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RESONANCE ABSORPTION OF *RF* ELECTRIC FIELD ENERGY BY NEGATIVE POINT-TO-PLANE GAP

B.A. Andrianov

Resonance absorption of *rf* energy, the maximum of which happens at the frequency equal to or a multiple of that of Trichel pulses, was discovered on connecting both an *rf* voltage of low amplitude and high direct voltage to the negative point-to-plane gap. Resonance curves were recorded by scanning the high voltage at fixed frequencies. It was found that the initial portion of dependence between resonance frequency and electrostatic field strength near the plane is linear, and has the same factor of proportionality for different gap lengths, estimated as (1.0 ± 0.2) Hz m/V.

The most remarkable property of the negative corona is Trichel pulses [1]. Together with strict periodicity the characteristic feature of these pulses is linear dependence between their repetition frequency and an average discharge current over a vast frequency range. Such a capability of the negative corona for the self-ordering of electrical processes in itself seems to be vague evidence suggesting that Trichel pulses are a quantum phenomenon, and their reason is concealed deeper than it has been supposed up till now [2].

This experimental study of such a discharge was carried out by subjecting it to both direct and alternating electric fields with the frequency of the latter being varied from tens of kilocycles to a few megacycles. Experiments were performed in air at normal atmospheric pressure and room temperature.

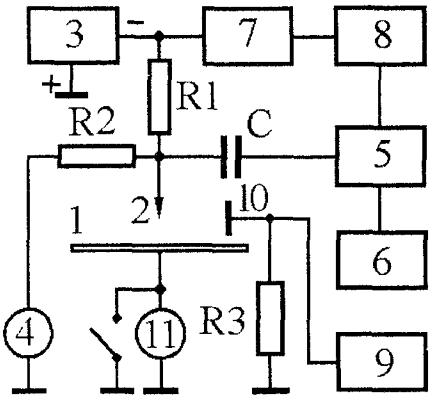

Fig.1. The scheme of the installation: 1 – plane; 2 – point; 3 – source of high voltage; 4 – kilovoltmeter C196; 5 – Q-meter E4-4; 6 – frequency meter 43-57; 7 – voltage divider; 8 – plotter H-307; 9 – oscilloscope C1-93; 10 – wire ring probe; 11 – microammeter M-494

The scheme of an installation is shown in Fig. 1. The electrode system consists of a grounded copper disk 1 and a sharp steel needle 2 which is connected through a resistor R1 to the negative pole of an adjustable source of high voltage 3. This voltage is measured by an electrostatic kilovoltmeter 4. Through a separating capacitor C the needle is also linked to the capacitor terminals of the Q-meter 5. A standard coil, from a kit of the Q-meter for a chosen frequency range, is connected to the inductance terminals of this device. The frequency is measured by a frequency meter 6. The output voltage of the Q-meter and the high voltage reduced by a divider 7 can be applied to the Y- and X-inputs of a two coordinate plotter 8 respectively. The oscilloscope 9 is connected to a ring wire probe 10 and used for observing the amplitude of alternating electric fields. This probe also detects the Trichel pulses, which are clearly seen when the alternating electric field is turned off. Under this condition a frequency of Trichel pulses can be measured by the frequency meter 6 when it is disconnected from the Q-meter and connected to the probe 10 in parallel to the oscilloscope.

To facilitate observance of these pulses at higher frequencies the fast amplifier U3-29 (not shown on the scheme) can be connected between the probe and the oscilloscope. The average discharge current can be measured by a microammeter 11. So the Q-meter serves the dual function of supplying an alternative voltage to the gap, and monitoring any changes in its electrical properties by varying quality-factor of an oscillatory circuit. The gap with the series capacitor C and the built-in measuring capacitor of the Q-meter are connected in parallel and serve as a composed capacitor in this circuit. The choice of capacitance of the capacitor C permits us to preset an amplitude of the alternating voltage applied to the gap. Resistor R2 eliminates the impact of kilovoltmeter's capacitance on the oscillatory circuit described above.

