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Minimum Breakdown Parameters Through H_2, He, N_2 and Ar Gases

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A minimum breakdown voltage of the cylindrical coaxial virtual cathode oscillator is investigated using nitrogen (N_2), argon (Ar), helium (He) and hydrogen (H_2) gases through different anode transparencies. The study includes the effect of secondary electron emission on the minimum breakdown voltage, $(V_b)_{min}$, and the product, $(Pd)_{min}$, of gas pressure, P, and inter-electrode distance, d. The changes in the minimum breakdown voltage with the gas pressure are studied where the pressure is the main factor of electric discharge. Paschen curve is studied through electric discharge for Ar and H_2 by using different anode transparencies.

Keywords: Glow discharge, Coaxial vircator, Anode transparency, Minimum breakdown voltage

Introduction

The gas discharge plasma has attracted the attention of scientists and technologists because it is a source of electrons and ion beams which are needed and used in several applications and modern instruments [1, 2]. Plasma can be classified into cold plasma and hot plasma. The first one is called partially low ionized plasma (non-equilibrium plasma) at which the plasma temperature is lower than 10 eV where the heavy particles temperature is very low compared to the electron temperature. The second kind is called totally ionized plasma (equilibrium plasma) in which the plasma exists at a temperature more than 10 eV and can reach 10 keV. In normal glow discharge glow discharge (GD), the ionization processes and breakdown occur between the two electrodes where the current density is nearly constant [3]. Normal GD is modified to act as an accelerator for electron beam leading to the current multiplication and is considered a source of high power microwave. A modification is done to the system by making the anode semi-transparent and the distance between the two electrodes less than the collision mean free path [4, 5]. Through this experiment, the electric discharge occurs on two stages, the first is forming a dense cloud of negative charges called virtual cathode (VC) behind the diode and the other stage is the breakdown process to create self-sustain electric discharge. The incoming electron beam will oscillate between the real cathode and the virtual cathode to produce energetic electron beam [6-8].

The mechanism of the breakdown applies when a DC voltage is introduced between two electrodes and as a result, free electrons are ejected from the cathode and accelerate towards the anode by the electric field. If the electrons have sufficient energy, they will cross the anode to form a virtual

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cathode outside the diode and many collisions occur behind the diode to generate pairs of free electrons and ions. In this case, the microwave is generated from the interaction between the energetic electron beam and the electric field around the virtual cathode. The breakdown occurs through two processes in the Townsend regime; the first ionization and secondary emission. The latter process makes the breakdown a self-sustaining electric discharge.

In 1889, Paschen presented a law stating that the breakdown voltage is dependent on the product of the gas pressure and the space between the two electrodes as $V_b = f$ (Pd) [9, 10].

In 1915, Townsend introduced two quantities to explain the current growth through the gas discharge known as the first Townsend ionization coefficient (α) and second Townsend emission coefficient (γ) [11]. The secondary electron emission has a great role in electron multiplication and is needed to maintain the discharge [8].

$$I = I_o \frac{e^{\propto d}}{1-\gamma(e^{-\propto d}-1)} \qquad (1)$$

Where I is the current flowing into the anode, I_o is the initial current at the cathode and d is the inter-electrode distance. In the above equation, if the denominator approaches zero, the discharge current is greatly amplified and I/ I_o tend to infinity. This is called the electric breakdown of the gas. Therefore, the breakdown requires the condition is:

$$\gamma\left(e^{-\propto d} - 1\right) = 1. \qquad (2)$$

using the Paschen relation gives [12]:

$$V_b = \frac{BPd}{\ln(Pd)+\ln[\frac{A}{\ln\left(1+\frac{1}{\gamma}\right)}]} \qquad (3)$$

where A and B are constants depending on the gas properties [10]. The value of Pd at which the minimum breakdown voltage occurs is:

$$(Pd)_{min} = \frac{ec}{A}\ln(1+\frac{1}{\gamma}) \qquad (4)$$

and the minimum breakdown voltage is:

