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High voltage breakdown in an inductively coupled ion source

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Abstract
An inductively coupled plasma source, designed for ion beam applications, is allowed to float up to several kilovolt positive. If one side of the radio frequency (rf) antenna is grounded and the dielectric source tube and the surrounding air are allowed to reach a threshold temperature corona breakdown at the rf antenna occurs. The experiments presented here show that a dc corona can be ignited with the presence of a dielectric barrier, which normally precludes dc breakdown. The formation of a negative barrier corona initiates a transition to a continuous arc from the rf antenna to the source tube. It is suggested that the onset of the first filaments heat the dielectric locally, such that the dielectric strength drops. DC current channels are then formed in the source tube, allowing a resistive corona with continuous arcs to exist.

1. Introduction

Radio frequency (rf) coupled plasmas such as inductively coupled plasmas (ICP) and helicon plasmas have been used for many years in ion acceleration applications, such as providing thrust in electric propulsion systems [1] or for deposition, etching and surface modifications in the microelectronic industry etc [2]. In recent years extensive research has been performed in developing these sources for the generation of focused ion beams [3–7].

Bright and narrow ion beams can be extracted and accelerated from the plasma by a set of biased grids, commonly referred to as the ion optics. In some cases the extraction method involves applying an anodic bias voltage to the entire discharge so that the plasma floats up to a potential of typically 10–30 kV positive, in order to accelerate ions to a kinetic energy of 10–30 keV as they reach a grounded surface [4, 5, 8]. An rf antenna powered by rf in the megahertz range needs a matching network to allow efficient transfer of power from the 50 Ω generator to the plasma; in a simple and quite common case this involves a pi-matching system where one side of the antenna is grounded via the generator. A large electric field will therefore exist between the plasma sitting at the anodic voltage and the grounded rf antenna. Normally, this large field should not be a problem as the capacitive nature and the dielectric strength of the source walls precludes dc breakdown. However, in this paper we present experiments showing a breakdown phenomenon in an ICP source that is floated up to a dc voltage of only 2–10 kV. As this phenomenon is typically 'just a problem' that can be easily fixed, by floating the antenna to the anode/plasma potential, these type of breakdowns are not commonly studied, but investigating this phenomenon might give new insight into corona and barrier breakdown in atmospheric air.

The corona discharge is a low-current discharge caused by partial or local breakdown of a gas gap with a strongly inhomogeneous dc electric field. These breakdowns have been studied intensively for several decades and are reasonably well understood [9–11]. The most common electrode configuration, where such corona discharges are studied, have one electrode much smaller than the other with a small curvature allowing field enhancement at the smaller electrode, i.e. pin-to-plane or wire-to-plane electrode configurations etc. The polarity of the high voltage stressed electrode (the pin electrode) relative to the larger one determines how the ionization processes are sustained and named positive corona if biased positive and negative corona if biased negative. The voltage required for the onset of a corona at a wire, cylinder or a sphere is found to be a function of the voltage polarity, gas temperature and pressure and is given by an empirical relation known as Peek's law [12, 13],

$$E_c = 30\delta\left(1 + \frac{0.3}{\sqrt{\delta r}}\right), \tag{1}$$

where E_c is the breakdown electric field at the pin electrode given in kilovolts per centimetre δ is the relative air density and r is the wire radius. Peek's law has later been verified analytically by several authors [13, 14].

It was found in the early 1940s that the breakdown between electrodes in a long air gap proceeds much faster than can be explained by the Townsend breakdown, which is based on the electron avalanche theory where the discharge is sustained by ions or photons creating secondary electron emission at the cathode [15]. The concept of a streamer breakdown was therefore established [16, 17], which is a much faster propagating process. The space charge fields in the electrode gap becomes of the order of the breakdown field such that a thin plasma channel (the streamer) can propagate through the gas by ionizing the gas in front of its charged head. The streamer velocity is about 10^8 cm s^{-1} and exceeds by a factor of 10 the typical electron drift velocity in an avalanche [15]. It is now recognized that the onset of a negative corona is determined by the Townsend breakdown criterion while the positive corona is determined by the streamer breakdown criterion [14].

Corona discharges at both polarities sometimes operate in the form of self-organized periodic current pulses even under constant voltage conditions. The frequency of these pulses is typically around 10 kHz in the case of positive coronas and around 1 MHz for negative coronas. These pulses are explained by the formation of slow moving positive space charges in the electrode gap, shielding the external electric field so that the streamer or electron avalanche is suppressed, which typically occurs in the intermediate voltage range just above the breakdown requirement [15, 18, 19]. Negative coronas present in electronegative gases also exhibit pulses attributed to the formation of both positive and negative space charge fields in the air gap between the electrodes and are called Trichel pulses [9, 20]. The time required for the establishment of the regular sequence of these trichel pulses is determined by the transit time of the negative ions, formed close to the cathode by electron attachment, propagating to the anode. The frequency is typically in the range 10–100 kHz with a peak current of 1–10 mA [21, 22].

