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FILAMENTARY PLASMA IGNITED BY MICROWAVES IN HIGH PRESSURE GASES

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A filamentary plasma is produced in the microwave cavity filled with argon gases of several atmospheric pressures and is ignited by low power microwaves. It is found that this plasma can be explained by the Schottky's theory of positive columns. The plasma has double structures, i.e. highly ionized part and weakly ionized part, which also is observed by Kapitza's experiments.

1. Introduction

It has been for long time to devote the research work of rf and microwave dischages in high pressure gases; nearly one or several atmospheric pressure. In these fields, there are many review and original articles [1)-3)]. P.L. Kapitza [4)] has proposed that a nuclear fusion reactor can be obtained with the microwave discharge in the high pressure gases. They made a highly ionized, high density and high temperature fusion plasma [3)] which is floating in the microwave cavity by injecting several handreds KW input powers. The working gases are high pressure deuterium or helium. The electron temperature of the plasma is about 10^6 K and the ion temperature is several ten electron Volts. They have explained that the reason why such a fusion plasma can be made is a adiabatic effect of neutral brancket of gases.

On the other hand, according to the excellent review articles of Raizer [2)], however he has showed that the temperature of electrons and ions is about 1 eV and is equal to the neutral gas of the environment. The frequency of RF field reported by him is several MHz and is lower than that of Kapitza's experiment, and the input power is about 30 or 40 KW. The parameters of this plasma are well explained by the localized thermal equilibrium theory. From the point of views of these two articles, these two discharge modes are different in essense. Thus the precise investigation of the characteristics of filamentary plasma and the comparison between these two plasmas are needed.

We made a filamentary plasma of few-hundred-watts-input-power in argon gases of several atmospheric pressure and we can show that thses

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plasmas are explained by Schottoky's theory of positive column.

In Sec. 2 experimental apparatus are explained and experimental results are shown in Sec. 3. In Secs. 4 and 5, discussion and conclusion of this experiment are given.

2. Experimental Apparatus

A filamentary plasma is produced in a microwave cyilindrical cavity whose dimension is 150 mm in diameter and 400 mm in the length. The microwaves used are 2.45 GHz in frequency. Three modes TM_{01}, TE_{11} and TE_{21} can be excited in this cavity.

As shown in Fig. 1, the mode conversion is made from rectangular wave guide mode of TE_{10} to the cylindrical mode of TM_{01} by a coupling hole of

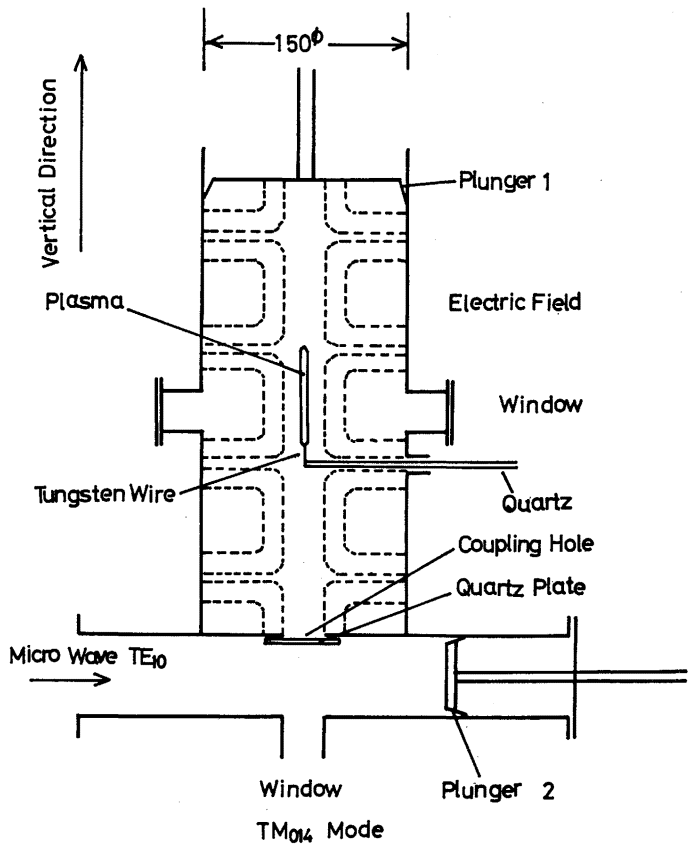

Fig. 1. The experimental apparatus. The plunger 1 is used to tune the cauity. The plunger 2 is used to select the mode.