$$(V_b)_{min} = \frac{ec}{A}\ln(1+\frac{1}{\gamma}) \qquad (5)$$

Where A, c are constants and determined experimentally for each gas

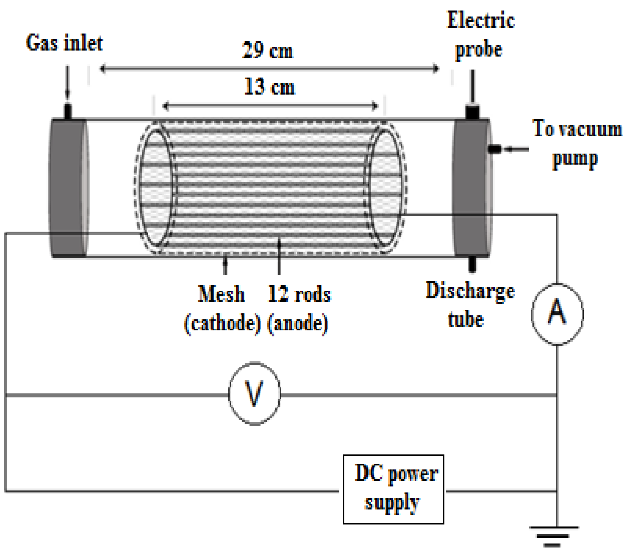
It has been proved that the microwave efficiency can be enhanced by modulating the injected electron beam. In all sources of microwave generation, the kinetic energy of the electron beam is converted into microwaves energy. Thus, the investigation of the breakdown processes is very necessary to enhance the microwave efficiency which is the aim of the present work.

The breakdown is studied through a pseudo discharge at various inter-electrode distances using different anode transparencies [13, 14]. The breakdown over a small gap for different distances and different gases was investigated [15]. The voltage breakdown in electric discharge, for several rare gases, is studied [16]. The physical process of an electrostatic discharge for a voltage less than 330V and gap distance of several micrometers is examined [17]. An electric characteristic of the oxygen plasma is investigated [18]. It was proved that the Townsend coefficient and minimum voltage are dependent on the inner and outer electrodes diameter [11]. The Paschen law is modified at low gas pressure [19].

The minimum breakdown voltage for rare gases depends on the cathode material and secondary electron emission [20, 21]. The minimum breakdown in normal glow discharge is larger than in virtual cathode oscillator [22, 23].

Experimental Setup

The cylindrical coaxial vircator is designed to produce an energetic electron beam in a radial direction is shown in Figure(1). It consists of two main parts; cylindrical coaxial diode and discharge vessel (resonance cavity). The diode is composed of two cylindrical electrodes; the outer electrode is a cylindrical stainless-steel mesh cathode 13 cm length and 10 cm diameter is connected to the negative potential. The inner electrode consists of different stainless-steel rods with different transparency numbers (6, 12 and 24 rods) distributed in a circular circumference of a 4.96 cm radius. These rods are electrically connected together by a thin copper wire that acts as an anode and has neutral potential. The distance between the two electrodes is fixed at 4 mm where the mean free path for electron collision is comparable or larger than the electrode gap at low pressure. The diode is immersed inside the vacuum glass tube which can be evacuated up to 10-2 Torr. The discharge vessel is fixed with two flanges. One has a hole to introduce the gas through a needle valve to a constant working gas pressure and the other is connected to the vacuum pump. A negative DC power supply is applied between two electrodes, 12 rods (anode) and Mesh (cathode), to provide a negative DC voltage up to 3 KV and current up to 10 mA. The discharge current is measured as a function of the discharge voltage.



Figure(1): Configuration of coaxial vircator and its associated electrical circuit

RESULTS

To understand the parameters that can affect the minimum voltage (Vb) min at which the gas transfers from a non-conducting state to a conducting state, the study is carried out on a cylindrical coaxial vircator for different gases and anode transparencies.

Figure (2) shows the effect of secondary electron emission on the minimum breakdown. Secondary electron emission (γ) is the main factor in changing the electric discharge from non-self-breakdown to self-breakdown for plasma continuity. So γ is an important factor that can affect the minimum breakdown voltage through plasma formation. The figure discusses the dependence of the minimum breakdown voltage on the secondary electron emission (γ) for H2, He, Ne and Ar gases using different anode transparencies.

