Coherent x-ray radiation induced by high-current breakdown on a ferrite surface

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Abstract
For the first time observed that at the initial stage of a high-current discharge, a low-divergence short (<2 ns) electromagnetic pulse is formed over a ferrite surface. The 50% part of the energy spectrum of this pulse lies in the region of sufficiently hard x-ray radiation (hν > 1 keV) with an energy of 0.6 mJ and an average power of 0.3 MW. The radiation propagates parallel to the surface in the anode direction with the angle divergence <2°. The high directionality of the radiation in absence of the aperture-limiting devices for the radiation beam and the quadratic dependence of the spatial radiation energy flux density on the length of working part of the ferrite prism points to the coherent nature of the observed radiation. A possible generation mechanism of the radiation is proposed. It is based on the short-lived magnetization of the ferrite plots by a high-power electromagnetic pulse and the subsequent coherent interference of unit waves irradiated by these plots.

Keywords: coherent, ferrites, x-ray, radiation, UV

(Some figures may appear in colour only in the online journal)

1. Introduction

In the studies of vacuum ultraviolet plasma radiation in a high-current discharge on a ferrite surface [1, 2] a low-divergence short electromagnetic pulse was detected at the initial stage of the discharge. The 50% energy part of this radiation is fairly hard—the corresponding energies of photons are higher than 1 keV. The brightness of this radiation significantly (by more than an order of magnitude) exceeded the brightness of the radiation of the ferrite surface measured in [1, 2].

The appearance of x-ray radiation from electrical discharges is now well known. Thus, in [3], an x-ray pulse was registered during the study of a formed-ferrite-flash plasma (initial voltage ~30 kV, discharge gap length 14.5 cm). Its formation began ~2 µs before the beginning of the high-current phase of the discharge, i.e. in the mode of heating the amorphous channel on ferrite and abruptly ended with the beginning of the high-current phase. In this mode, intense electron-ion emission occurred, electrons falling into a strong electric field formed beams of fast electrons that excited high-energy states of atoms and ions, followed by the emission of x-rays. This radiation was observed in [3] perpendicular to the ferrite surface and did not have a pronounced directivity.

The generation of x-ray radiation occurs not only with surface breakdowns. Thus, in [4, 5] x-ray radiation was observed in the pre-breakdown stage of pulsed atmospheric discharges caused by runaway electrons. In [6], intense x-ray radiation was recorded in a meter-long megavolt atmospheric discharge. A model of electronic acceleration with subsequent generation of x-ray quanta due to bremsstrahlung is proposed. In [7], it was discovered for the first time that x-ray bremsstrahlung at
a megavolt nanosecond breakdown of atmospheric air is characterized by a sufficiently high directivity (angular divergence $\sim 10^{\circ}$).

It is important to understand that the novelty of the present does not come from simply the fact of pre-breakdown x-ray radiation being registered. It is its unique properties that present interest and suggests a potentially useful and new mechanism for its formation.

2. Experiment and diagnostics description

The experiments were performed on a BIN generator with an output current amplitude of up to 270 kA and a rise time of 20 ns. A detailed description of the generator is given in [8]. The impedance of the generator forming line was $\sim 1 \Omega$, and the voltage at the generator output reached 240 kV, with the charging voltage of the forming line about 350 kV. The generator load was a rectangular ferrite (Ni–Zn) Fe$_2$O$_4$ prism of grade M1000NN with transverse dimensions $10 \times 20$ mm$^2$. The prism was mounted perpendicular to the diode axis (see figure 1(a)). By changing the electrode length on the cathode side, the length of the working part of the ferrite prism was varied from 1.5 cm to 7 cm. The current flow path on the ferrite surface was set by a pattern drawn with a graphite pencil. This path was generally the same during consecutive discharges in the experiment [1, 2]. The generator load was unmatched, and its impedance varied greatly during the pulse. The pressure in the discharge chamber did not exceed $10^{-3}$ Torr.

The radiation from the discharge was studied using calibrated diamond photoconductive detectors (PCDs) with flat spectral response $C = 5 \times 10^{-4}$ A W$^{-1}$ in the energy range from 10 eV to 10 keV. In the high-energy region, the sensitivity smoothly decreases with the absorption of carbon [9]. The transverse size of the detector crystals was $\sim 3 \times 1$ mm, whereas in the detection direction it was 0.5 mm, which provided sufficient sensitivity for the detector up to energies of 10 keV. Detector response time was less than 0.3 ns. The total time resolution of the recording channel was $\sim 2$ ns, with the bandwidth of the Tektronix TDS 3104B oscilloscope and the cable lines are taken into account. The detectors were typically placed at a distance of 26 cm from the end face of the ferrite prism at various angles for the discharge direction ($x$ axis in figure 1(a)).