The presence of a dielectric barrier in front of one or both electrodes normally precludes a dc discharge as it acts as a barrier for the conduction current and is used in many applications in order to avoid catastrophic breakdown. The barrier effect on the onset voltage has been reported on in many meetings, but the physics involved in point/wire-to-plane electrode geometries where the plane is covered by the dielectric is still poorly understood considering dc voltage breakdown [23, 24]. Comparisons between the dc corona (without barrier dielectrics) and barrier coronas and barrier discharges operated at ac frequencies (where the larger anode is covered by the dielectric) have been performed by many groups [24–28]. It is well accepted that the presence of a dielectric barrier on the plane electrode significantly changes the electrical characteristics and spatial structure of the corona, whereas the main phases of the discharge evolution remain unchanged as the voltage increases. It was found that the onset voltage in barrier coronas is lower than for the normal dc corona and they can pass larger currents without transforming into the spark region [24]. It was also found that for short electrode separation gaps, the charging of the dielectric plays a significant role in the time separation between each trichel pulse and could increase by a factor of 10 (from 10 to 100 μs) depending on the dielectric size and thickness [25].

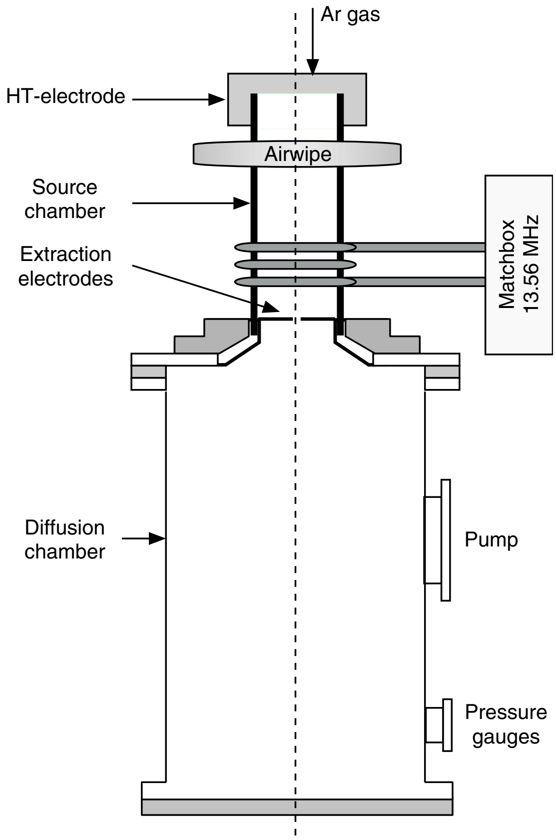

Figure 1. Sketch of the experimental set-up.

In this paper a breakdown phenomenon appearing between a grounded rf antenna and a positively biased plasma column is investigated, which is similar to having a negative corona configuration with a negatively biased wire and a positive plane electrode covered by a dielectric. The influence of the dielectric temperature, charging/discharging of the glass, airflow perpendicular to the discharge axis and the response of the dc voltage supply is determined.

2. Experimental set-up

The experimental set-up is shown in figure 1 and consists of a 2.5 cm diameter, 10 cm long glass source tube with 3 mm thick walls, attached to a 15 cm diameter, 30 cm long stainless steel diffusion chamber. A single floating electrode with a 1 mm diameter central aperture is placed at the bottom of the source separating the source and the diffusion chamber. The argon feed gas enters at the top of the source, and a turbomolecular/rotary pumping system is connected to the sidewall of the diffusion chamber. The operating pressure, regulated by a needle valve, is typically 20 mTorr in the source and 0.2 mTorr in the diffusion chamber.

The plasma is generated by a three loop antenna fed by rf power of 13.56 MHz via a pi-matching network, allowing one side of the antenna to be grounded via the rf generator. The antenna is made of 3 mm diameter copper tubing, with each loop having an inner diameter of 30 mm leaving an air gap of 2.5 mm between the glass wall and the antenna. Effective cooling of the source and rf antenna is achieved by forcing air through a distributor (Airwipe) that surrounds the source tube. This system is fed by compressed air and provides a uniform 360° airflow along the tube.

