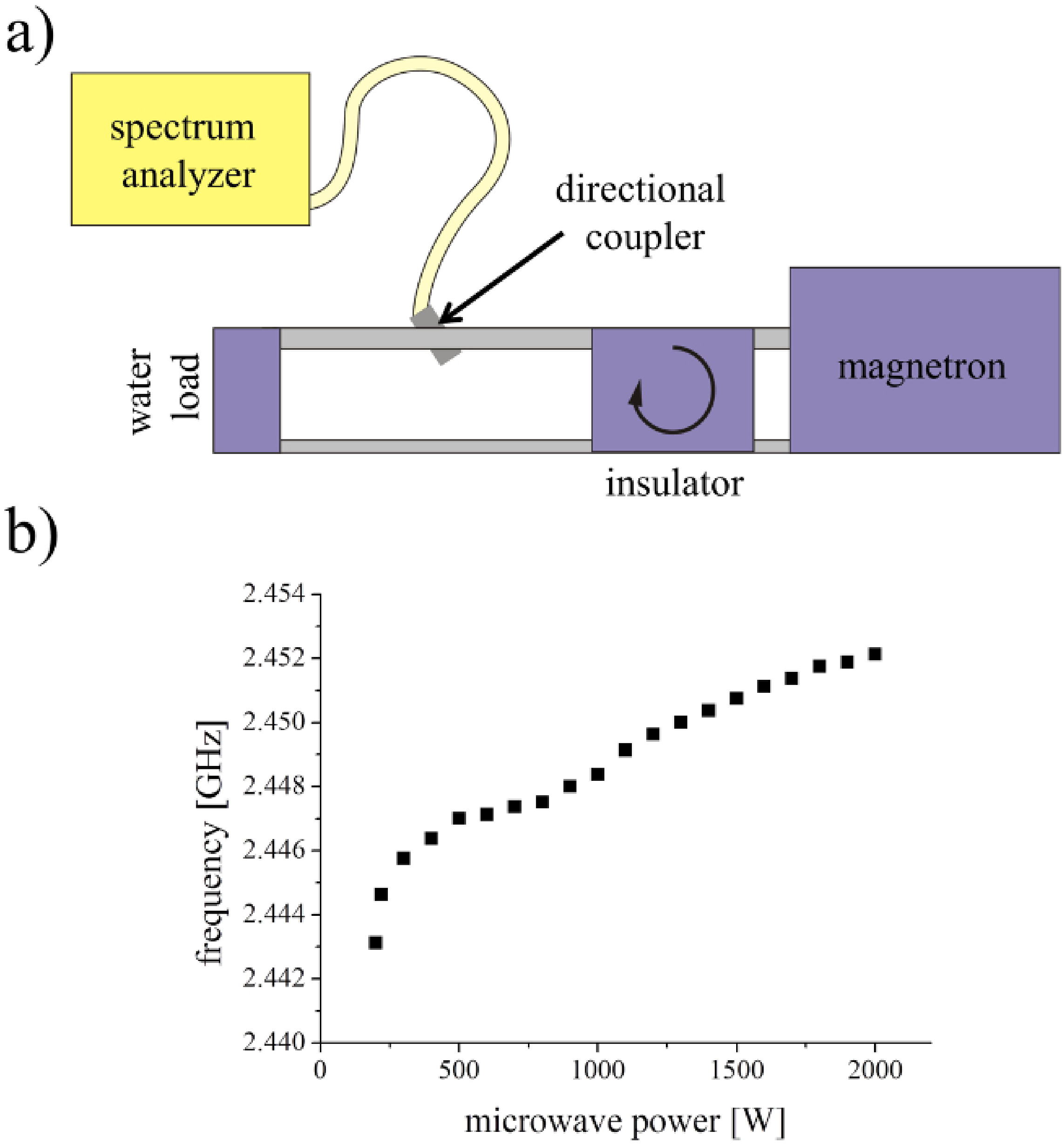

Figure 1. Measurement of the magnetron. The schematic in (**A**) shows how the frequency dependence of a magnetron of the microwave output power can be measured by means of a spectrum analyzer. The frequency dependence of the used magnetron of the output power is depicted in (**B**). Please click here to view a larger version of this figure.