It is clear from Figure(2) that the minimum breakdown voltage, (Vb)min, decreases with the increase of secondary electron emission when the rate of electron emission from the cathode is small, then by increasing the secondary emission, (Vb)min slightly decreases until it reaches a constant value. This means that, at first, the rate of electron emission is not sufficient to induce a large number of ionization collisions which are required to complete the breakdown and transfer the discharge to self-discharge. By increasing the secondary emission, the gas changes into the self-electric breakdown and the plasma is formed. Therefore, no extra energy is consumed for the continuity of the glow discharge. Thus, once breakdown occurs, there is no effect of secondary electron emission on the minimum breakdown voltage. Also, it is clear from the figure that there is no noticeable effect of the anode transparency on the variation of the minimum breakdown after self-discharge. It is also clear that the four gases have nearly the same behavior through variation of the minimum breakdown voltage with the secondary electron emission.

A typical process is shown in Figure (3) which explains the dependence of (Pd)min on the secondary electron emission (γ) for different gases and anode transparencies. At low secondary emission, the value of Pd decreases with increasing the secondary electron emission with the same value; except for helium which has a higher value because its interatomic space is very large and needs a higher value of energy to induce enough number of electrons to cause the electric breakdown as shown in the figure. This figure proves that before the plasma formation, secondary electron emission has a great effect and plays an important role to increases the electron density and to sustain the electric discharge. But after breakdown, there is no effect for secondary emission. It is also clear that the effect of anode transparency appears through the ionization processes and breakdown processes only and that the gases in this experiment have the same behavior.

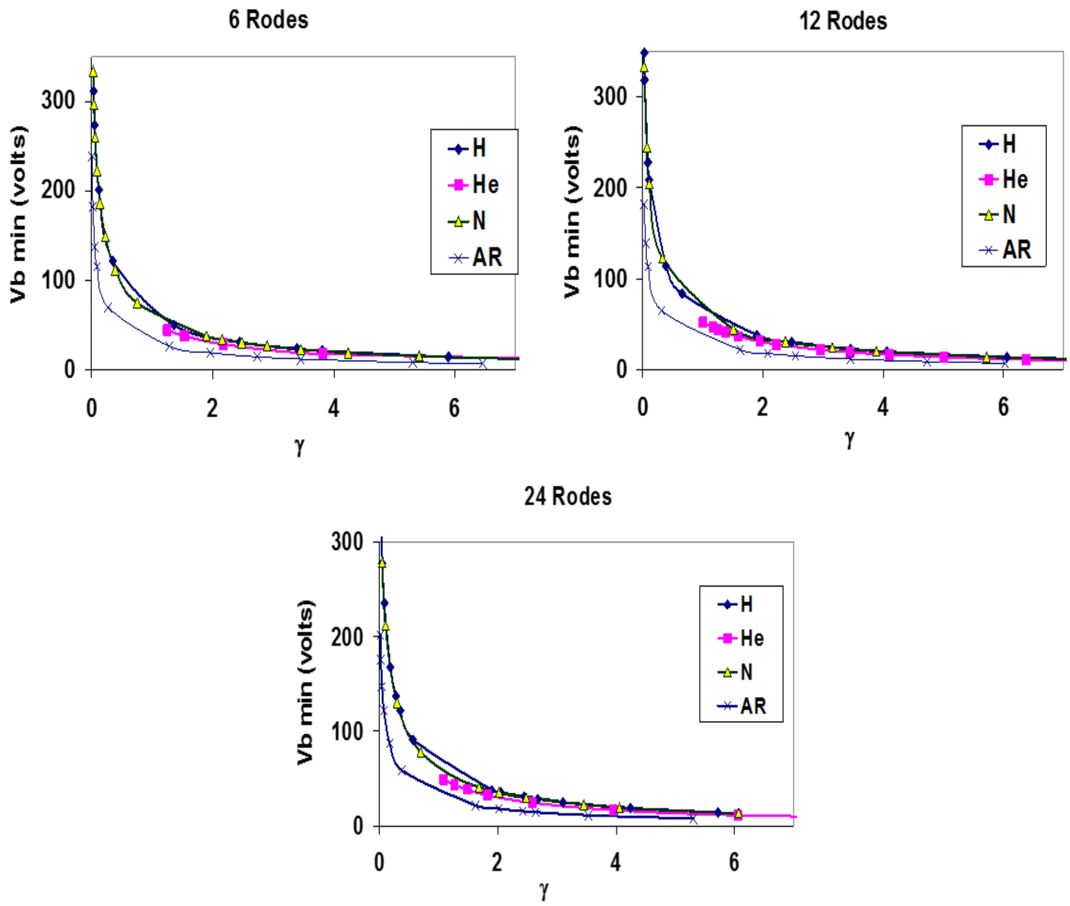


Figure (2): The minimum breakdown voltage as a function of secondary electron emission for different gases and anode transparencies