A Spellmann 0–20 kV high voltage dc power supply is connected to an electrode placed at the top of the source tube. As the lower electrode, between the source and the diffusion chamber, is floating (see figure 1) the plasma is allowed to float up to the applied dc voltage. Under certain conditions atmospheric breakdown appears between the copper tubing and the plasma, and the diagnostic used to characterize the breakdown are as follows. The dc voltage applied to the top electrode is measured by a high voltage Tektronix probe (1:1000) connected to a 100 MHz HP oscilloscope, and the data is transfered to the computer via a GPIB bus using LabView. The bandwidth and rise time of the probe are 75 MHz and 4 ns, respectively.

Optical emission lines between 300 to 900 nm are measured by a monochromator (SPEX 500X) connected to a fibre optic bundle positioned a few centimetres from the source tube near the rf antenna. The emission intensity is measured by a fast time response photomultiplier tube (Hamamatsu) connected to the 100 MHz oscilloscope.

The dc current is monitored from the built-in analog ammeter on the Spellmann dc voltage supply. The source tube temperature is measured continuously with an infrared gun, calibrated by a thermocoupler.

3. Experimental results

3.1. Breakdown evolution as a function of time

Figure 2 shows simultaneous measurements of the dc voltage (*a*) and the emission intensity (*b*) from a 507.3 nm line (corresponding to NII excitation) as a function of time through a typical breakdown event. The applied dc voltage is 6 kV, the rf power is 150 W, the initial tube temperature is 21 °C (room temperature) and the Airwipe cooling system is turned off during the operation.

For the first 20 s after the plasma is ignited and the dc voltage is switched on, no visible or auditory indications of breakdown are observed. The average dc voltage is 6 kV with ±0.7 kV fluctuations (12%) and the emission intensity of the 507.3 line is at the background level of 0.1 V. The dc current read from the Spellmann voltage supply is about 0.2 mA, and the temperature increases from 21 °C to 50 °C. We will see in the following experiments that the large fluctuations in the dc voltage before breakdown is due to poor dc grounding of the HV-probe.

After 20 s a pre-breakdown stage is reached where 'gentle' hissing is heard in the neighbourhood of the rf antenna, and the dc current (from the voltage supply) shows small oscillations of 0.2 ± 0.1 mA. However, no changes are measured in the dc voltage and emission line intensity. This stage lasts for about 30–35 s and the temperature increases linearly from 50 to about 130 °C.

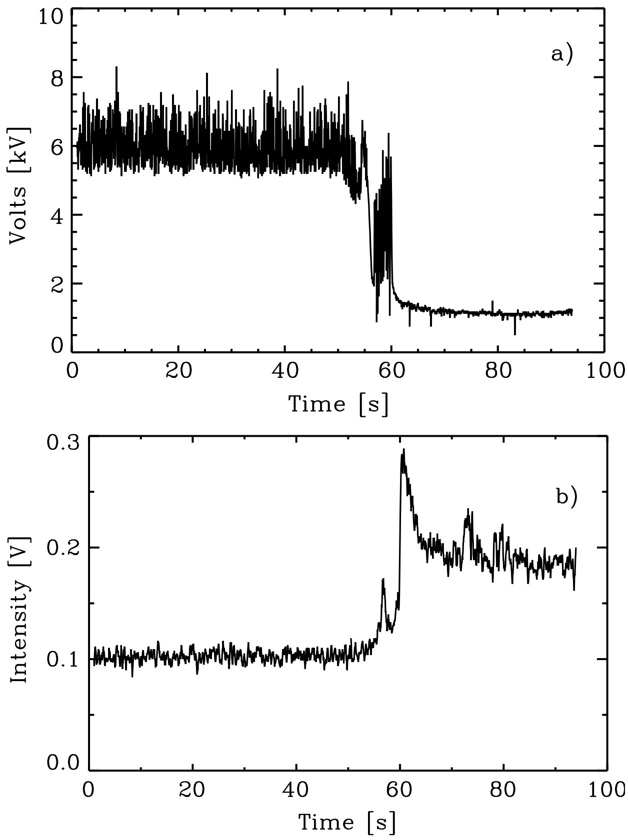

Figure 2. DC voltage on the HT-electrode (*a*) and emission intensity from a N I line (507.3 nm) as a function of time. Hissing is heard after 20 s, pulsating filaments are observed after 55 s and a continuous arc is seen after 60 s.