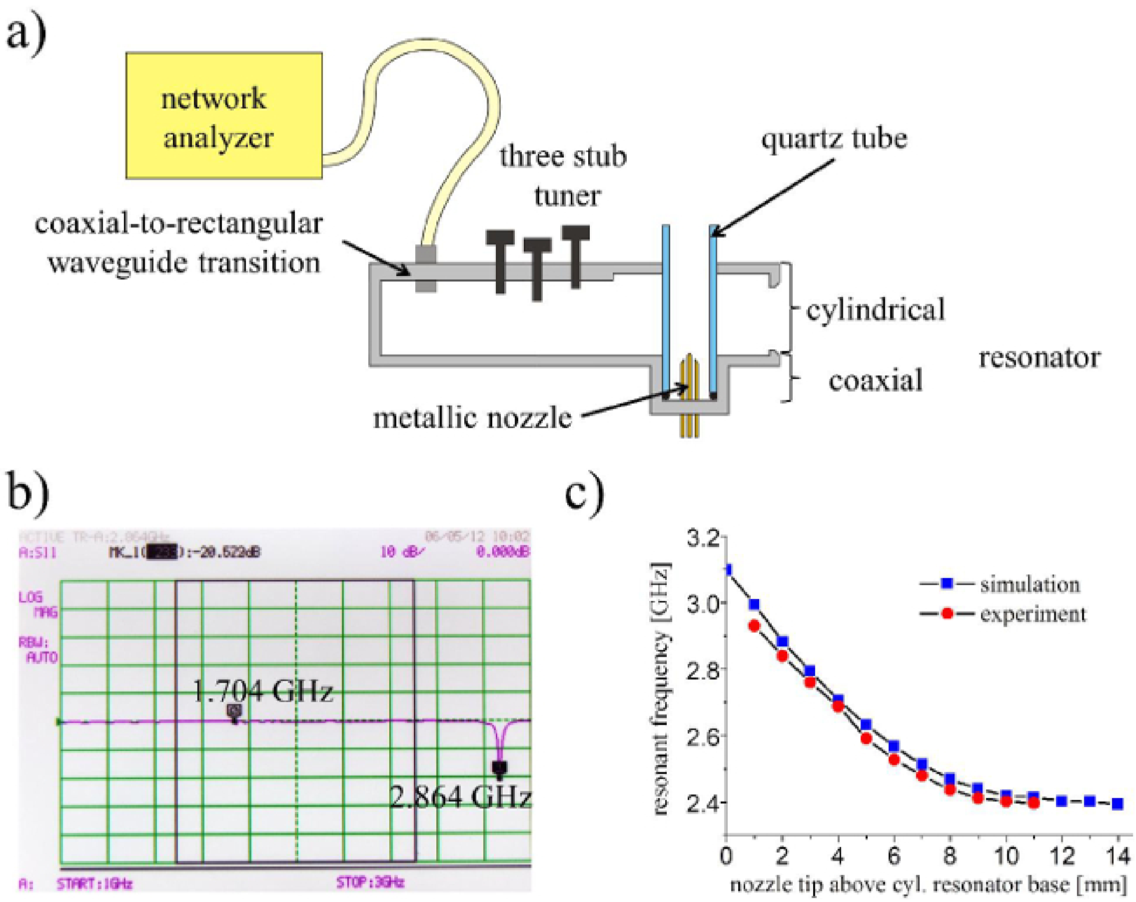

Figure 2. Measurement of the resonance frequency. The setup for the measurement and adjustment of the resonance frequency of the microwave plasma torch by means of a network analyzer is given in (**A**). (**B**) shows a typical measurement of the S11 parameter. The dip in the S11 parameter reflects the resonance frequency of the microwave plasma torch. The measured dependence of the resonance frequency on the metallic nozzle position and the results of the numerical simulations are summarized in **c**). Please click here to view a larger version of this figure.