Figure (4) shows the effect of gas pressure on the minimum breakdown voltage. Pressure has a great effect on the electric breakdown process to transfer the gases from an insulator medium to a conductor medium, where it plays an essential role in the collision mean free path between the electrons extracted from the cathode and the atom of the gas. Each gas has its own ionization energy (depending on several parameters, such as atom size, binding energy and the number of electrons in the outer shell). The number of gas atoms outside the two electrodes increases with the increase of gas pressure; i.e. there is a direct proportional relationship between them as shown in Figure(4). When the gas pressure increases, the number of natural atoms increases and the distance between the atoms become extremely small. Consequently, the arriving electrons must have sufficient energy to ionize a huge number of atoms which require more voltage for the collision and ionization processes to complete the electric discharge. Thus, once the breakdown takes place, the pressure is the main factor that can affect the minimum breakdown. It is noticed from this figure that helium gas (He) has a low density, so it is easy to be ionize by the lowest energy while argon gas (Ar) needs more energy for the ionization process because it is one of the rare gases and has a large atomic number. Hydrogen (H_2) and nitrogen (N_2) have the highest minimum breakdown value due to the large binding energy of H_2, while N_2 needs more ionization energy because it has large atomic size and a large number of electrons in its outer shell.

It is clear that there is no effect on the anode transparency after self-sustaining the discharge and plasma formation. Also, the variation of the minimum breakdown voltage $(V_b)_{min}$, for the four gases, have a similar behavior through the variation of the gases pressure.

