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A STUDY OF HIGH POWER MICROWAVE AIR BREAKDOWN

Liu Guo-zhi (刘国治), Liu Jing-yue (刘静月), Huang Wen-hua (黄文华),
Zhou Jin-shan (周金山), Song Xiao-xin (宋晓欣), and Ning Hui (宁 辉)
Northwest Institute of Nuclear Technology, Xi'an 710024, *China*

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This paper presents the results of research on microwave breakdown in air, it includes the experimental study and the theoretical analysis. The experimental study has been done in a waveguide with a frequency of 9.37GHz, the peak power up to 200kW, pulse width from 0.3 to 2.0μs. The repetition rate of microwave source is from single pulse to 970 pulse per second. The process of the breakdown of repetition pulse has also been recorded for a burst of ten pulses. A theoretical model for breakdown threshold is presented also. The theoretical are in good agreement with the experimental ones.

Keywords: high power microwave, air breakdown
PACC: 5240D, 5280, 5240M

I. INTRODUCTION

The propagation of high power microwave (HPM) through the air is a process which strongly concerns with such factors as air breakdown effect, air absorption and scattering, and the reflection, diffraction scattering of HPM from all kinds of ground obstacles.[1,2] The high energy density of HPM makes air breakdown effect the most significant phenomena for the study of the propagation of HPM through atmosphere. In the meantime, several events may arise from the HPM air breakdown. These events are: the decay of HPM pulse, erosion, and the power reflection from the air breakdown point. The decay and erosion of the HPM pulse limit the power that can be transmitted to targets, and consequently decrease the efficiency of the HPM source; moreover, the reflected power caused by the air breakdown plasma may be dangerous to the HPM source. Furthermore, for the design of HPM systems, it is very important for the designers to have a deep understanding of the mechanism of HPM air breakdown and obtain relevant experimental data, including the breakdown thresholds for different HPM parameters (frequency, pulse duration, repetition rate and power). Therefore, a waveguide was set up to study HPM air breakdown, and theoretical analysis was made to understand the mechanism of it. The experimental and theoretical results were compared with each other and some conclusions were drawn.

The high density plasma generated by HPM air breakdown results not only in the reflection, absorption, and erosion of HPM pulse, but also in such phenomena as enhancement of field amplitude, broadening of spectrum, and self-focusing of HPM while certain conditions are satisfied. The enhancement of HPM amplitude may be due to the dispersion characteristic of the plasma, sometimes the amplitude of the field can be higher than that of the injected HPM pulse. As for the broadening of HPM spectrum, the main reason is that the pulse duration of the incident HPM is shortened by the breakdown plasma. When the plasma density satisfies some conditions, the transmitted HPM pulse will be focused. As the first step, this study focused only on the generation of plasma and the HPM air breakdown thresholds for different HPM parameters.

II. THEORETICAL ANALYSIS OF HPM AIR BREAKDOWN

A. The mechanism of HPM air breakdown

When the air is subjected to a microwave electric field, the free "seed" electrons are accelerated. If the microwave electric field is high enough to transfer sufficient energy to the "seed" electrons, and the accelerated electrons can suffer more than one collisions during the microwave period, i.e., $E\lambda_e \geq V_0$ then one could expect more electrons to be freed from neutral molecules and atoms. Most of the collisions are inelastic so that ionization of molecules and atoms is induced under certain condition; as a result the number of free electrons will be sharply increased till the avalanche breakdown occurs. As for the following interaction between microwave field and the plasma, it

should be noted that the energy transferred to the electrons is much greater than that transfered to the ions because of the mass difference, therefore in most cases the motion of ions can be neglected. The energy transferred to the plasma could be divided into two parts, namely, the field energy and the thermal motion energy of positive ions and electrons. The plasma can make the incident microwave decay. As the avalanche breakdown is developing, the density of free electrons and the plasma frequency increase. When the plasma frequency is approximately equal to that of incident microwave, the microwave pulse would be shielded by the plasma, and part of it is reflected. This effect is called tail-erosion. Since the formation of the plasma needs time, a part of incident microwave can go through the plasma before complete absorption or reflection occurs. The width and energy of the microwave transmitted through the plasma depend on the parameters of the air, the power density and the frequency of the incident microwave, etc.