At 55 s the hissing sound stops and the air gap between the rf antenna and the glass tube breaks down with faint arcs/filaments seen in the gap. The breakdown is measured by a sudden drop in the dc voltage from 6 to 2 kV and at this minimum voltage the emission intensity reachs a peak of 0.15 V. The temperature on the glass tube is now about 150 °C. The filaments appear in a regular pulsed fashion for 3–5 s, where the frequency is so low that each filament can be detected by eye. During this time large regular fluctuations are measured in the dc voltage with ±1.4 kV peaks and the needle of the analogue ammeter on the high voltage supply deflects from 0 to about 3–4 mA. Pinpoint discharges are seen in the plasma sheath adjacent to where the atmospheric arc strikes.

At 60 s a pronounced 'continuous' arc is established between the rf antenna and the outside of the dielectric tube, and more frequent pinpoint discharges are observed on the inside of the tube. The dc voltage drops rapidly to 1.5 kV and the fluctuations vanish completely. The emission intensity increases to a maximum of 0.3 V followed by a decrease during the next few seconds to an average value of 0.2 V. In this regime the dc current cannot be measured with the existing apparatus as the ammeter is off scale, suggesting that the current is larger than 5 mA.

The 'continuous mode' remains until the rf power and dc voltage are turned off at 90 s. The tube still holds vacuum,

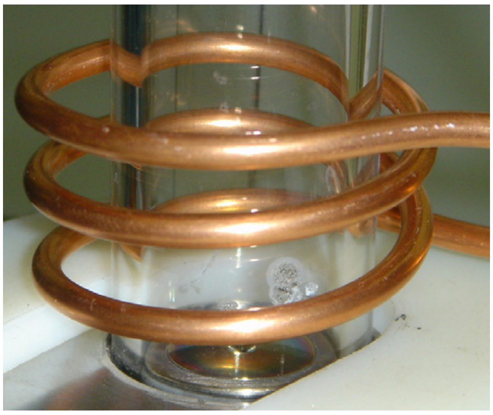

Figure 3. Photo of the tube and antenna after one breakdown event lasting about 1 min. A non-transparent white area of about 0.5 mm diameter appears on the outside where the filaments strike the surface. An ensemble of small circular spots resulting in a large rough surface of about 5 mm diameter appears on the inside where the pinpoint discharges are seen.

(This figure is in colour only in the electronic version)

but the breakdown has changed the surface of the glass on both sides of the tube as seen in the photo (figure 3). On the air side, a tiny non-transparent white spot about 0.5 mm in diameter is created by the filaments or arc. On the vacuum side, an ensemble of small circular spots with a total rough surface of about 5 mm diameter is created where the small pinpoint discharges were seen.

3.2. Breakdown evolution measured with higher time resolution

As the results shown in figure 2 are obtained by using the oscilloscope in roll mode with 5 s/div resolution to capture the complete breakdown sequence, a new set of experiments is shown in figure 4 with a resolution of 200 ms/div. The regular pulses of 5 Hz measured in the dc voltage are clearly seen, and the emission intensity from a wavelength of 589.9 nm (corresponding to NII excitation) peaks/increases corresponding to the voltage drops. Note that the large fluctuations measured before breakdown in the previous case have vanished due to a better grounding of the HV-probe.

3.3. Tube temperature and breakdown time

An important finding of this breakdown phenomenon is that it never occurs when the Airwipe cooling system is turned on, blowing cold air along the source tube. Experiments were done with the same parameters as the ones discussed above, but with the Airwipe turned on. The experiment ran for 15 min without any indication of breakdown, and the steady state temperature on the tube was 120 °C.

The temperature on the source wall at the breakdown point (when the first sudden drop in the dc voltage is measured and the subsequent filaments are seen) is measured as a function of the applied dc voltage and is shown in figure 5(*a*). This temperature will be called the breakdown temperature. Each data point in figure 5(*a*) is obtained with the same initial conditions, where the rf power and the dc voltage are turned on when the tube has returned to room temperature (21 °C) and during operation there is no air flow from the Airwipe. An inverse linear relationship between the breakdown temperature and the breakdown voltage is obtained. At 2 kV the breakdown temperature reaches 210 °C, while at 10 kV only 100 °C is reached. Note that during operation with an rf power of 150 W the tube temperature reaches a steady state of 120 °C when the Airwipe is on.

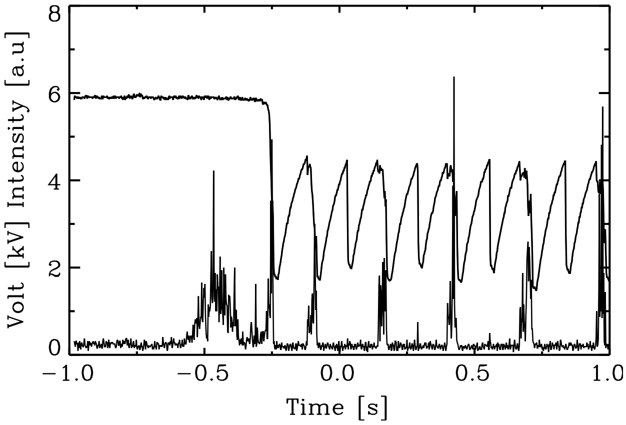

Figure 4. Dc voltage on the HT-electrode (——) and emission intensity from a Eu^{2+} line (589.9 nm) (——) as a function of time. Voltage are oscillations measured to 5 Hz.