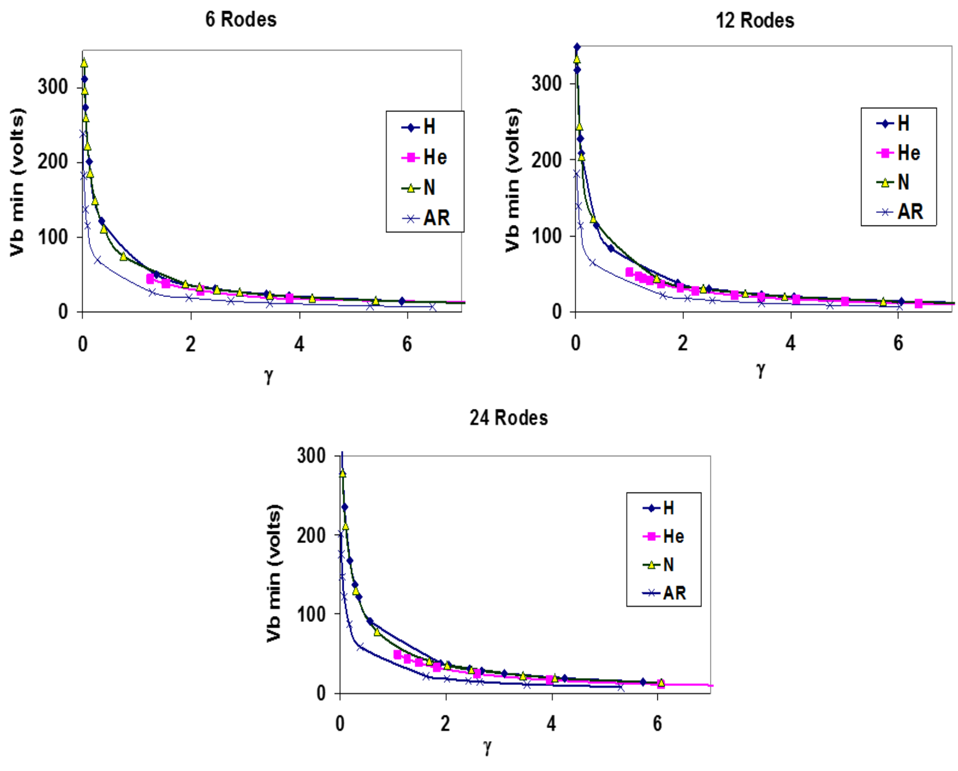
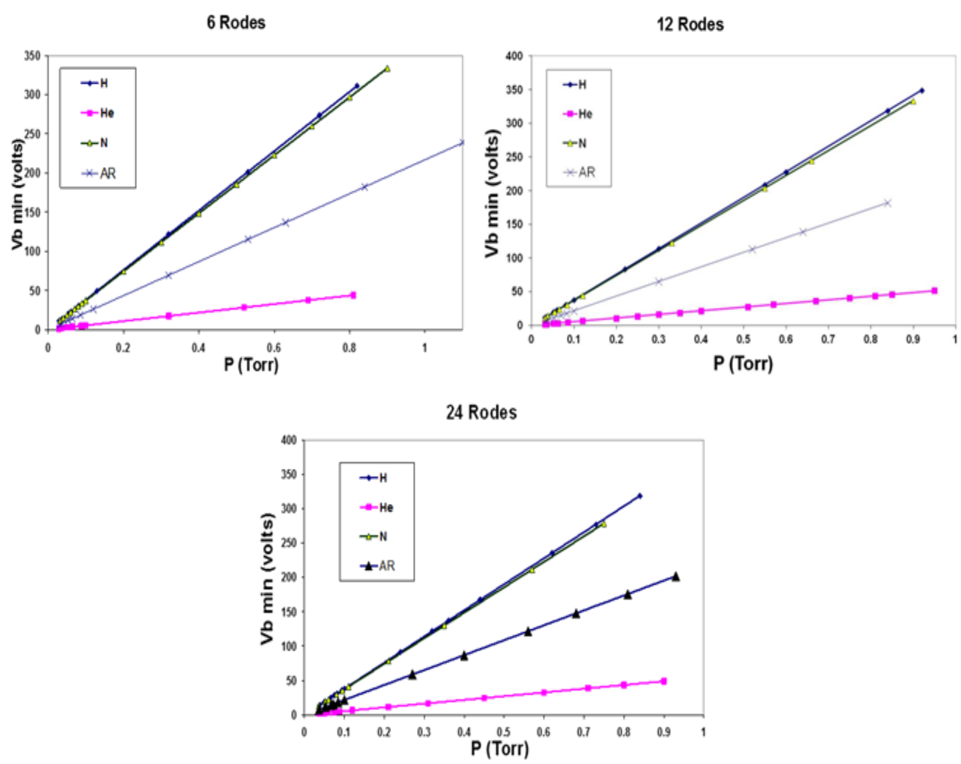


Figure (3): Variation of $(Pd)_{min}$ with the variation of the secondary electron emission (γ)



Figure(4): The minimum breakdown voltage for different gas pressures and anode transparencies

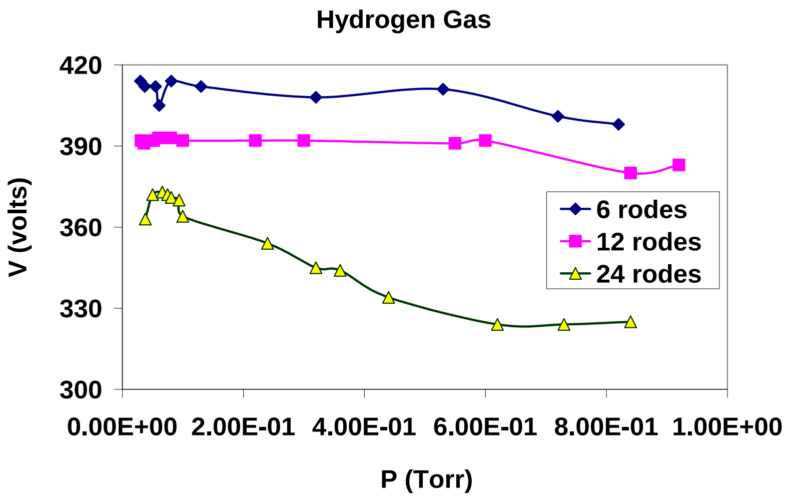


Figure (5): Paschen curve for hydrogen discharge at different anode transparencies