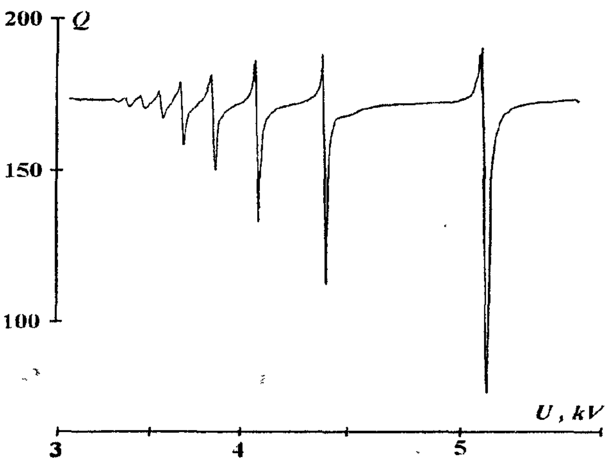

Fig. 2. Quality-factor Q of oscillatory circuit versus high direct voltage U at f = 1 MHz, h = 5 mm (f is a frequency of a built-in oscillator of the Q-meter, and h is a gap length)

The Q-meter is tuned to a chosen frequency, then a high direct voltage is applied to the gap. In the vicinity of certain values of this voltage one can observe a resonance decrease of the quality-factor as can be seen in Fig.2. By the smooth detuning of the Q-meter in the resonance minimum it can be easily verified that the natural frequency of the oscillatory circuit has remained intact (if, of course, the decrease of the quality-factor is not too much). Under resonance conditions the amplitude of the oscilloscope signal is subjected to an abrupt fall indicating considerable (sometimes almost complete) absorption of *rf* energy in the gap. The average discharge current changes monotonously under these conditions, so that the observed decrease of the quality-factor is not caused by any abrupt increase of the total conductance of the gap.

Nevertheless, the possibility of a local conductivity increase must not be ruled out if one takes into account not the total dc conductance but the resonance admittance of the equivalent oscillatory circuit where the gap is regarded as an imperfect capacitor, represented by a pure capacitance C* shunted by a resistance R. From considering this model the quality-factor of the circuit due to the loss in capacitor alone may be written as [3] $Q \approx \omega_r C^* R$ (ω_r is the resonance cyclic frequency). Therefore, the relative change of the quality-factor may be expressed through the relative change of R as $\Delta Q/Q \approx \Delta R/R$ (The sign Δ above and below means an absolute change of the value to its right). Taking into account that a resistance varies in inverse proportion to a carrier concentration n (the number of carriers per unit volume) [3] when a carrier mobility is assumed to be constant, one may write

$$\Delta Q/Q \approx -\Delta n/(n + \Delta n). \qquad (1)$$

In other words, the resonance decrease of quality factor may be caused by resonance increase of an electron density in a space charge of the negative corona.

A family of resonance curves, presented in Fig.2, was recorded by scanning the high voltage at a fixed frequency. Measurements of the frequency f_{Tr} of Trichel pulses show that the resonance values of the high voltage correspond to the direct or multiple resonance frequency f_r of the alternating voltage to that of the Trichel pulses according to the equation

$$f_r = N f_{Tr} \; (N = 1, 2, 3, \ldots). \qquad (2)$$

In Fig.2 the extreme right resonance curve was recorded at the equality $f_r = f_{Tr}$ (N=1), while the adjacent curve corresponds to N=2 etc. One can follow resonances up to the eight-fold, i.e. when the Trichel pulses frequency is less than the tuned frequency by a factor of 8. No resonances are observed over the whole area where the Trichel pulses frequency exceeds that of the alternating electric field.

The shape of the resonance curve, as is obvious in Fig.2, is apt to be a mixture of absorption and dispersion signals well-known from ordinary magnetic resonance phenomena (see, for example, Fig.12 in [4]).

The contribution of each of these signals seems to depend on the accuracy of tuning and/or uncontrolled phase shifts in the measuring system.

Another feature of described phenomenon, in common with magnetic resonance, is *rf* widening: it was noticed that the half-width (the width at half height) of the resonance curve, recorded by scanning the high voltage, doubles when the amplitude of the *rf* voltage is increased two-fold as shown in Fig.3.

At first sight resonance absorption of *rf* energy in phase with Trichel pulses (or with their garmonics) would seem to be wholly expected. Nevertheless a detailed analysis, based on the expansion of Trichel pulses in the Furier series, shows that all expectations are disproved by the experiment. Above all this is concerned with the shape of the resonance curve. If Ω is not exactly equal to ω_r, one must observe beats on the difference frequency $|\Omega - \omega_r|$. These beats should be expected because they are the characteristic property of a superposition of any two vibrations with neighbouring frequencies. As the frequency of Trichel pulses is approached ω_r, these beats should be better distinguished, that is they must be necessarily observed just close to the resonance minimum at $\Omega=\omega_r$. Therefore the shape of the resonance curve must be determined by these beats. In spite of these predictions, no beats are observed within the resonance curve even during the very slow scanning, as it can be seen in Fig.3: the shape of this curve has obviously nothing in common with the expected beats. Thus the absorption shape of the resonance curve is unexpected as well as the existence of this resonance itself.