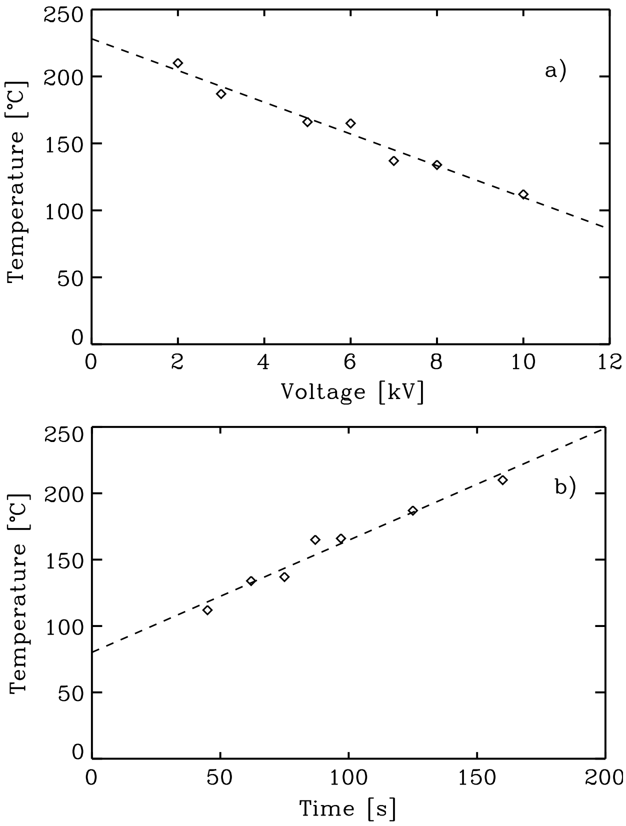

Figure 5. (*a*) Source tube breakdown temperature as a function of the applied high tension voltage and (*b*) the source tube breakdown temperature as a function of time to reach breakdown. The initial tube temperature is 21 °C and the airwipe is turned off with an applied rf power of 150 W.

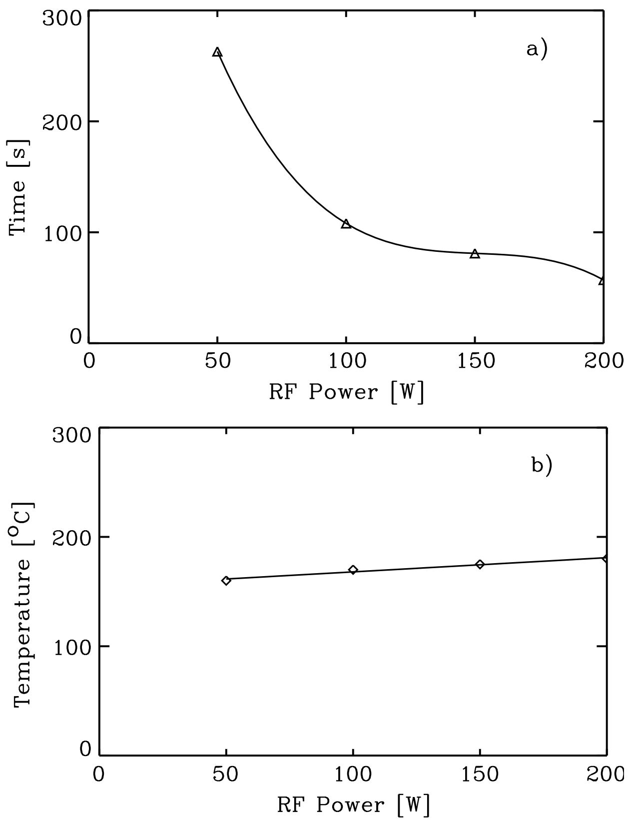

Figure 6. (*a*) Breakdown time and (*b*) breakdown temperature as a function of rf power. The dc voltage on the HT electrode is 6 kV.