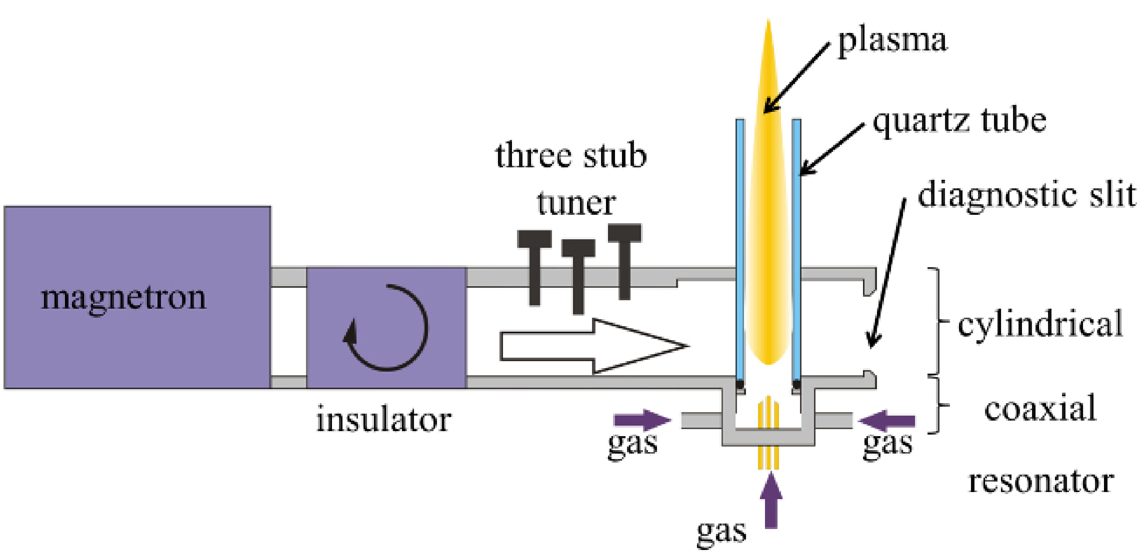

Figure 3. Plasma torch setup. Schematic of the setup of the atmospheric microwave plasma torch. Please click here to view a larger version of this figure.

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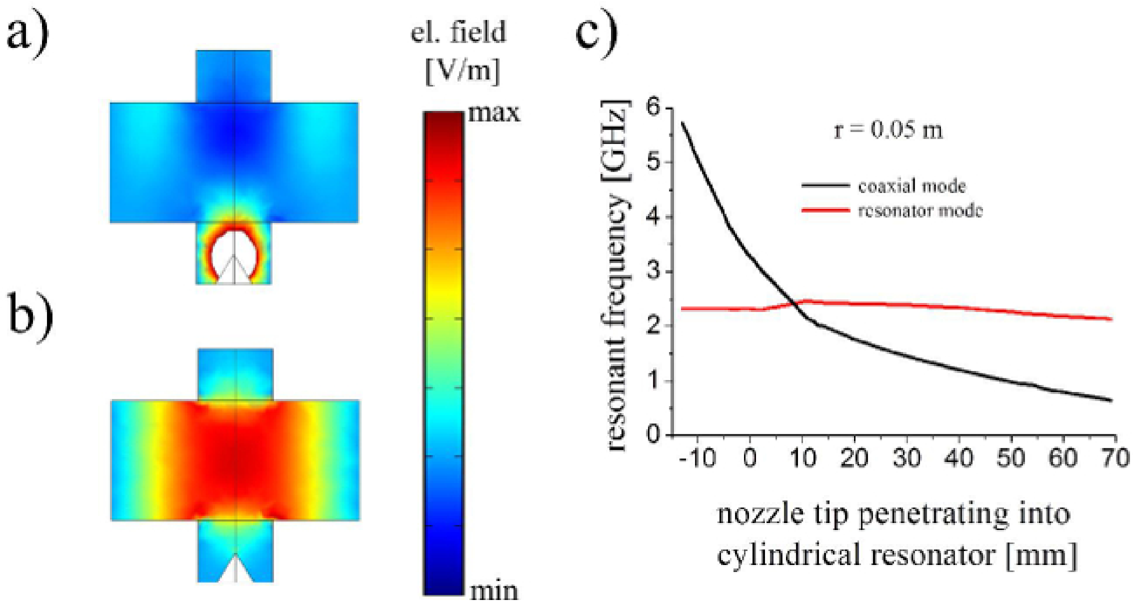

Figure 4. Coaxial and cylindrical mode. The distribution of the electrical field strength is depicted in (**A**) and (**B**). (**A**) shows the distribution for the coaxial mode while (**B**) shows the one for the cylindrical mode. The diagram in (**C**) shows the dependence of the resonance frequency of both the coaxial and the cylindrical mode on the position of the metallic nozzle in the plasma torch. The resonator has a diameter of 0.05 m and a height of 0.0482 m. Please click here to view a larger version of this figure.