65 mm in diameter and a plunger in the rectangular wave guide. By this plunger, we can get a strong coupling to TM_{01} cylindrical mode and a weak coupling to other modes. The electric fields in the cavity are recieved by a loop antena. The Q-values in the cavity is observed to be about 2000 by using a sweep oscillator of the microwave region.

An output power of a magnetron is changed by contralling a high voltage of cathodes of the tube and is calibrated by calorimeters. The microwave cavity are exhausted to 10^{-2} Torr by a rotary pump and filled with the argon gas of from one to three atmospheric pressure. The gas pressures are observed by the high pressure gauge.

The filamentary plasma is ignited on a needle of a tungsten wire of 1 mm in diameter and 2 cm in length. The tungsten wire is supported by a quartz lod of 6 mm in diameter. When the filamentary plasma are ignited along the microwave electric field, the Q-value of the cavity decreases strongly. The filamentary plasma is 3 mm in diameter and 8 cm in length using the travelling microscope. As is seen in Fig. 1, the observing window is located under the waveguide and at the center of the cavity. Through this window, the density and the temperature of electrons of the filamentary plasma are measured out by spectroscopic methods.

The temperature of the electron in plasmas is obtained from the intensity slope of free-bound continuum spectrum, which is proportional to exp $(-h\nu/\kappa T_e)$ where h is the plank constant, ν is the frequency, κ is the Boltzmann constant and T_e is the electron temperature. The spectroscope is calibrated by the standard lump in advance. The typical spectrum is shown in Fig. 2. The electron density is measured by the use of the stark broaden-

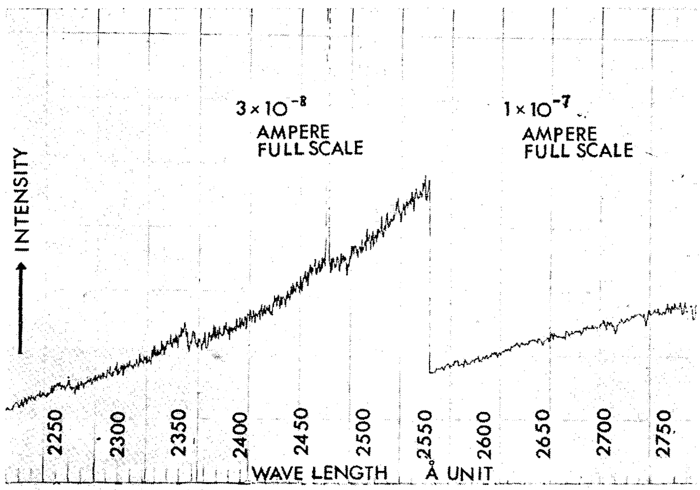

Fig. 2. The continuum spectrum of the plasma. The slope of the intensity is propotional to exp $[-hc/\lambda\kappa T_e]$, so the electron temperature is obtained from this spectrum.

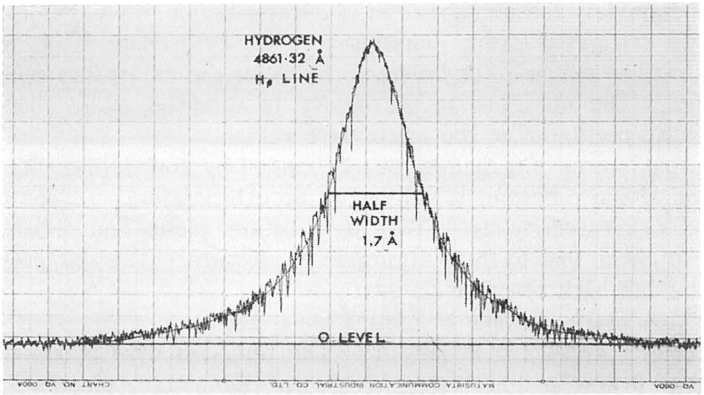

Fig. 3 The typical line spectrum of Hβ. This line is broaded by Stark effect and the half width corresponds to $N_e=7\times10^{14}$ [1/cc].