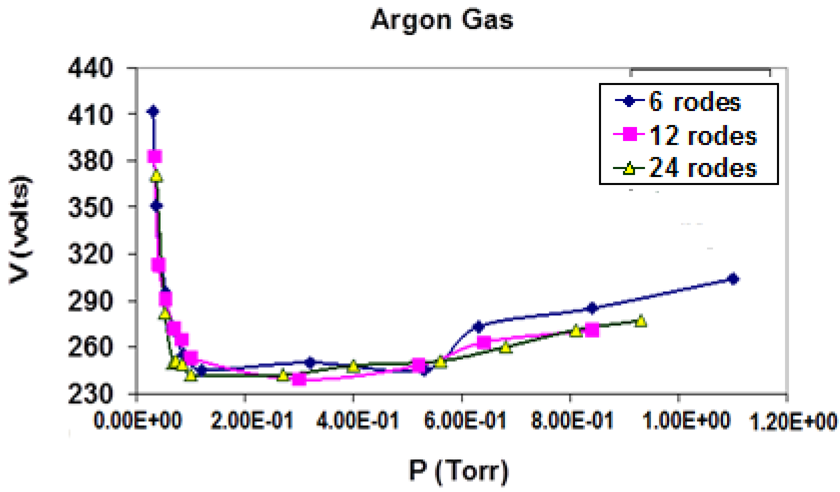


Figure (6): Paschen curve for argon discharge at different anode transparencies

Figure (5) shows the Paschen curve for hydrogen (H2) through different anode transparency of 6, 12 and 24 rods. It is clear that the lowest breakdown voltage is required for the lowest transparency (24 rods) where the small distance between the rods allows the electrons to cross the anode at high intensity which leads to increasing the ionization potential as well as increasing the ionization process to cause the electric breakdown (minimize the breakdown voltage); i.e. the electrons cross the anode with an energy sufficient to ionize the gas and complete the breakdown process. The breakdown voltage slightly decreases with increasing the pressure. This could be due to the small number of collisions where the hydrogen atom has one electron which reduces the collision number.

Figure (6) shows the Paschen curve for argon (Ar) through different rods anode transparency of 6, 12 and 24 rods. Argon gas has an ideal behavior similar to the Paschen curve of rare gases. When the pressure is sufficiently low, the number of natural atoms is small and the distance between the atoms is large, hence the arriving electrons must have sufficient energy to overcome the long collision mean free path and require more voltage to collide with the atom. At the left-hand side, the ionization mean free path is long so the ionization process occurs outside the diode and the electrons need more energy for the collision process as shown in the curve. On the other hand, at higher pressure, the collision mean free path decreases while the gas density is large so the breakdown consumes more energy to start the electric discharge. It is clear from the curve that the highest transparency (6 rods) needs a slightly higher energy due to the large number of collisions between the electrons and atoms while the lowest transparency (24 rods) requires less voltage because the electrons cross the anode with large intensity.

Conclusion

The minimum breakdown voltage of the cylindrical coaxial virtual cathode oscillator is investigated using nitrogen (N2), argon (Ar), helium (He) and hydrogen (H2) gases through different anode transparencies. The secondary electron emission has a great role in electrons multiplication which is required to maintain the electric discharge only before plasma formation. It is concluded that, after self-sustaining, the minimum breakdown voltage does not depend on the anode transparency nor on the secondary electron emissions. The dependence of (Pd)min on the secondary electron emission ensures that once the breakdown occurs, there is no effect of the secondary electron emission on the electric discharge. There is a directly proportional relationship between the gas pressure and the minimum breakdown voltage.

The gases in this experiment have a similar behavior to that of the classical glow discharge. The Paschen curves are studied for hydrogen and argon through different anode transparency rods, 6, 12 and 24 rods. Argon gas has an ideal behavior similar to the Paschen curve. For argon gas, the highest transparency (6 rods) needs the highest energy because the number of collisions between the electrons and atoms is large while the lowest transparency (24 rods) requires less voltage because the electrons cross the anode with large intensity. Also, for hydrogen gas, the lowest transparency requires the lowest breakdown voltage as argon gas. Finally, it is concluded that at cold plasma conditions, the main factor, that affects the plasma after the occurrence of the breakdown, is the pressure.

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