The plasma frequency is $\omega_{\rm p} = (n_{\rm e}e^2/m_0\varepsilon_0)^{1/2}$; taking $\omega_{\rm p} = \omega$, we can get the critical plasma electron density for breakdown $n_{\rm e}^{\rm cr} = 10^{14}/9\lambda^2 \quad (1/{\rm cm}^3)$.

Some processes, including attachment, recombination and diffusion of electrons in the plasma, take place during the development of the air breakdown plasma. The attachment of electrons occurs mainly between the electrons and oxygen molecules in the air, and the number of electrons decreases exponentially due to this process. The number decrease caused by recombination process varies directly as t^{-1}. All these effects will be taken into consideration only when the plasma density is more than a certain value.

B. HPM breakdown thresholds of air

In the air, the equation of motion for free electrons can be expressed as

$$m\frac{{\rm d}\boldsymbol{v}}{{\rm d}t} = -\nu_{\rm m}m\boldsymbol{v} - e\boldsymbol{E}, \tag{1}$$

where $\nu_{\rm m}$ is the electron collision frequency for momentum transfer, $\boldsymbol{E}$ the incident electric field, and $\boldsymbol{v}$ the velocity of electrons. By solving Eq.(1) for d.c. and a.c.(microwave) applied E-field cases respectively, one can obtain the solutions for electron energy, the a.c. (microwave) field is equivalent to d.c. solution of the formula

$$E_{\rm e} = E_{\rm rms}\left(\frac{\nu_{\rm m}^2}{\omega^2+\nu_{\rm m}^2}\right)^{1/2}, \tag{2}$$

where $E_{\rm e}$ is the effective E-field, $E_{\rm rms}$ the mean square root of the applied E-field, and ω the frequency of the microwave radiation.

From Eq.(2) one can see that if $\nu_{\rm m} \gg \omega$, then $E_{\rm e} \approx E_{\rm rms}$, which means if the microwave frequency is far less than $\nu_{\rm m}$, the applied microwave can be treated as effective d.c. E-field. It should be noted that Eq.(2) requires that $\nu_{\rm m}$ is independent of electron energy, which is not true in the case of low pressure. The electron collision frequency for momentum transfer can be approximately expressed as

$$\frac{\nu_{\rm m}}{P} = \frac{2.35\times10^9(E_{\rm e}/P)}{1+0.58(E_{\rm e}/P)} \qquad 1 \le E_{\rm e}/P \le 30, \tag{3}$$

$$\frac{\nu_{\rm m}}{P} = \frac{3.24\times10^8(E_{\rm e}/P)}{1+0.04(E_{\rm e}/P)} \qquad 30 \le E_{\rm e}/P \le 54, \tag{4}$$

$$\frac{\nu_{\rm m}}{P} = \frac{2.93\times10^8(E_{\rm e}/P)}{1+0.041(E_{\rm e}/P)} \qquad 54 \le E_{\rm e}/P \le 120, \tag{5}$$

$$\frac{\nu_{\rm m}}{P} = 5.2\times10^8(E_{\rm e}/P)^{1/2} \qquad 120 \le E_{\rm e}/P \le 3000, \tag{6}$$

where $E_{\rm e}/P$ is in the units of V/(Pa·cm). The electron density of plasma satisfies

$$\frac{{\rm d}n_{\rm e}}{{\rm d}t} = n_{\rm e}\nu_{\rm i} - n_{\rm e}\nu_{\rm a} - n_{\rm e}\nu_{\rm r} - n_{\rm e}\frac{D}{\Lambda^2}, \tag{7}$$

where $\nu_{\rm i}, \nu_{\rm a}$ and $\nu_{\rm r}$ are the collision frequencies for ionization, attachment and recombination respectively, D is the diffusion coefficient, and Λ the characteristic dimension of the plasma. For continuous wave, when ${\rm d}n_{\rm e}/{\rm d}t \ge 0$, the air breakdown may occur, ${\rm d}n_{\rm e}/{\rm d}t = 0$ is defined to be the critical air breakdown condition, i.e.,