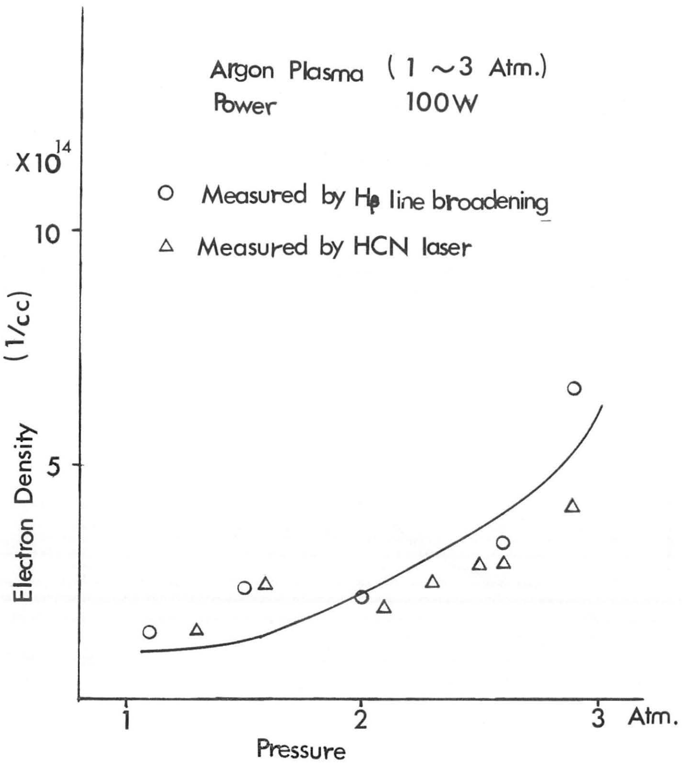

Fig. 4. The relation of electron densities to the pressure, where the plasma length is fixed at 8 cm.

ing of H_β line (4861 Å) where we mixed a few percent of hydrogen as a search gas to the argon plasma. The typical spectrum is shown in Fig. 3. In order to get the radial distribution of the electron density, we use a Michelson type interferometer with the HCN laser (λ=337 μm) where λ is the wavelength of HCN laser. Fig. 4 shows the relation of the electron density *versus* the gas pressure due to the spectroscopic method and interferometer method.

3. Experimental Results

As is shown in Fig. 1, the plasma is produced along the electric field in the cavity. The maximum plasma length is about a half wavelength in the cavity.

As the pressure of the gas in the cavity is increased, both the diameter

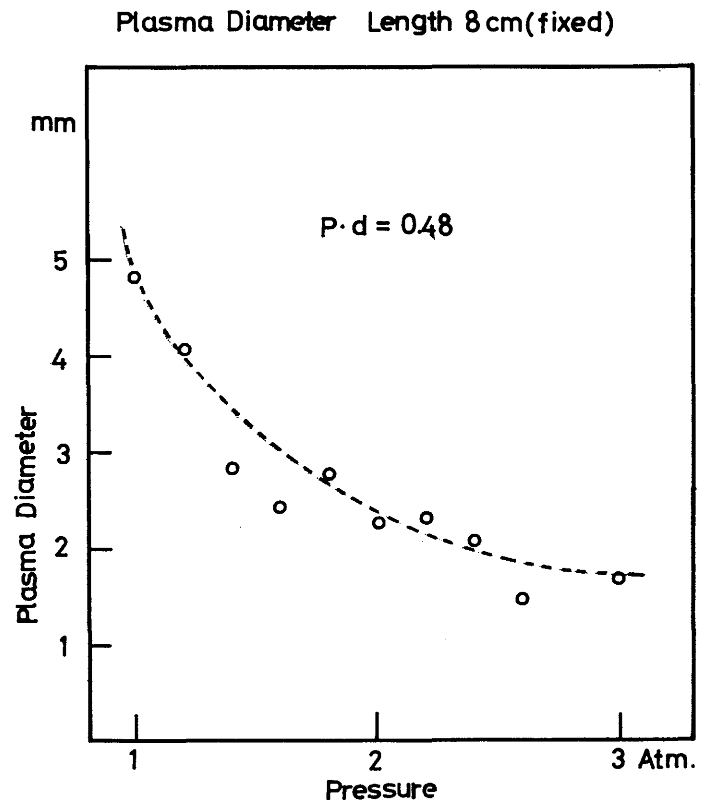

Fig. 5. The dependence of the diameter on pressures, where the plasma length is fixed at 8 cm, P is the pressure in atmosphere and d is the radius in cm.

and the length of the plasma becomes small. When the input power to the plasma is increased, the length of the plasma becomes long and satulates at a constant length (8 cm) which corresponds to the half wave length in the cavity.