As the temperature increases linearly as a function of time as shown in figure 5(*b*), a new set of experiments is performed measuring the breakdown time and breakdown temperature simultaneously as a function of the rf power. A constant dc voltage of 6 kV is applied. Once again, the tube is brought to room temperature prior to each measured point. The results are shown in figure 6(*a*) and (*b*), respectively. For higher rf powers, the breakdown time is shorter while the breakdown temperature remains constant, suggesting that the breakdown appears when the necessary temperature on the dielectric is reached.

4. Discussion

4.1. The onset of a negative corona

To a first approximation, the electrode configuration resembles a negative corona system, where the electric field between the rf antenna (the cathode) and the plasma column (the anode) is strongly inhomogeneous. A numerical simulation of the dc electric field along a straight line from the plasma to the antenna neglecting the rf electric fields is shown in figure 7. The plasma-anode is at the left side of the model with an applied dc voltage of 6 kV. Adjacent to the anode is a slab of dielectric material with a thickness of 3 mm and a dielectric constant of $k = 3.8$, representing the glass source tube. The cylindrical antenna-cathode with a radius of 1.5 mm is 2.5 mm from the dielectric and is surrounded by atmospheric pressure air (room air) with a dielectric constant of $k = 1$. As shown in figure 7, the electric field is highest at the cathode-antenna surface with

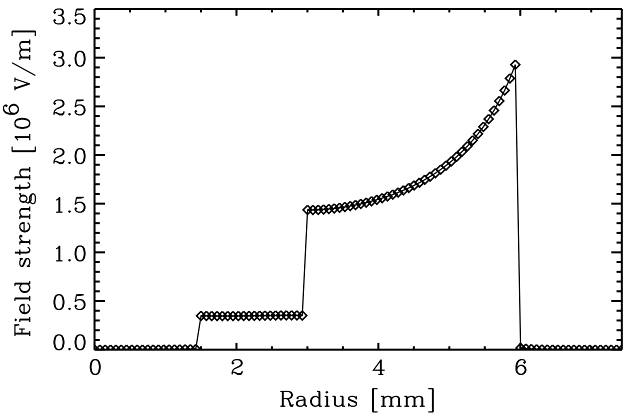

Figure 7. The electric field strength in the gap between the rf antenna and the plasma source column as a function of the radius from the plasma source. The dielectric tube is between 1.5 and 3 mm and the antenna starts at 6 mm.

some field enhancements due to the radius of curvature and is more or less excluded from the dielectric due to its k-value. With 6 kV applied to the anode the field strength at the cathode surface reaches ~3.0 kV mm^{-1}.

The ignition criterion for a corona discharge in air is found by the empirical Peek formula and is given by equation (1). At room temperature ($\delta = 1$) the critical electric field at the rf antenna of radius 1.5 mm is $E_c = 5.3$ kV mm^{-1}, which is higher than the calculated field around the rf antenna for 6 kV. The temperature threshold for a corona breakdown at this voltage is only 54°C according to equation (1), and at 100 °C the critical electric field is reduced to $E_c = 1.9$ kV mm^{-1} and at 200 °C $E_c = 1.2$ kV mm^{-1}, only.

The active volume of the corona around a 'sharp point' with radius r can be expressed as [15]

$$r_{ac} \approx \sqrt{\frac{rV}{E_c}}, \tag{2}$$

where r_{ac} is the active corona radius, V the applied dc voltage and E_c is the breakdown electric field given by equation (1). At the temperature threshold of 54 °C the active corona around the rf antenna is 1.7 mm, while at 150 °C the active corona extends over the whole air gap between the rf antenna and the glass wall.

The avalanche radius, in a negative corona breakdown, using a diffusion dominated model where the electrons have a gaussian distribution, is given by [15]

$$r_A = \sqrt{4D_e t} = \sqrt{\frac{4T_e}{eE_c}x_0}, \tag{3}$$

where D_e is the diffusion coefficient of the electrons, T_e is the electron temperature, E_c is the breakdown electric field given by equation (1), and x_0 is the distance from the cathode. Assuming that $T_e = 3$ eV and $E_c = 3$ kV mm^{-1}, the avalanche radius hitting the dielectric is $r_A = 0.1$ mm.

The above estimates are in good agreement with the experimental observation; the hissing sound heard after 20 s of operation occurs at the temperature threshold of ~50 °C, indicating a corona breakdown. As the plasma itself is very bright, faint corona discharges around the rf antenna would not be possible to observe. However, when the corona is able to bridge the air gap between two electrodes (when the temperature rises to 150 °C) filaments are formed that apparently are strong enough to be detected both by the naked eye and by the monochromator. The avalanche radius calculated by equation (3) is in good agreement with the white spot created on the outside tube.

