On the initiation of explosive emission processes in the accelerating structures of compact linear colliders

S A Barengolts$^{1,2}$, Yu A Barengolts$^1$, V G Mesyats$^1$ and M M Tsventoukh$^2$

$^1$ Prokhorov General Physics Institute of the Russian Academy of Sciences, Vavilova 38, Moscow 119991, Russia
$^2$ Lebedev Physical Institute of the Russian Academy of Sciences, Leninsky Avenue 53, Moscow 119991, Russia

E-mail: sabarengolts@mail.ru

Abstract. The feasibility of the explosive emission mechanism of the initiation of vacuum breakdown in the accelerating structures of TeV-scale linear electron-positron colliders has been investigated. It has been shown that the experimentally observed relationship between the amplitude of the rf electric field and the delay in the development of breakdown can be caused by the effect of the space charge of the emitted electrons. For the delay times of the order of tens of nanoseconds, the amplitude of the rf electric field is about twice that of the dc electric field.

1. Introduction

Intensive work is currently underway to develop a TeV-scale electron-positron collider in the context of the international cooperation on the creation of the compact linear collider (CLIC). The accelerating structure of the CLIC, made of copper, operates in the x-ray range, namely at 11.994 GHz. In a system of this type, the amplitude of the particle accelerating electric field is mainly limited by the vacuum breakdown that may occur at the walls of the accelerating structure.

The initiation of vacuum breakdown is accompanied by the absorption of the electromagnetic field energy and the generation of a dense plasma propagating into the space of the accelerating structure. The propagation of the plasma leads to a partial or complete reflection of the electromagnetic wave and, as a consequence, to a decrease in the rate of acceleration of the particles. In addition, vacuum breakdown results in erosion of the walls of the accelerating structure, reducing its lifetime. At present, the maximum attainable accelerating field is 100 MV/m. At this accelerating field, the macroscopic electric field at the wall of the accelerating structure is over 200 MV/m [1,2]. The present study of the mechanism of rf vacuum breakdown is aimed at finding the maximum permissible characteristics of the walls of the accelerating chamber (surface roughness, material, etc) to lengthen the lifetime of the chamber for the operation at record high accelerating fields.

It should be noted that the recent work on the creation of an electron-positron collider has rekindled interest in investigating the mechanism of vacuum breakdown, breakdowns in dc electric fields included. Relevant theoretical studies have been performed that make use...
of modern numerical simulation methods and capabilities of novel computer equipment (see, e.g., [3]). The aim of this paper is to demonstrate the possibility of explosive electron emission occurring in the CLIC accelerating structures by using simple qualitative relations obtained in studying the pulsed vacuum breakdown [4, 5].

2. Criterion for the initiation of explosive electron emission in an rf field

The studies of rf vacuum breakdown have been underway since the development of the linear collider, however, little progress has been made in the understanding of its mechanism [1]. To date, two criteria for the development of vacuum breakdown in an rf field have been experimentally established. One of them relates the breakdown development rate (BDR), i.e. the probability of breakdown to occur within an rf pulse of duration \( t_p \), with the electric field amplitude \( E_A \):

\[
E_A^{30}/\text{BDR} = \text{const.}
\]  

(1)

The other criterion relates the quantities \( E_A \) and \( t_p \) at a constant BDR:

\[
E_A t_p^{1/6} = \text{const.}
\]  

(2)

The mechanism of vacuum breakdown in rf electric fields has not yet been adequately studied theoretically. Mesyats proposed the explosive-emission mechanism of vacuum breakdown [6]. According to this mechanism, breakdown is caused by heating of the microprotrusions present on the cathode surface by the emission current. A two-temperature (electrons and phonons) numerical simulation has shown that a microprotrusion can be heated to the melting point within tens of nanoseconds if the electric field at the microprotrusion is \( \sim 10^8 \) V/cm [7]. The time it takes for the microprotrusion to be heated to the melting point, \( t_m \), is related, like in the case of pulsed breakdown, with the current density as

\[
j_{av}^2 t_m = \text{const},
\]  