We get the relationship between the diameter of the plasma and the pressure of the neutral gas, keeping the plasma length constant by adjusting the input power. Since the internal electric field in the cavity is changed greatly by the macroscopic propaties of the plasma. The diameter of the filamentary plasma decreases with increasing the gas pressure as shown in Fig. 5.

The diameter of the plasma is determined by the recombination process between the electrons and the ions. This diameter is much smaller than the rf skin depth under the condition that the electron-neutral collision frequency $\nu_{ea}=1.17\times10^{12}$[1/sec], determined from the neutral density $N_n=3\times10^{19}$[1/cc] and the electron temperature T_e=leV, is much higher than the microwave frequency 2.45 GH_z.

The skin depth, δ, is as large as about one order of magnitude to the plasma diameter so that the microwave can penetrate into the plasma. Since the collision frequency, ν_{ea}, is much larger than the microwave frequency, $\omega_0(\omega_0 \ll \nu_{ea})$, we can neglect the high frequency effect on the plasma and treat the plasmas obtained in the present experiments as a DC discharge.

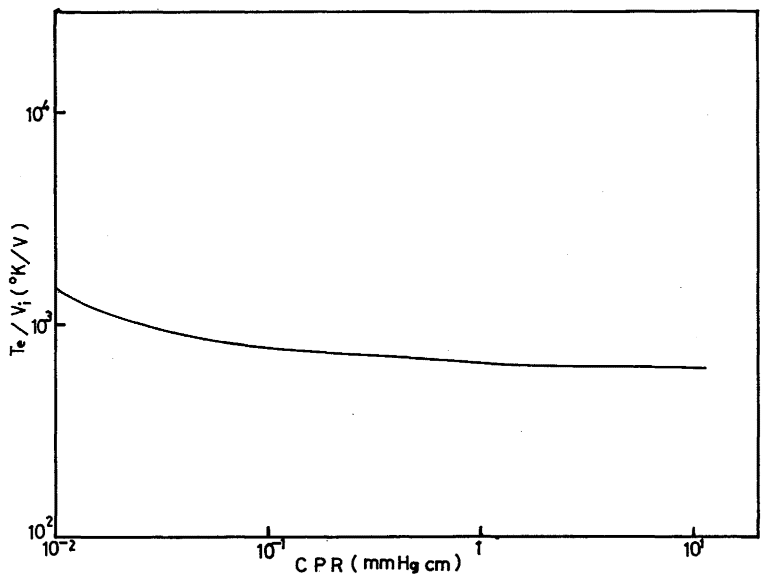

Fig. 6. The theoretical curves of Schottky's theory [6], where P is the pressure in mmH_g, R is the radius of plasma and C is the numerical factor 4×10^{-2} for the argon gas. The relationship leV =7740K is used in this graph.

From Fig. 5, we can easily find that

$$P \cdot d = 0.4 \sim 0.5 \text{ (atm} \times \text{cm)}$$

where P is the neutral pressure and d is the diameter. From the Schottky's theory [6], the electron temperature of the plasma is uniquly obtained by the use of $P \cdot d \cdot c$ parameter in Fig. 6, where c is the gas characteristic value. In the case of the argon gas, $c = 4 \times 10^{-2}$ and the ionization potential $V_i = 15.76$ eV, so we get $T_e = 9456$K by inserting the numerical value $c \cdot P \cdot d = 14.6$ into Fig. 6. This electron temperature is just the same temperature $T_e = 10640$ K as from that the spectroscopic measurement value. As the electric field strength in the plasma is considered to be equal to the strength in the cavity, the output signal, I, from the semiconductor detector, which is connected to the loop antena in the cavity, is proportional to the square of the electric field in the plasma.