$$\nu_{\rm i} = \nu_{\rm a} + \nu_{\rm r} + D/\Lambda^2. \tag{8}$$

In the case of pulse microwave, solving Eq.(7) yields

$$\ln\frac{n_{\rm e}^{\rm cr}}{n_{\rm e0}} = \int_0^\tau \nu{\rm d}t, \tag{9}$$

$$\nu = \nu_{\rm i} - \nu_{\rm a} - \nu_{\rm r} - D/\Lambda^2. \tag{10}$$

If the waveform of the microwave pulse is square, we have

$$\frac{\nu}{P} = \ln\left(\frac{n_{\rm e}^{\rm cr}}{n_{\rm e0}}\right)\times\frac{1}{P\tau}, \tag{11}$$

where P(Pa) is the air pressure, $n_{\rm e}^{\rm cr}$ the critical electron density for air breakdown, $n_{\rm e}^{\rm cr} = (10^{14}/9\lambda^2)\,(1/{\rm cm}^3), n_{\rm e0}$ the initial electron density and τ the time duration from the starting of the pulse to the moment at which the electron density is equal to $n_{\rm e}^{\rm cr}$. Suppose that when $\omega_{\rm p} = \omega$, the power of the incident microwave decays by about 10%. Since the

rise time of the microwave pulse, namely t_r, is not zero even for square waves, supposing the relationship of ν and t is linear, we obtain

$$\frac{\nu}{P} = \ln\left(\frac{n_e^{cr}}{n_{e0}}\right)\frac{1}{P(\tau' - t_r/2)} = \ln\frac{n_e^{cr}}{n_{e0}}\frac{1}{P\tau}. \quad (12)$$

Equation (12) indicates that the transmitted microwave pulse width τ is determined by the difference of τ' and $t_r/2$, here τ' is the time from the starting of the pulse to 90% of the falling edge of the pulse. The impact ionization frequency ν_i can be expressed as

$$\frac{\nu_i}{P} = [1.32 + 0.054(E_e/P)] \cdot 10^7 \exp\left(-\frac{208P}{E_e}\right) \quad 30 \le E_e/P \le 54; \quad (13)$$

$$\frac{\nu_i}{P} = [5.0 + 0.19(E_e/P)] \cdot 10^7 \exp\left(-\frac{273.8P}{E_e}\right) \quad 54 \le E_e/P \le 120; \quad (14)$$

$$\frac{\nu_i}{P} = 54.08 \times 10^6 (E_e/P)^{1/2} \exp\left(-\frac{359P}{E_e}\right) \quad 120 \le E_e/P \le 3000. \quad (15)$$

The attachment coefficient ν_a is expressed as

$$\frac{\nu_a}{P} = \frac{8.3 \times 10^6}{T_e^{3/2}} e^{-6.7/T_e} + \frac{3.98P}{T_e^{3/2}}, \quad (16)$$

$$DP = 2736\left(1 + \frac{T_e}{5}\right), \quad (17)$$

where T_e is the electron temperature (eV), and can be expressed as

$$T_e = 0.1(E_e/P)^{1.43} \quad 1 \le E_e/P \le 5; \quad (18)$$

$$T_e = 0.4(E_e/P)^{0.577} \quad 5 \le E_e/P \le 54; \quad (19)$$

$$T_e = 2.17(E_e/P)^{0.15} \quad 54 \le E_e/P \le 150; \quad (20)$$

$$T_e = 0.18(E_e/P)^{0.65} \quad 150 \le E_e/P \le 500. \quad (21)$$

The recombination coefficient ν_r is

$$\frac{\nu_r}{n_e} = 4.8 \times 10^{-8}(T_e)^{-0.39} + 2.1 \times 10^{-8}(T_e)^{-0.63}. \quad (22)$$

Assuming $P = 1.013 \times 10^5$Pa, E_e/P=0.488 V/(Pa·cm), one can evaluate $T_e \approx 4$eV, $\nu_i \approx 1.44 \times 10^8 s^{-1}$, $D/\Lambda^2 \approx 6.5/\Lambda^2$, before air breakdown occurs, i.e., for $n_e \le 10^{13} cm^{-3}$, $\nu_r \le 3.6 \times 10^5 s^{-1}$. These evaluations show that it is reasonable to omit the losses due to electron diffusion and recombination; furthermore, it is also acceptable to ignore ν_a because ν_i is 10 times greater than ν_a.

By employing formula (2)–(15), the calculated results are plotted in Figs.1 and 2. The figures show E_e/P vs $P\tau$ and E_{rms} vs P curves for different frequency(f=1,3,5 and 10GHz), respectively (the pulse width in Fig.2 is 50ns).