(3)

where \( j_{av} \) is the current density averaged over the rf field oscillation period. Relation (3) indicates that the main source of heat release in a cathode microprotrusion is its Joule heating by the emission current. The study [7] took no account of the effect of the space charge of the emitted electrons on the electric field at the microprotrusion tip. Therefore, the simulation predicted that the heating time \( t_m \) decreased exponentially with increasing rf electric field amplitude. At the same time, the pulsed vacuum breakdown studies have revealed that at a high electric field at the cathode, the electric field dependence of the breakdown delay time is described by the power function \( t_d \sim E_{av}^3 \) (\( E_{av} \) is the macroscopic field at the cathode) rather than by an exponential one. For planar electrodes, we have \( E_{av} = U/d \), where \( U \) is the voltage across the diode and \( d \) is the electrode gap spacing. The power-law field dependence of the breakdown delay time is due to the effect of the space charge of the emitted electrons. This effect is responsible for that the emission current density obeys the three-halves-power law [4]

\[
j_{3/2} = \frac{1}{9\pi} \left( \frac{2e}{m_e} \right)^{1/2} \frac{U^{3/2}}{d_{eff}^2},
\]  

(4)

where \( e \) and \( m_e \) are the electron charge and mass, respectively. The effective electrode gap spacing is given by \( d_{eff} = U/(\beta E_A) \), where \( \beta \) is the factor of field enhancement at cathode surface microprotrusions.

For rough estimates of the effect of the space charge of the emitted electrons, we may put \( d_{eff} = r_{em} \), where \( r_{em} \) is the radius of the emitting cathode microprotrusion [4]. Figure 1 presents the breakdown delay time \( t_d \) as a function of the amplitude of the rf field at the microprotrusion tip \( \beta E_A = U/r_{em} \). The value of \( t_d \) was estimated by a formula similar to formula (3), and the constant in equation (3) was taken equal to the specific action of current for an exploding copper
Figure 1. Breakdown delay time versus electric field at the tip of a cathode microprotrusion for \( r_{em} = 0.04 \) (points and curve 1), 0.1 (2) and 0.4 \( \mu \)m (3).

wire, \( \bar{h} = 4.1 \times 10^9 \, \text{A}^2 \text{s/cm}^4 \) [5]. To estimate \( j_{av} \), the field emission current density increasing with electric field was calculated by the Fowler–Nordheim formula, and for \( j_{FN} > j_{3/2} \), it was calculated by formula (4).

The plots given in figure 1 indicate that for a cathode microprotrusion heated by the emission current, an empirical relation similar in form to relation (2) can hold. The matter is that for the space charge effect be absent in the conditions of an rf breakdown experiment, the electric field enhancement factor \( \beta \) should be anomalously high, therefore, an intermediate situation between those described by curves 1 and 3 seems to be more realistic.

3. Relationship between the parameters of rf breakdown and dc breakdown
To clarify this issue and to find the relationship between the parameters of rf breakdown and dc breakdown, we estimate the time characteristics of the process of explosive electron emission initiation for these types of breakdown. To do this, we use the data on dc breakdown in vacuum given in [8]. The authors of this study used the same cathode material and processing methods as in rf breakdown experiments.

To estimate the electric field at the tip of a cathode microprotrusion \( E_0 \), we use a one-dimensional approximation and then discuss its domain of applicability.

In a 1D approximation, the field emission current density and the electric field at the cathode are related as [9]

\[
4kAU^{3/2} \exp \left(-B/E_0\right) - 3U = 9k^2A^2E_0^2d_{eff}^2 \exp \left(-2B/E_0\right) - 3E_0d_{eff},
\]

where \( A \) and \( B \) are the factors in the Fowler–Nordheim equation \( j_{FN} = AE^2 \exp(-BE) \) and \( k = 2\pi/(2m_e/e)^{1/2} \).

Figure 2 presents the electric field at the tip of a cathode microprotrusion as a function of the applied voltage, plotted using the data of [8]. To construct this plot, the electrode gap spacing \( d = 20 \, \mu \)m and the experimentally obtained average field enhancement factor \( \beta = 77 \) were used.
Figure 2. Electric field at the tip of a cathode microprotrusion versus applied voltage, according to the data of [8].