Fig. 7 shows that the electric field strength, E, increases and E/P is nearly constant, with increasing the pressure. The Schottky's theory shows

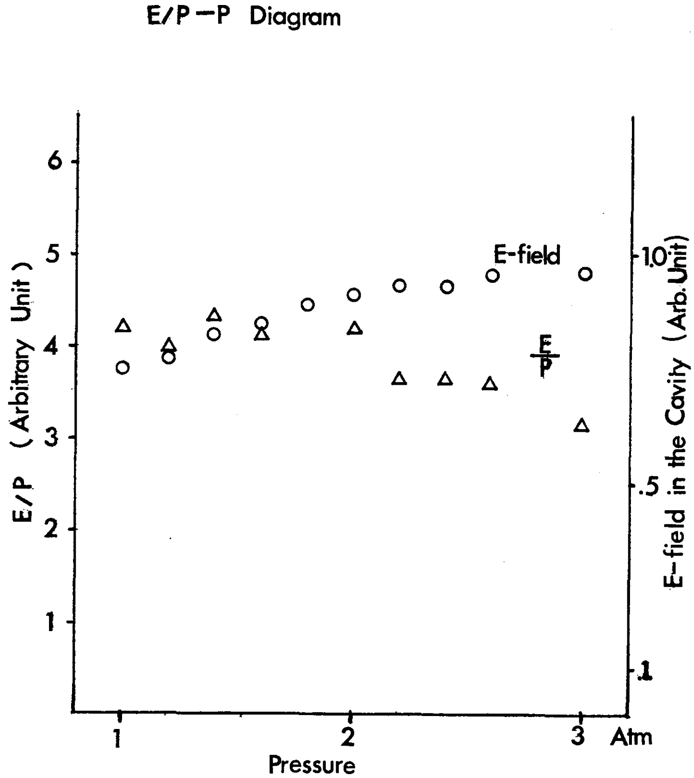

Fig. 7 The relation of E and E/P to pressures, where E is the microwave electric field strength.

that [7]

$$\frac{E}{P}=\beta kT_e\sqrt{1-\frac{T_n}{T_e}},\tag{1}$$

where T_n is the neutral temperature and β is the numerical factor which does not depend on the pressure. This fact means that the Schottky's theory is applicable to this plasma. The decrease of E/P at $P=2$ atm is probably due to the finite neutral temperature or the neutral gas convection in the cavity.

4. Discussion

According to the customary theory of the high pressure-high frequency discharge, the electron temperature has been determined under the assumption of the local thermal equilibrium which $T_e=T_i=T_n$. Raizer has worked out the way to determine the temperature of the plasma torch which acts with several MHz rf field and determined its temperature by solving the following integral equation

$$\int_0^{T(r)}\sigma(T)\chi(T)\mathrm{d}T=\frac{c^2H_0^2}{64\pi^2}\left[1-\frac{H^2(r)}{H_0^2}\right],\tag{2}$$

where T is the plasma temperature, σ is the conductivity, χ is the thermal diffusion constant, c is the light velocity and H is the magnetic rf field. He shows that the temperature calculated from eq. (2) is qualitative agreement with the experimental results.

In order to confirm the local thermal equilibrium assumption, we mixed several percent of hydrogen gas to the argon plasma, and get the electron temperature from the intensity ratio of Balmer series. The local thermal equilibrium assumption is not good in this case since the electron temperature which determined from the intensity ratio of Balmar series is about from 0.2 to 0.7 eV and does not agree with that measured from the free-bound transion continuum.

P. L. Kapitza has made a filamentary plasma, which size of the plasma is 10 cm in length and 0.45 cm in diameter. The microwaves used are 19.3 cm in wavelength and the input power to the plasma is 12.4 KW. This plasma has a high electron temperature of 100 eV and ion temperature of several ten eV. He explains these phenomena by the assumption that anomalous resistivities by hot electrons in the plasma increase the electron temperature and a neutral blancket made from weakly ionized gases keep the plasma hot. The neutral blancket models are firstly proposed by H. Alfvēn and E. Smärs [5]. P. L. Kapitza also explains the difference between the filamentary mode and diffusion mode, to which he refer the customory rf mode, depends on the gas impurity and gas species. He succeeded in making the filamentary hot plasma by the deutrium and the helium, and by other gases