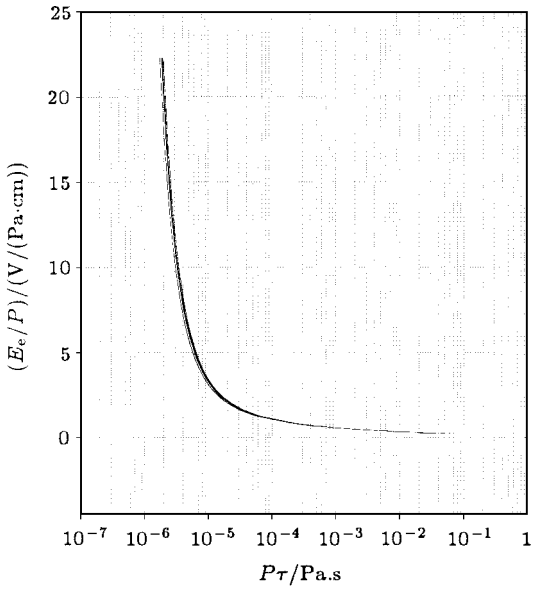


Fig.1. Theoretical curve of E_e/P vs $P\tau$.

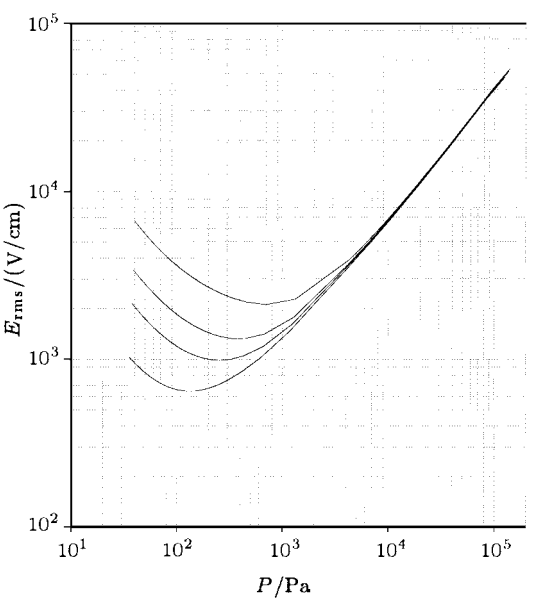


Fig.2. Theoretical curve of E_{rms} vs P for 50ns microwave pulse.

Ⅲ. EXPERIMENTAL APPARATUS

The air-breakdown experiment was done in a waveguide.[3] There are some advantages to employ this method: for example, a relative low-power microwave source is required and the measurement can

be performed easily and exactly. Furthermore, the key point to use this method is that this work can be carried on present microwave source.

Because the electric field obtained by using the radiate focusing under the restriction of the diffractive limits is much lower than that obtained in a matched waveguide for a given microwave source, the study can be done in a much wider range of air pressure and microwave pulse width in a waveguide. But there is an important problem to study air-breakdown in a waveguide because of the influence of the waveguide wall effect. Analysis indicated that the wall effect can be ignored when the mean free path of plasma electron is much shorter than the waveguide dimension. The mean free path of the electron in the air can be expressed approximately as

$$\lambda = 1/(N\sigma) = 0.028/P \qquad (\mathrm{cm}),$$

when the pressure is greater than 13.3Pa, λ will always be much less than the waveguide dimension (1.0 cm), and the condition ignoring the wall effect will be met.

Another problem is the influence of the field emission from the waveguide wall. Under an ideal condition, the field emission will take place under the effect of intense electric field (about 3–6GV/m), however, in an ordinary waveguide because the electric field threshold of the field emission will be influenced by the factors such as frequency and the surface status, etc., the field emission start-up electric field is about 1GV/m, and this value is greater than that in our experiments(below 2×10^7V/m). Therefore, we can consider that no field emission will occur. According to the above analysis, the conclusion can be drawn that it is feasible to carry out the HPM air-breakdown study in a waveguide.

In our experiments, the working frequency and the peak power of the microwave source we employed are 9.37GHz and 200kW, respectively, and this source can be fixed at four pulse widths τ=2.0, 1.5, 1.0, 0.5μs, corresponding to the repetition rate of the pulse of 500, 667.5, 976.5 and 2000Hz, respectively; and it can be run at single pulse mode and pulse string mode in every case. In the experiment, with the incident pulse width τ of the microwave source being fixed firstly, the input power is measured using an average power meter, and the waveforms of the incident, reflected and transmitted microwave pulses are recorded. The experimental arrangement is shown in Fig.3.