Care must be taken using the above equations as they are only given for a variety of metallic electrode configurations without the presence of a dielectric barrier. Numerical simulations of negative coronas have shown that the total current at the anode is mostly carried by the displacement current [21]. The presence of a dielectric barrier may therefore not conflict with the existence of dc operated negative coronas, although these so-called 'barrier coronas' are normally operated at alternating voltages. The breakdown might therefore be initiated by the onset of a negative corona breakdown between the rf antenna and the plasma column as soon as the threshold temperature is reached. When the temperature increases even further the active corona region increases to bridge the airgap between the antenna and the dielectric source tube.

4.2. Pulsed regime

In electronegative gases, such as room air, a negative corona generally starts with a series of Trichel pulses [20]. This regime exhibits frequent and regular relaxation current pulses accompanied with short and faint streamers propagating away from the cathode. The reason for these pulses is normally explained by the formation and propagation of space charge fields in the gap between the electrodes. As the ions are almost stationary compared with the mobile electrons, positive space charges accumulate in front of the cathode, shielding the external electric field. The electron avalanches originating from the cathode therefore cease, until the space charges are dissipated and the external electric field restored [11]. The pulse frequency is normally controlled by the ionization frequency of the positive ions and the dissipation rate of the negative charge carriers (electrons and negative ions from electron attachment) propagating towards the anode. Normally, Trichel pulses in metallic electrode configurations appear with much higher frequency, generally of the order of 10–100 kHz, where each pulse duration is very short, approximately 100 ns. The time constant for these pulses can be found solving the continuity equation for the electronegative ion current given by [21],

$$\epsilon_0 \frac{\partial E}{\partial t} + \mu_n q_n E = 0, \tag{4}$$

where ϵ_0 is the permittivity, μ_n is the negative ion mobility and $q_n = e n_n$ is the electronegative charge density. Solving this equation with respect to $E(t)$ gives a time constant $\tau_{\text{trichel}} = \epsilon_0/\mu_n e n_n$ which is in the order of nano-seconds.

The much slower pulsation of around 5 Hz measured in our experiments, and shown in figures 3 and 4, is far too slow compared with the above phenomenon. If we assume that the voltage measured as a function of time, in figure 4, can be described by an equivalent circuit consisting of a resistor and a capacitor in series the voltage evolution is given by

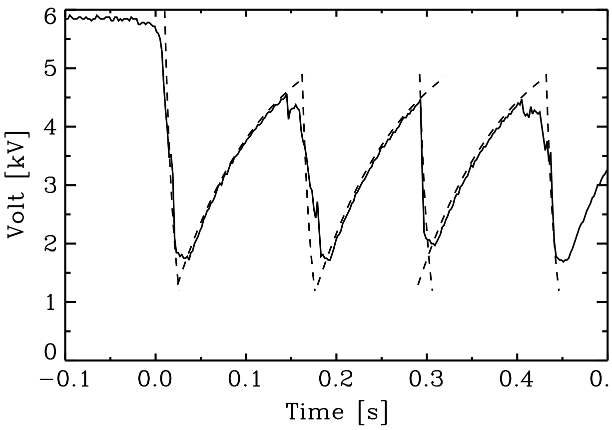

Figure 8. DC voltage on the HT-electrode (——) corresponding to the first 0.5 s of breakdown measured in figure 4. DC voltage (- - - -) calculated from charging and discharging through a rc-circuit with time constant of 0.1 and 0.01 for the charging and discharging, respectively.

$$V(t) = V_0 \left[1 - \exp\left(-\frac{t}{\tau}\right)\right], \tag{5}$$

and

$$V(t) = V_0 \exp\left(\frac{t}{\tau}\right), \tag{6}$$

for the charging and discharging of the capacitor through the resistor, respectively, where V_0 is the applied voltage and $\tau = RC$ is the time constant in the RC circuit. Figure 8 shows the measured (solid line) and calculated/fitted voltage evolution (dashed line) as a function of time during the first 0.5 s of the breakdown. The fit is obtained using equations (5) and (6) with $V_0 = 6$ kV, $\tau_{\text{charging}} = 0.1$ s and $\tau_{\text{discharging}} = 0.01$ s. The calculated voltage fits extremely well with the measured values, for the chosen time constants. The factor of at least 10 difference between τ_{charging} and $\tau_{\text{discharging}}$ is due to the charging and discharging passing through two different circuits.

The charging time constant of 0.1 s is due to the internal impedance of the Spellman dc voltage supply as it uses an arrangement of capacitors and rectifier diodes to generate the required dc voltage. This has been verified by measuring the rise time and decay time of the supply when the voltage is turned on and off, using the same experimental set-up but without igniting a plasma (avoiding rf interference, heating and the dc breakdown). The rise time is measured to be 0.1 s while the decay time is measured to be 0.5 s, i.e. it is 5 times higher.