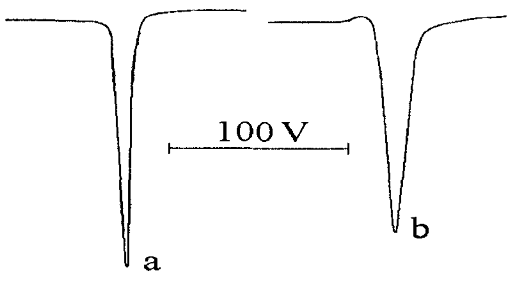

Fig. 3. *Rf* widening of the resonance curve at f = 800 kHz, h = 2 mm: *rf* voltage applied to the gap while recording the curve *b* is nearly twice as large as that for the curve *a*. Both curves are recorded according to the same horizontal scale, but the vertical scale for the curve *b* is halved. The resonance value of the high direct voltage is the same for both curves

Due to oscillatory circuit selectivity, frequency scanning cannot be performed in this installation, but frequency dependence of the resonance can be constructed from Q-values measured at different frequencies and fixed direct voltage. One example of that reconstruction is shown in Fig.4. It shows that the half-width of the resonance curve is about 10 kHz.

Thus the resonance curve can be obtained not only by the dc electric field scanning at a fixed frequency, but also by varying the frequency at a fixed dc electric field strength, just as in a well-known magnetic resonance phenomenon one can obtain a resonance curve by a dc magnetic field scanning or by a frequency scanning [4].

The resemblance of these phenomena manifests itself from another more important side: as it will be seen further, the particular relation between the resonance values of frequency and the dc electric field strength does exists, that it is something akin to a gyromagnetic ratio [4] in magnetic resonance.

Measurements of different pairs of resonance values of direct voltage U_r and frequency f_r, corresponding to a minimum of a resonance curve at fixed electrode distances h, and providing N=1 in Eq.(2), show that the initial portion of the plot of f_r versus U_r is linear. Such a result may be expected because it is a consequence, on the one hand, of linear relationship between frequency of Trichel pulses and discharge current [1] and, on the other, of linearity of current-voltage curves in their initial portion [5]. The latter linearity was easily verified be direct recording of these curves on the XY-plotter.

The slope of the straight lines $f_r(U_r)$, of course, differs with different h-values. Nevertheless, the unexpected peculiarity is that one can get approximately the same slope for all lines by changing the voltage U_r to some electric field strength

$$E_r = kU_r/h, \qquad (3)$$

where h is the gap length, and k is a constant to be found.

With a burning corona k certainly cannot be equal to 1 at any point on the symmetry axis of the gap owing to the influence of a space charge.

To clear up whether such a spot really does exist in the corona discharge, where the electric field strength would satisfy the Eq.(3), one can use the results contained in the book [6]. This book includes a description of theoretical calculations and experimental research of electrostatic field distribution in the corona discharge in the point-to-plane gap, and the following approximate formula (independent of a point tip radius of curvature) was presented there for the electric field strength E on the symmetry axis of the gap at the distance x from the point tip towards the plane:

$$E = (3U/2h)\sqrt{x/h}\,. \qquad \mathbf{(4)}$$

Here U is a voltage between electrodes.

Experimental verification of Eq.(4) showed [6] that its calculation error does not exceed 10% even at distances up to 0.7 h from the plane (i.e. at $0.3 \le x/h \le 1$). Moreover, the electric

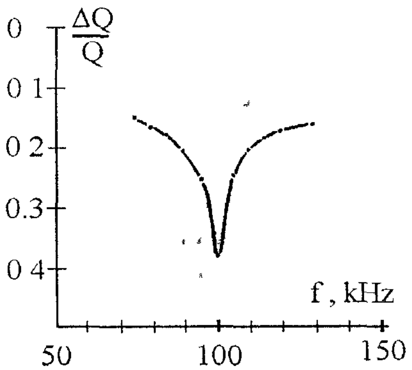

Fig.4. A relative decrease of the quality-factor ΔQ/Q *vs* frequency at fixed high direct voltage U = 2.2 kV and h = 2 mm

field strength does not differ from its value on the surface (i.e. at x=h) more than by 10÷15% everywhere within the mentioned region.

From these results it is possible to make a rough estimate of the electric field strength E_r in the most part of the gap as this strength on the plane:

$$E_r = (3/2)(U_r/h). \qquad (5)$$

Hence k=3/2 in Eq.(3) is well suited to the requirement above, and there is not only a spot, but a vast region within the gap where the electric field strength approximately satisfied Eq.(5).