Table 1. Parameters of dc vacuum breakdown.

| $U$ (kV) | $E_{av}$ (MV/m) | $\beta E_{av}$ (GV/m) | $E_0$ (GV/m) | $j$ (A/$\mu m^2$) | $t_d$ (ns) |
|----------|-----------------|------------------------|---------------|-------------------|-----------|
| 2.3      | 115             | 8.86                   | 7.98          | 1.1               | 342       |
| 2.6      | 130             | 10.1                   | 8.55          | 2.12              | 91        |
| 2.9      | 145             | 11.2                   | 8.94          | 3.19              | 40        |

Table 2. Parameters of vacuum breakdown in an rf field.

| $U$ (kV) | $E_{av}$ (MV/m) | $\beta E_{av}$ (GV/m) | $j_{av}$ (A/$\mu m^2$) | $t_d$ (ns) |
|----------|-----------------|------------------------|-----------------------|-----------|
| 4        | 200             | 15.4                   | 1.82                  | 123       |
| 4.4      | 220             | 17.0                   | 2.26                  | 80.3      |
| 4.8      | 240             | 18.5                   | 2.73                  | 54.9      |
| 5.2      | 260             | 20.0                   | 3.24                  | 39.0      |

For these values, the field can be approximated, taking into account the space charge, by the formula

$$E_0 = \left[ (3.8 \times 10^4 U)^{-8} + (1.25 \times 10^7 U^{1/4})^{-8} \right]^{-1/8},$$

where $E_0$ is measured in V/cm and $U$ in V.

Tables 1 and 2 present the time characteristics of the process of initiation of explosive electron emission calculated for dc and rf voltages.
Table 3. Experimental data on breakdowns in dc and rf fields. The second and the third line give the averaged values of the dc breakdown characteristics reported in [8] and [10], respectively. The last column gives the maximum surface field from the rf experiment [11].

| Average breakdown field $\langle E_{av} \rangle$ (MV/m) | Average field enhancement factor $\langle \beta \rangle$ | Average local breakdown field $\langle \beta E_{av} \rangle$ (GV/m) | Maximum surface field in rf experiment $\langle E_A \rangle$ (MV/m) |
|----------------------------------------------------------|------------------|-----------------------------|-----------------|
| 159                                                      | 77               | 10.8                        | 260              |
| 170                                                      | 57               | 10.35                       | —                |

Despite the simplicity of the model under consideration, the data given in the tables are in good agreement with the experimental results (see table 3). Thus, the average value of $\beta E_{av}$ for a dc breakdown, $\langle \beta E_{av} \rangle = 10.8$ GV/m [8], corresponds to a delay time of about 50 ns. For vacuum breakdown delay times of the order of tens nanoseconds, the average macroscopic field is about 150 MV/m. Note that the breakdown initiation delay times (minus the rise time of the voltage across the gap, $\sim 100$ ns) measured for a copper cathode at a dc voltage are in the same range [8]. The rf field amplitude for these values of $t_d$ is 220–260 MV/m.

The field dependence of the delay time for an rf breakdown at $U = 4$–5.2 kV, $t_d \sim E_A^{-4.5}$ (see table 2), is somewhat weaker than that observed experimentally. This discrepancy may be accounted for by an incorrect estimate of the electric field at the microprotrusion tip. The matter is that the space charge of the emitted electrons is localized at a distance of $\sim 2 \times 10^{-6}$ cm from the cathode [9]. For microprotrusions of radius $< 10^{-5}$ cm (according to estimates [2], microprotrusions like these are present on the walls of the accelerating structures), the 1D approximation yields an underestimated electric field because of dimensional effects. Thus, according to the calculation of the electric field for micropoints of tip radius 10 nm in terms of a 2D model, the space charge of emitted electrons affects the breakdown parameters when we have $E_{av} > 9$ GV/m [12].

4. Conclusion
The simple model considered in this paper, while giving some agreement with experimental data, is unsuitable to quantitatively describe the characteristics of a rf vacuum breakdown. For doing this, it is necessary to solve self-consistently the two-dimensional problem of the heating of a microprotrusion and of the electron emission from it [13]. Nevertheless, we believe that the above estimates suggest that the considered mechanism of vacuum breakdown initiation in an rf electric field due to heating of microprotrusions by the emission current is feasible.

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