The time constant for the discharging, 0.01 s, is a factor of 10 shorter than the charging time and a factor of 50 shorter than the decay time of the voltage supply. However, this time constant is also extremely long and is not likely to be related to the diffusion of negative ions in the airgap between the rf antenna and the dielectric, nor to the charging of the source wall or a collapse and re-formation of the plasma sheath, as all these events will occur in nano-second to micro-second time scales.

4.3. Transition to a continuous resistive corona breakdown

A transition to a continuous bright arc occurs after the onset of the negative corona with faint regular pulsed filaments. The transition occurs at 60 s in figure 2, where the dc voltage drops dramatically, the fluctuations vanish completely and it is accompanied by an increase in the dc current and in the N II emission.

Usually the increase in the average current density for negative coronas leads to the onset of an instability and the conversion of the corona into a short lived spark. Long lived continuous filaments or arcs are seldom observed.

In addition to the global heating of the dielectric from the plasma, local heating will occur as soon as the first filaments strike the dielectric surface. When a dielectric material heats up sufficiently, its electric resistivity and dielectric strength decrease. Glass has typically an electric resistivity of about $10^{16}\,\Omega\,\mathrm{cm}$ at room temperature, but decreases dramatically as the temperature increases, and at 400 °C the resistivity drops 10 orders of magnitude to about $10^{6}\,\Omega\,\mathrm{cm}$ [29]. At this temperature, the tube undergoes a local transition from a dielectric material to a resistive material, allowing dc current channels to form in the tube wall and hence allowing an increase in the dc current. When the current increases and become continuous, the Spellman dc power supply will sense the rise in output current due to its short circuit condition and will automatically cross over into current mode to regulate the output current, as Spellman supplies have built-in output limiting assemblies. Hence, the dc voltage supply can no longer deliver the required voltage and the voltage pulses cease.

Why the continuous mode can exist for an extended period (until the power is turned off, or the tube breaks) is still not understood as the electric field in the airgap decreases dramatically as soon as the dc voltage is reduced. The continuous mode is so ‘strong’ that the rf power can be turned off, and the arc in the gap is strong enough to sustain a faint pulsating plasma in the tube.

4.4. Air flow and runaway ions

As mentioned earlier, the breakdown phenomenon appears only when the Airwipe cooling system is off. The Airwipe provides a ‘uniform’ flow of compressed air along the source tube and this allows the tube temperature to stabilize at 120 °C (for 150 W rf power). Even when the temperature on the dielectric reaches a value where breakdown normally occurs without the blowing air (at 10 kV the breakdown temperature is 100 °C, see figure 5), no discharges were observed.

This observation suggests that although the corona breakdown voltage is reached and the electron avalanche ‘propagates’ from the cathode, the ions created in the air gap between the rf antenna and the dielectric source tube are blown away, thus preventing the corona from bridging the airgap and the first filament is not formed.

Another explanation might be that the cold flow of air keeps the air in the gap cool, although the tube heats up, and thus keeps the required electric field at the cathode just below the electrical breakdown at this temperature. The latter argument is consistent with the simulation in figure 7, showing that the field is below E_c at room temperature.

5. Conclusion

In the design of ICP sources for ion beam applications where the plasma is floated up to several kilovolts positive, care must be taken to avoid electric breakdown in the air between the rf antenna and the dielectric plasma source. If one side of the rf antenna is grounded, and the dielectric source tube and the surrounding air are allowed to reach a threshold temperature corona breakdown at the rf antenna occurs. The experiments presented here have shown that the dc corona can be ignited with the presence of a dielectric barrier, which normally precludes the dc operation.

The formation of a negative barrier corona initiates a transition to a continuous arc from the rf antenna to the source tube. It is postulated that the onset of the first filaments heat the dielectric to sufficiently high temperatures to locally transform the dielectric into a resistive material. DC current channels are then formed in the source tube, allowing a resistive corona with continuous arcs to exist. Electrons can now flow from the resistive channels in the dielectric to the plasma, causing the plasma sheath to collapse. The mobile plasma electrons can then reach the source wall causing pin-point discharges. The plasma sheath is re-stored when the ambipolar electric field is formed.

The breakdown can be avoided by floating the rf antenna up to the same voltages as the plasma. Another solution is to remove the airgap between the source tube and the antenna and reduce the field below the breakdown threshold. In this respect one needs to consider the dielectric strength of the materials and in the environment in which they are used.

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