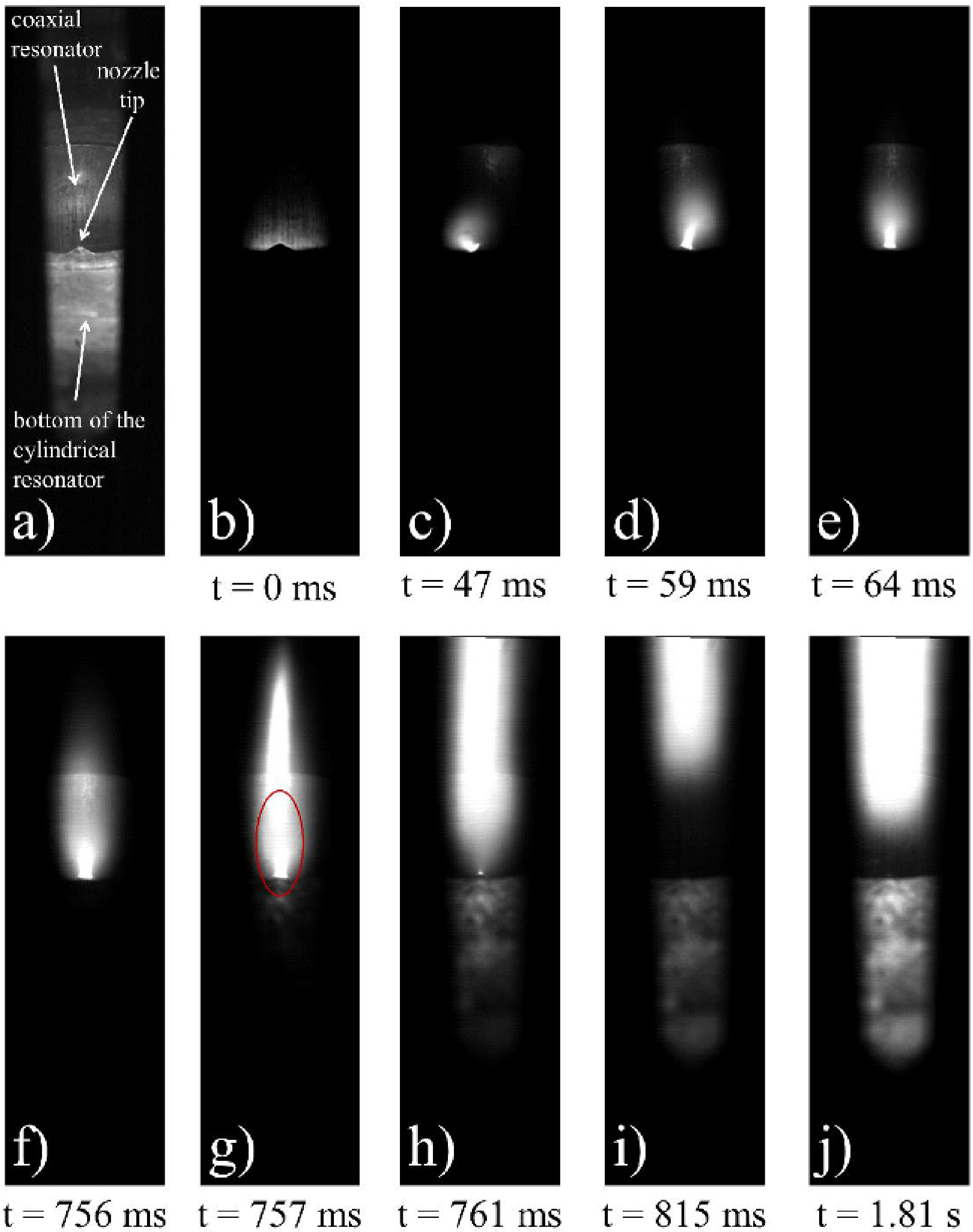

Figure 5. Ignition of the plasma. Images of each phase of the ignition of the plasma recorded by a high speed camera at 1,000 fps and at a microwave power of 1 kW and a gas flow of 15 slm air. (**A**) View from above, looking down on the nozzle at an angle through the diagnostic slit at the front of the inoperational plasma torch. (**B**) Ignition of the plasma in the coaxial resonator. (**C**) – (**E**) Winding up of the plasma to the tip of the metallic nozzle until it burns in the coaxial mode. (**F**) The plasma increases. (**G**) – (**I**) The plasma breaks away from the metallic nozzle and burns freely above the nozzle tip in the cylindrical mode. (**J**) The plasma increases due to the readjustment of the three stub tuner to maximize the forward power. Please click here to view a larger version of this figure.