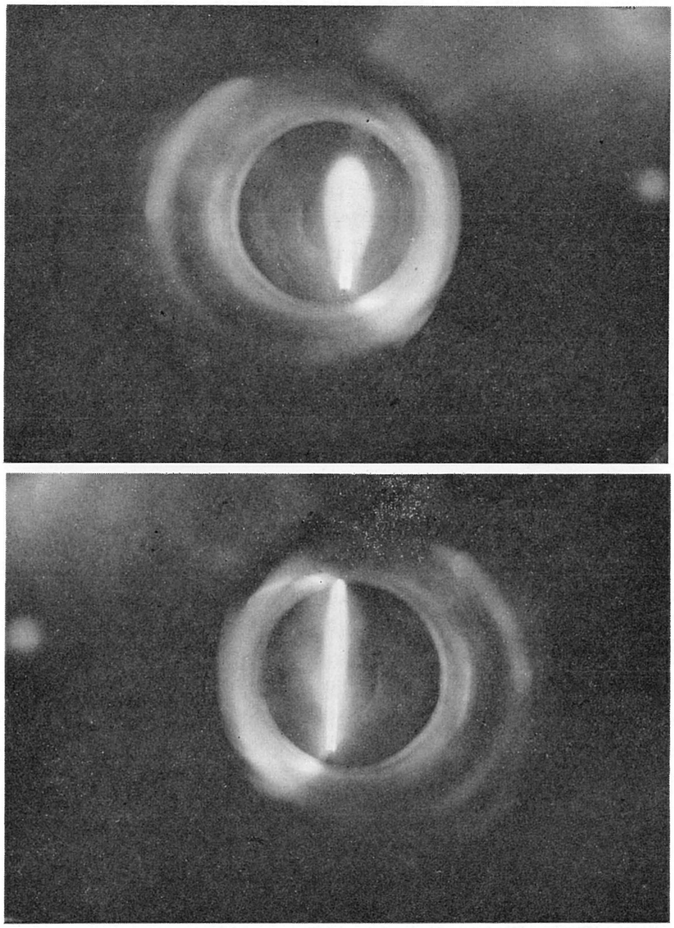

Fig. 8. The plasma ignited on the tungsten needle. The upper photograph is in 1 atm. and the lower is in 1.8 atm.

can such a plasma not be made. The filamentary type plasma has double layers, that is to say, fully ionized hot part and weakly ionized thermal blanket part like photograph of Fig. 8.

In order to heat our plasma, we increased the input power to the plasma, then at some power, one plasma divides into two filament type plasmas along the *E*-field. This phenomena also observed by Kapitza. More increase of the input power make the two filament connect one another and a sudden instability occours. This can be explained that the bar of the plasma in the cavity changes microwave TM_{11} mode into coaxal mode and that this mode transition of the microwave changes the axial electric field into a radial directional electric field. By this radial field a discharge occures between the filamentary plasma and cavity wall. As a result of this dischrage, the microwave mode goes out of order and plasmas jumps up and touches the upper wall by buoyancy forces. So we can not enter the power into the plasma with this non-gas-circulation cavity. The limits of the input power to the filament plasma are about from 100 to 200 watts in our experiment. In this power level, the electron temperature of the plasma is 1.4 eV. This type of plasma is not a diffused type but a filamentary one, while the electron temperature is low compared with Kapitza's one. So we must distinguish the filamentary plasma explained by the Schottky's theory from above two types.

As is seen in Fig. 8, the filamentary plasma has double layers, so we mesure this layer by the interferometer method with HCN laser. The electron concentration increase steeply in the central part suggesting that the central part of the plasma is rather in highly ionized state. A radial distribution of T_e is not measured precisely because it is difficult to measure it by spectroscopic methods.

5. Conclusion

(1) The filamentary plasma ignited by low microwave powers can be explained by the Schottky's positive column theory.

(2) This filamentary plasma is not in the local thermal equilibrium and the central part has a rather highly ionized part than out side one, which shows that this plasma has a double layer as mentioned by P. L. Kapitza.

(3) We can easily get a filamentary plasma in the argon gas diffrent from the helium and the hydrogen gases by which Kapitza made a filamentary plasma.

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