The microwave pulse enters the transmission system after passing through a circulator, then the pulse propagates through a directional coupler and is injected to the test waveguide section, which is sealed by a waveguide window. There are vacuum pumping systems in the test section to change the air pressure. At the terminated end of the test section, some microwave devices ,such as directional coupler, attenuator and detector, etc. , are connected to record the transmitted pulse waveform through the test section. The incident pulse and the transmitted pulse in the test section are sampled and recorded from the upstream and downstream of the 40dB directional coupler respectively, before passing through attenuator and detectors, etc.

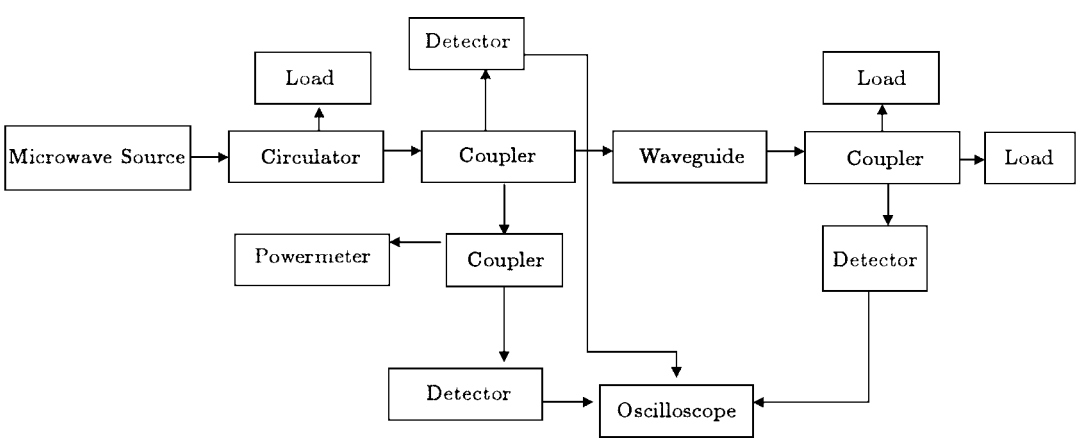


Fig.3. Schematic diagram of the HPM air breakdown experiment.

IV. EXPERIMENTAL RESULTS AND ANALYSIS

Two kinds of experiments were done. At first, single pulse was used, then a series of pulse was used and the transient process of the breakdown was recorded.

A. Single pulse experiment

In this experiment, the pulse width τ and the power P_w of the incident microwave pulse and the air pressure in the test section were constant, the incident, reflected and transmitted pulse waveforms were recorded, and the typical waveforms are shown in Fig.4. Figure 4(a) shows the incident, reflected and transmitted pulse waveforms under the condition of incident power 178kW and pressure 1.33×10^3Pa, the transmitted pulse width is about 8 ns. Figure 4(b) shows those under the condition of incident power 172kW and pressure 2.66×10^4Pa. By analyzing the reflected and transmitted waveforms , one can conclude that the plasma has been produced at different positions several times in the breakdown process and most of the microwave energy was absorbed by the plasma. The waveforms can be explained by the movement of the breakdown points. The duration between the breakdown points is 100 ns (read from the duration between two peaks) , and it equals to the forming time of the plasma. The movement of the breakdown point is caused by the standing wave formation of the incident microwave pulse. When the plasma at one certain position is intense enough, the incident microwave is reflected from plasma, then the standing wave is formed. The E-field can be as great as 2 times of the incident wave at $\lambda/4$ position from the reflected point; for this reason, the breakdown would appear in this point. The same process can repeatedly take place, making the breakdown point moving towards the microwave source. According to this, it is reasonable for us to expect that in the interaction of HPM with metallic targets, the air breakdown most likely occurs at the $\lambda/4$ position from the surface of targets, As a result, the threshold of HPM breakdown decreases. Figure 4(c) shows the incident, reflection and transmission pulses (the incident power 165 kW, air pressure 4.40×10^4Pa).