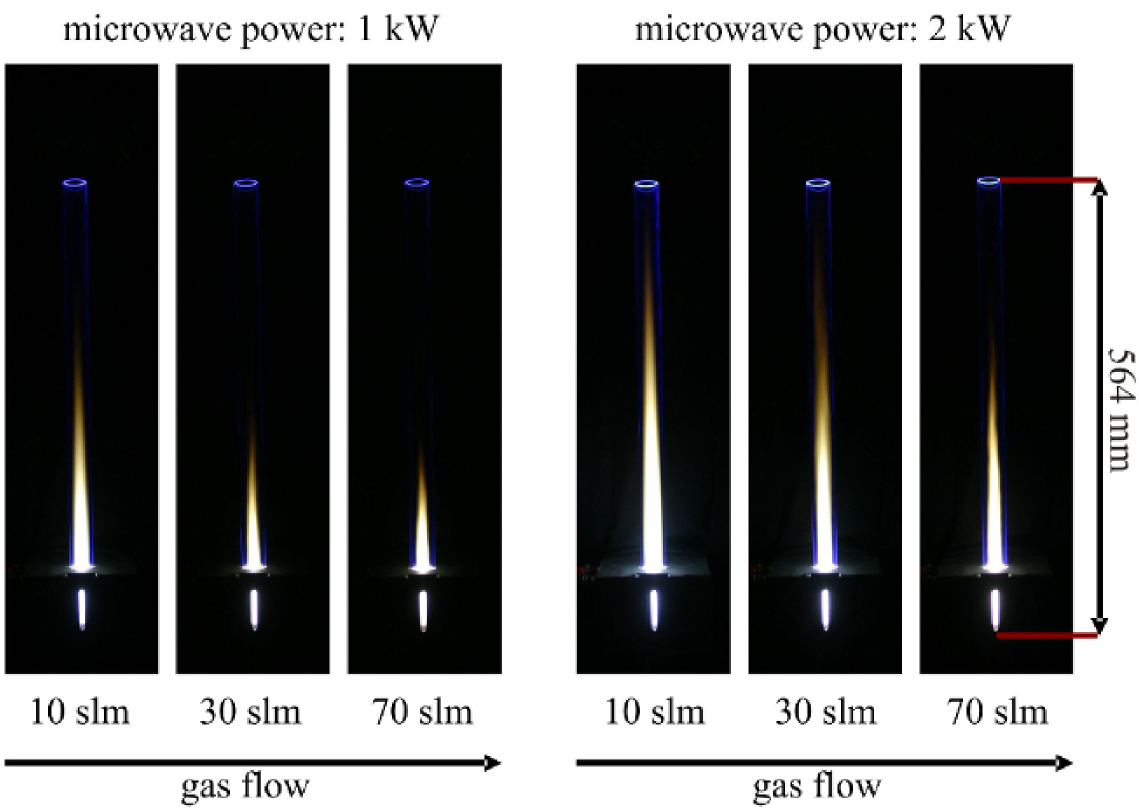

Figure 6. Photos of an air plasma for different supplied gas flows of 10, 30 and 70 slm and microwave powers of 1 and 2 kW. The extent of the plasma depends on the supplied microwave power and gas flow and it increases with an increase of the microwave power and a decrease of the gas flow. Please click here to view a larger version of this figure.