Now the plots of f_r versus E_r can be constructed. They are presented in Fig.5 and really show the above-mentioned same slope at their initial portion which can be described by linear relationship

$$f_r = \gamma_E(E_r - E_0), \qquad (6)$$

where E_0 is some strength value, proportional to initial voltage and also satisfying Eq.(5), and γ_E is the sought-for proportionality factor. First of all, the same slope of these curves means that the main processes responsible for this slope are localized within an outer region of the negative corona, perhaps in the vicinity of the plane, because Eq.(5) describes an electric field just there. From experimental results presented in Fig.5 it follows that

$$\gamma_E = (1.0 \pm 0.2)\ \text{Hz m/V}. \qquad (7)$$

(The error includes both systematic and random components). An estimation based on the half-width of resonance curves, taken from similar curves to those of Figures 2,3 and 4, gives a γ_E -value of the same order, but with much more error.

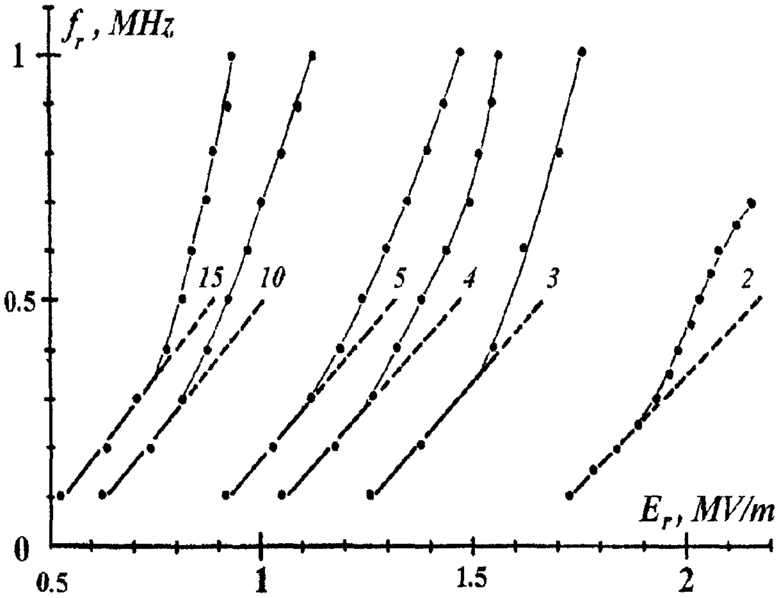

Fig. 5. Resonance frequency f_r *vs* resonance electrostatic field strength E_r on the plane against the point for different gap lengths. Denoted in mm near the each curve

Thus the described phenomenon of resonance absorption of *rf* energy in an electrostatic field in its main features may be regarded as an electrical analogy to the well-known phenomena of magnetic resonance. Just as a gyromagnetic ratio reflects the ability of Zeeman sublevels to absorb *rf* magnetic field energy under certain conditions [3,4], the existence of the single factor of proportionality γ_E may bear witness to the similar fundamental property exhibited by a substance confining the space charge of a negative corona. It suggests that a ground energy state of this substance in the dc electric field becomes capable of splitting up into some peculiar set of discrete sublevels whose populations can be equalized by the resonance absorption of the *rf* electric field energy at the frequency corresponding to an energy difference between adjacent sublevels. Incidentally, this point of view makes more understandable and explainable

- a sudden change of Trichel pulses frequency between different oscillation modes [5];
- the existence of the two-mode oscillation regime [5] of Trichel pulses, when two modes of different frequency were presented simultaneously;

- in particular almost the same slope of current-voltage curves for different modes as can be seen in the Figures 4 and 5 in [5].

This also raises the question of whether γ_E -value is responsible for some rotary motions caused by the dc electric field much like the gyromagnetic ratio is connected with precessional motions of magnetic moments round the direction of the dc magnetic field [3,4]. Does not this point of view give us some reason for believing that periodic electron avalanches, forming the Trichel pulses, can originate from an inverse population in this substance and represent a self-oscillation followed by destruction of some structural products of negative corona and liberation of electrons bound in these products (regarding to Eq.(1))? In any case the exact relation, expressed by Eq.(2), between the frequencies of two different phenomena – the resonance absorption of *rf* energy and the Trichel pulses–cannot be accidental and points to their deep interconnection and common origin. Hence, among possible unexpected applications, the discovered phenomenon may become the promising approach to studying the negative corona since the shape and half-width of a resonance curve apparently reflect kinetics of formation and decay of the space charge.

Of course, many questions still remain to be answered, so that further investigations are of doubtless interest.

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