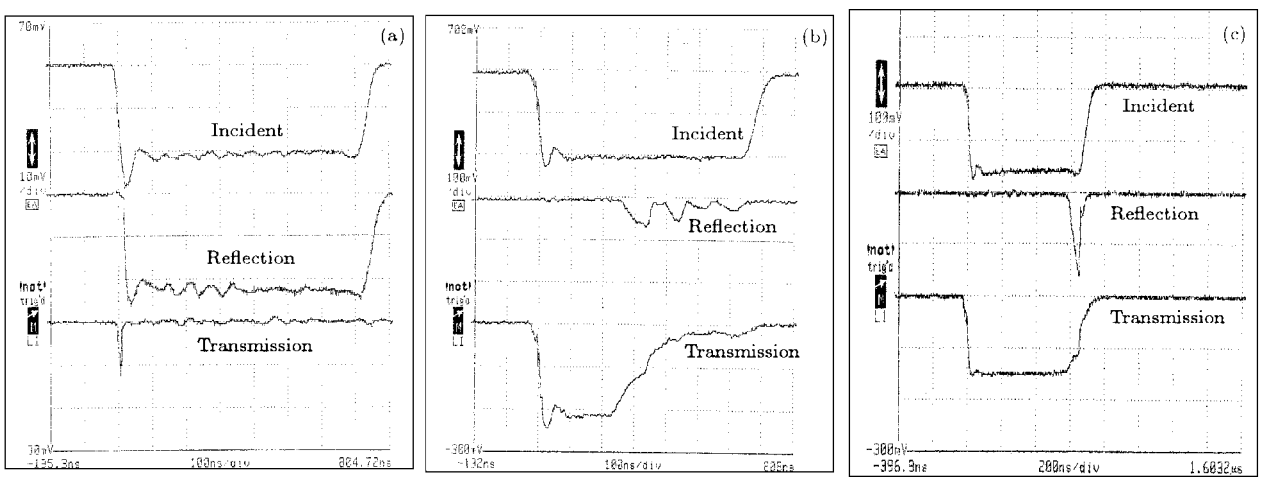


Fig.4. (a) Waveforms of incident, reflection and transmission when the incident power is178 kW and the atmospheric pressure is 1.33×10^3Pa; (b) Waveforms of incident, reflection and transmission when the incident power is172 kW and the atmospheric pressure is 2.66×10^4Pa; (c) Waveforms of incident, reflection and transmission when the incident power is165 kW and the atmospheric pressure is 4.40×10^4Pa.

A total number of 147 experiments were performed for air pressure range covering 1.33×10^3, 2.66×10^3, 3.99×10^3, 6.67×10^3, 1.07×10^4, 1.33×10^4, 2.00×10^4, 2.31×10^4, 2.39×10^4, 2.66×10^4, 3.33×10^4 and 4.40×10^4Pa. The statistical results are plotted in fig.5. The experimental results support our theoretical analysis.

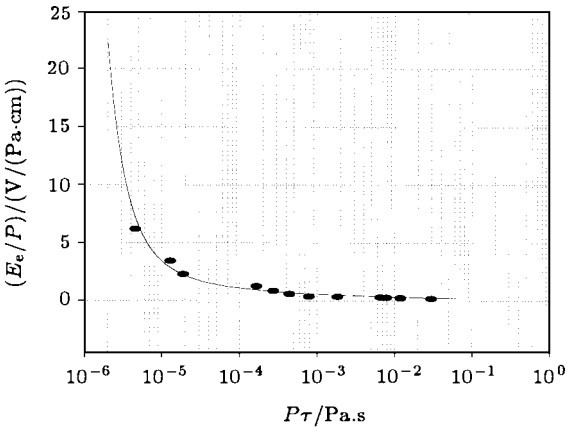


Fig.5. Comparison between the theoretical curve and experimental results of microwave air breakdown.

B. Repetitive pulses experimental results

The threshold of air breakdown is lowered and forming time of it is shortened by repetitive HPM pulse. It is attributable to the following events. First, the breakdown channel is heated and this effect results in the increase of the speed of ionization; second, the air density decreases due to breakdown channel heating; third, the ionization process arise by one pulse would not disappear completely when the following pulse arrives, if the duration between each pulse is short enough. The ionization of the first pulse will provide additional free electrons for the following pulse, resulting in relatively low threshold and short breakdown period. It should be noted that this effect is notable only in the case of high repetition rate. Figure 6 shows the experimental results for stable air breakdown under multi-pulse situation, the incident power is 156 kW, air pressure 7.18×10^3Pa, and pulse repetition rate 976.5Hz. As the power of incident pulse is 166 kW, pulse width 1μs, and air pressure 4.40×10^4Pa, a series of breakdown events were recorded, as shown in Fig.7. The experimental results indicate that the first transmission pulse width is about 730 ns, the following pulse width ranges from 12 to 20 ns.