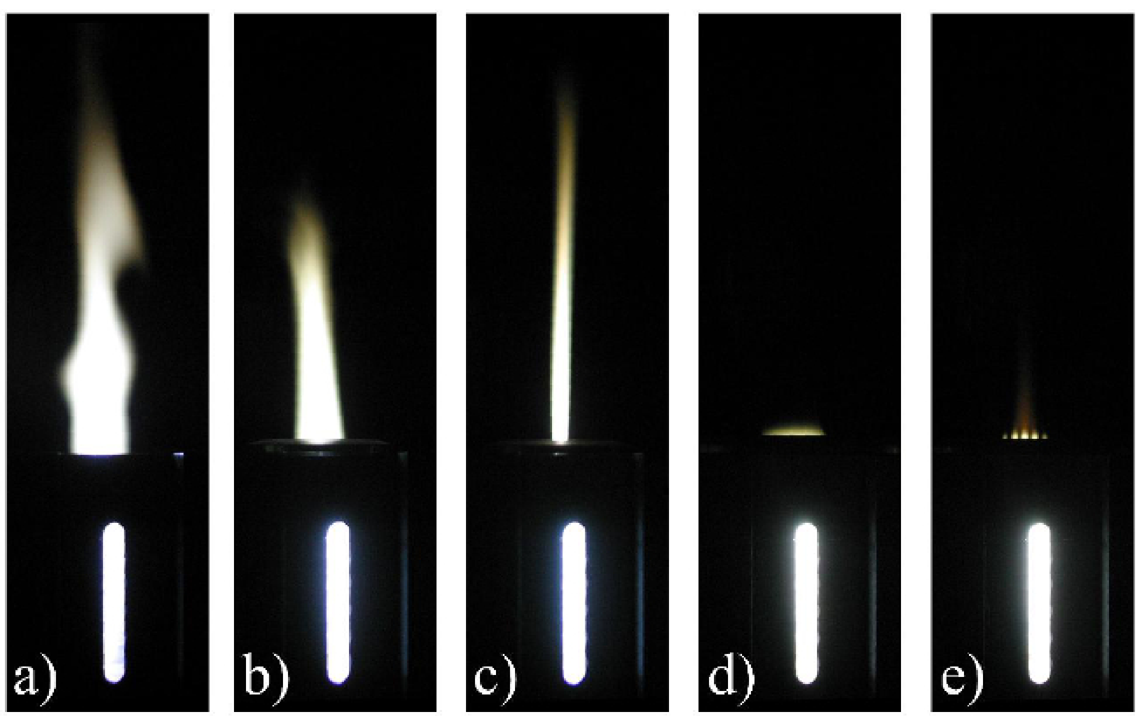

Figure 7. Different orifices. By using differently shaped orifices the plasma can be formed. (**A**) The confining quartz tube does not extend outside of the resonator and the plasma can burn freely above the resonator. (**B**) The plasma is shaped into a brush with a slit orifice. (**C**) A plasma needle is formed by a hole orifice. (**D**) A very smooth plasma brush can be achieved by using an orifice with a narrow slit and (**E**) a smooth plasma area is formed by an orifice with some small holes arranged in a circle. Please click here to view a larger version of this figure.

Discussion

The presented movie explains how an ignition of an atmospheric pressure microwave plasma without any additional igniters can be realized, the basic principles of this microwave plasma torch, its adjustment, the ignition process of the plasma and its stable and continuous operation. As described in the introduction, there are already different kinds of microwave plasma torches but none of those provide an ignition of the plasma without any additional igniters as well as stable and continuous plasma operation.

To obtain an ignition of the plasma without any additional igniters at atmospheric pressure a high electrical field is necessary and therefore a resonator with a high quality while for a continuous and stable plasma operation a low quality is needed. This can be realized by combining a high quality coaxial resonator which guarantees the ignition of the plasma and a low quality cylindrical resonator which provides a continuous and stable plasma operation.

The frequency of the supplied microwave has to perfectly match the resonance frequency of the high quality coaxial resonator so that the provided power is coupled into the resonance chamber. Therefore the frequency dependence of the magnetron has to be well known and the resonance frequency of the coaxial resonator has to be adjustable. The sending frequency of the magnetron can be measured with a spectrum analyzer while the resonant frequency of the coaxial resonator can be measured by means of a network analyzer and adjusted by the movable nozzle.

To guarantee the ignition of the plasma solely by the supplied microwave, it is crucial that the resonance frequency of the coaxial resonator perfectly matches the sending frequency of the magnetron. Furthermore, the microwave has to be coupled completely into the coaxial resonator of the plasma torch assembly which is achieved by maximizing the forward power with the three stub tuner. If these critical steps are not conducted carefully it is possible that the plasma will not ignite or that the microwave is coupled into the experimental setup somewhere what could lead to some damage of these parts. Thus if no ignition of the plasma is observed, these steps have to be checked carefully again. Furthermore, it is possible that the plasma ignites but does not switch to the coaxial or cylindrical mode by itself. In this case the plasma can commonly be switched first to the coaxial mode and then to the cylindrical mode by varying the gas flow and the supplied microwave power.

To obtain a more automatic ignition and operation of the plasma an automatic three stub tuner which automatically adjusts its stubs to maximized forward power can be used instead of the manual one. Thus the adjustment of the stubs for ignition of the plasma and afterwards the adjustment for the operation of the plasma are automatically conducted by this three stub tuner. To achieve plasma ignition without any additional igniters and stable and continuous plasma operation the presented smart combination of the two resonator structures and the presented technique of the measurement of the magnetron by a spectrum analyzer and the measurement and adjustment of the resonant frequency by means of a network analyzer are crucial.

The ignition of the plasma was investigated in detail with a high speed camera. It revealed that the plasma ignites in the coaxial resonator, winds up to the tip of the nozzle burning in the coaxial mode, increases in intensity and volume, breaks away from the metallic nozzle, increases further and then burns freely above the metallic nozzle in the cylindrical mode. After the ignition of the plasma and its transition to the cylindrical mode the plasma can be operated stably and continuously. The dimension of the plasma depends on the supplied microwave power and gas flow and increases when the supplied microwave power is increased or the gas flow is decreased. Furthermore, the plasma can be shaped to needles, brushes or smooth afterglow plasmas by using orifices.

The gas flow and the microwave power of the presented microwave plasma torch are limited to about 100 slm and some kilowatts which also limits the volume of the plasma. Since the quartz tube must not be damaged the radial diameter of the plasma is limited to the inner diameter of the quartz tube. If a larger plasma volume is required or large gas flows have to be treated, the plasma source can be up-scaled by using a lower microwave frequency, for example 915 MHz instead of 2.45 GHz. With 915 MHz more microwave power is available, leading to larger plasma volumes which allow larger gas flows to be handled. However, when higher powers are used, the risk of damage, especially of the metallic nozzle, during the ignition of the plasma or during operation increases and therefore another ignition mechanism has to be considered. Furthermore, the plasma parameters, like electron and gas temperature, are independent of the outer parameters like gas flow and supplied microwave power. Thus, if an atmospheric pressure plasma with different plasma parameters is needed, a different source has to be used or one which meets the required needs has to be newly developed.

Since the presented atmospheric pressure microwave plasma torch provides ignition of the plasma without any additional igniters as well as stable and continuous plasma operation, the plasma source is suitable for many industrial applications. The advantage of the ignition of the plasma without any additional igniters for industrial processes, especially when an automatic three stub tuner is used, is that only the microwave has to be switched on and the process starts to run reliably and automatically. Furthermore, if a discontinuous operation is needed where the process is running for some time followed by intermittency, the plasma process can be restarted quickly, reliable and automatically and there is no attrition of an additional ignition system. Volume processes like chemical synthesis as well as surface treatments with the afterglow plasma can be named as applications of the microwave plasma torch. Studies on the successful degradation of harmful waste gases, especially for greenhouse gases like perfluorinated compounds which are used in the growing semiconductor industry, on the dissociation of CO_2 to CO and O as well as on the pyrolysis of methane to hydrogen and carbon have already been conducted. Furthermore, the afterglow plasmas were used for the treatment of surfaces to increase the adhesion of glue and paint and for decontamination and sterilization purposes. For example, the plasma source can be used for the decontamination of the surface of cork stoppers to degrade trichloroanisole, which causes the so called cork taint. Another application is the reduction of germs on surfaces, like on packaging materials or on food.

The presented technique how the sending frequency of a high frequency power supply is measured by means of a spectrum analyzer and how the resonant frequency of a resonant structure is measured and adjusted by means of a network analyzer can also be applied to other high frequency plasma sources. As an example a tiny little micro microwave plasma jet which is based on a λ/4-resonator can be named [25–27].

Lastly, the presented movie will lead to further developments and improvements of atmospheric pressure and/or microwave plasma sources.

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Disclosures

The authors have nothing to disclose.