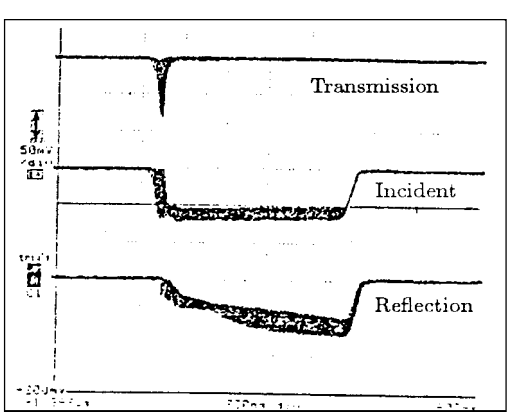


Fig.6. Waveform of stable breakdown of repetition rate is 976.5Hz when the incident power is 156 kW, the atmospheric pressure is 7.18×10^3Pa.

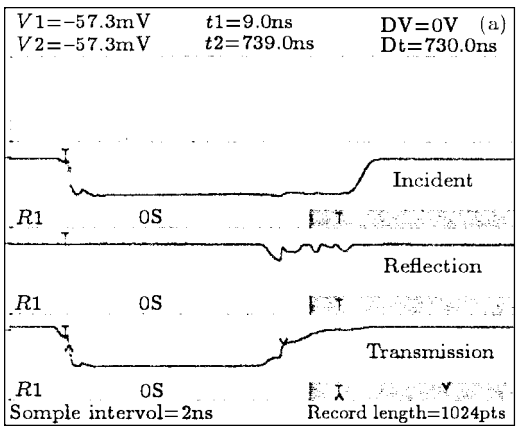


Fig.7. (a) The first waveform in the processes of the breakdown of repetitive pulse.

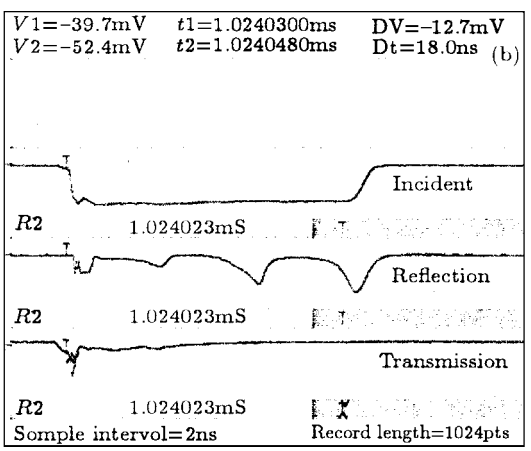


Fig.7. (b) The second waveform in the processes of the breakdown of repetitive pulse.

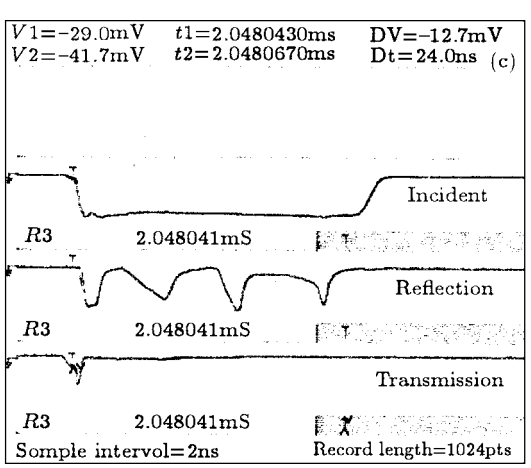


Fig.7. (c) After the third waveform in the processes of the breakdown of repetitive pulse.

V. CONCLUSIONS

This paper mainly introduce some experimental results of HPM air breakdown, but some correlative physics phenomena of air breakdown need to be further analyzed. As the first part of a long-term research program, the future work will concentrate on the study of short-pulse, low air pressure HPM air breakdown.

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