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References

1. Hong, Y. C., *et al.* Microwave plasma torch abatement of NF3 and SF6. *Phys. Plasma.* **13**, 033508 (2006).
2. Kabouzi, Y., *et al.* Abatement of perfluorinated compounds using microwave plasmas at atmospheric pressure. *J. Appl. Phys.* **93**, (12), 9483-9496 (2003).
3. Kabouzi, Y., Moisan, M. Pulsed Microwave Discharges Sustained at Atmospheric Pressure: Study of Contraction and Filamentation Phenomena. *IEEE Transaction on Plasma Science.* **33**, 292-293 (2005).
4. Hong, Y. C., Uhm, H. S. Abatement of CF4 by atmospheric-pressure microwave torch. *Phys. Plasma.* **10**, (8), 3410-3414 (2003).
5. Leins, M., *et al.* Development and Characterisation of a Microwave-heated Atmospheric Plasma Torch. *Plasma Process. Polym.* **6**, 227-232 (2009).
6. Alberts, L., Kaiser, M., Leins, M., Reiser, M. über die Möglichkeit des Abbaus von C-haltigen Abgasen mit atmosphärischen Mikrowellen-Plasmen. *Proc. UMTK, VDI-Berichte 2040 P3.* 217-221 (2008).
7. Leins, M., *et al.* Entwicklung und Charakterisierung einer Mikrowellen-Plasmaquelle bei Atmosphärendruck für den Abbau von VOC-haltigen Abgasen. *Proc. UMTK, VDI-Berichte 2040 P3.* (2008).
8. Fridman, A. *Plasma Chemistry.* Cambridge University Press New York (2008).
9. Azizov, R. I., *et al.* The nonequilibrium plasma chemical process of decomposition of CO2 in a supersonic SHF discharge. *Sov. Phys. Dokl.* **28**, 567-569 (1983).
10. Moisan, M., Zakrzewski, Z., Pantel, R., Leprince, P. A. Waveguide-Based Launcher to Sustain Long Plasma Columns Through the Propagation of an Electromagnetic Surface Wave. *IEEE Transaction on Plasma Science.* **3**, 203-214 (1984).
11. Moisan, M., Pelletier, J. *Microwave Excited Plasmas.* Elsevier New York (1992).
12. Moisan, M., Sauvé, G., Zakrzewski, Z., Hubert, J. An atmospheric pressure waveguide fed microwave plasma torch: the TIA design. *Plasma. Sources Sci. Technol.* **3**, 584-592 (1994).
13. Jin, Q., Zhu, C., Borer, M. W., Hieftje, G. M. A microwave plasma torch assembly for atomic emission spectrometry. *Spectorchim. Acta Part B.* **46**, 417-430 (1991).
14. Baeva, M., Pott, A., Uhlenbusch, J. Modelling of NOx removal by a pulsed microwave discharge. *Plasma Sources Sci. Technol.* **11**, 135-141 (2002).
15. Korzec, D., Werner, F., Winter, R., Engemann, J. Scaling of microwave slot antenna (SLAN): a concept for efficient plasma generation. *Plasma Sources Sci. Technol.* **5**, 216-234 (1996).
16. Tendero, C., Tixier, C., Tristant, P., Desmaison, J., Leprince, P. h Atmospheric pressure plasmas: A review. *Spectorchimica Acta Part B.* **61**, 2-30 (2006).
17. Ehlbeck, J., Ohl, A., Maaß, M., Krohmann, U., Neumann, T. Moving atmospheric microwave plasma for surface and volume treatment. *Surface and Coatings Technology.* **174-175**, 493-497 (2003).
18. Pipa, A. V., Andrasch, M., Rackow, K., Ehlbeck, J., Weltmann, K. -D. Observation of microwave volume plasma ignition in ambient air. *Plasma Sources Sci. Technol.* **21**, (3), 035009 (2012).
19. Baeva, M., *et al.* Puls microwave discharge at atmospheric pressure for NOx decomposition. *Plasma Sources Sci. Technol.* **11**, 1-9 (2002).
20. Pott, J. *Experimentelle und theoretische Untersuchung gepulster Mikrowellenplasmen zur Abgasreinigung in Gemischen aus Stickstoff, Sauerstoff und Stickstoffmonoxid.* Düsseldorf (2002).
21. Rackow, K., *et al.* Microwave-based characterization of an athmospheric pressure microwave-driven plasma source for surface treatment. *Plasma Sources Sci. Technol.* **20**, 1-9 (2011).
22. Nowakowska, H., Jasinski, M., Mizeraczyk, J. Electromagnetic field distributions waveguide-based axial-type microwave plasma source. *Eur. Phys. J. D.* 1-8 (2009).
23. Leins, M., Walker, M., Schulz, A., Schumacher, U., Stroth, U. Spectroscopic Investigation of a Microwave-Generated Atmospheric Pressure Plasma Torch. *Contrib. Plasma Phys.* **52**, (7), 615-628 (1002).
24. Leins, M. *Development and Spectroscopic Investigation of a Microwave Plasma Source for the Decomposition of Waste Gases.* Stuttgart (2010).
25. Langbein, C. *Entwicklung und Optimierung eines mikrowellenbasierten Atmosphärendruck-Mikroplasmas für lokale Oberflächenbehandlungen.* Stuttgart (2008).
26. Kamm, C. *Spektroskopische Untersuchung eines Mikrowellen-Mikroplasma-Brenners.* Stuttgart (2011).
27. Weinrauch, I. *Spektroskopische Charakterisierung eines Mikrowellen-Mikroplasmabrenners für die lokale Oberflächenbehandlung.* Stuttgart (2012).

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