In each experiment, two photodetectors were placed at different angles. The variation of the positions is shown in figure 1(a). In most cases, one remained stationary, and the other was placed at different angles. The radiation intensity was measured relative to one direction ($\sim$ position 2 in the figure). Photodetectors were connected to $-300$ V power supply and to an oscilloscope. The angular range of radiation detection in the ferrite surface plane $xy$ was $-8^\circ < \theta < +22^\circ$ (azimuthal angle), and in the $xz$ plane, orthogonal to the ferrite surface, it was $-1^\circ < \alpha < +5^\circ$ (polar angle). To estimate the width of energy distribution over the cross-section of the generated beam, we used Fuji BAS TR imaging plates sensitive to both x-ray and UV radiation; the plates were placed at a distance of 26 cm from the end face of the ferrite prism. To filter the bright UV emission of the discharge [1, 2], the films were covered by an aluminum foil. The time dependence of the load current was calculated by numerical integration of the signal from the Rogowski coil (with a bandwidth of $>500$ MHz). The output voltage on the discharge gap was measured by a resistive-capacitance voltage divider. All measuring instruments and diagnostics are connected through cables of known length, which allows positioning in time signals with an accuracy of more than 0.5 ns.

3. Experimental results

The time dependences of the discharge current, applied voltage, and the radiation intensities recorded along and perpendicular to the ferrite surface (PCDs in positions 2 and 7) are shown in figure 2. Also, a first derivative of the voltage is presented in this figure. The experimental conditions were the following: the length of the working part of the ferrite prism was $l = 6.5$ cm; one detector was placed parallel to the working surface of the prism at a distance $L = 26$ cm from its end face, and the other was placed perpendicular to the working surface at the same distance.

It is seen in figure 2(a) that at the initial (pre-breakdown) stage of the discharge, when there is almost no discharge current yet, a short ($\tau < 2$ ns) radiation pulse is observed along the discharge axis. The intensity of this pulse exceeding the intensities of radiation detected in the same time points in the perpendicular direction by an order of magnitude. Note that the actual signal duration is probably shorter since the measured value coincides with the time resolution of the recording channel.

Also, it should be noted, that the initial stage of the studied pulse formation coincides in time with a maximum of the applied voltage first derivative. At this point the speed of the voltage growth is maximal and at that time an inflection point in the dependence of the applied voltage on the time is reached.
However, it is seen from the figure 2 that the discharge current at this point is practically zero. After this time, the voltage is still increased, and only when it reaches a maximum, the nonzero discharge current appears and a breakdown of the gap occurs.

We studied the angular distribution of radiation intensities. The detectors were placed at a distance \( L = 15 \text{ cm} \) from the prism end face. The ferrite prism had a length \( l = 2 \text{ cm} \). The measurement results are presented in figure 1(b). It can be seen that the radiation is concentrated in a region with angular sizes of \( \sim 4^\circ \) and \( \sim 5^\circ (\pm 2.5^\circ) \) in the planes perpendicular and parallel to the working surface of the ferrite prism. Regarding the fact that in our measurement geometry, the angular resolution is \( \sim 2^\circ \), the presented results should be thought of as an evaluation.

In vacuum discharges at such a high voltage (100 \( \sim 300 \text{ keV} \)) high-energy electron beams can be formed [10, 11]. Such a beam can cause a response on the registration equipment similar to the response caused by high-energy photons. For this reason, some experiments providing proof of the electromagnetic origin of the studied radiation were carried out. First of all, transmissions of an aluminum filter with a thickness of 50 \( \mu \text{m} \) and a beryllium filter with a thickness of 10 \( \mu \text{m} \) (see below) were established. Corresponding measurements allow for the estimation of the average energy of the electron beam [12]. In the case of the present work, for the Al filter \( I_{\text{Al}} = 0.09 I_o \), where \( I_o \) is intensity without the filter) the energy of the beam should be \( E_o = 95 \text{ keV} \) while for the beryllium filter \( I_{\text{Be}} = 0.56 I_o \) the beam energy should be \( E_o = 37 \text{ keV} \). These results contradict each other. Thus, the initial assumption that the observed phenomena are associated with the passage of an electron beam is not true.

Another series of experiments was carried out when at the end of the ferrite prism was mounted a permanent magnet with the size \( h = 1 \text{ cm} \) providing a constant magnetic field with the intensity \( H = 700 \text{ G} \). An estimations show that a shift of the trajectory for electrons with the kinetic energy \( E_o = 100 \text{ keV} \) \( \Delta y \approx 20 \text{ cm} \). At the electron energy \( E_o = 50 \text{ keV} \) this shift is \( \Delta y \approx 32 \text{ cm} \). Our experiments show (figure 1) that the deviation of the peak amplitude of the studied radiation does not exceed the 20% part of the peak average intensity. The magnetic field with the induction \( H = 700 \text{ G} \) does not lead to a measurable change in the amplitude of the radiation peak higher than this deviation. Consequently, it is proved that the nature of studied radiation is electromagnetic.

A spectral composition of the radiation was investigated. For this purpose, integral intensities \( I_{\text{Al}}, I_{\text{Be}} \) and \( I_{\text{PP}} \) behind the aluminum, beryllium and polypropylene filters were measured. The filters had the following transmissions: \( \text{Al}: d = 50 \mu \text{m}, h > 4 \text{ keV}, (\lambda \leq 2.5 \text{ Å}), I_{\text{Al}} = 0.09 I_o; \text{Be}: d = 10 \mu \text{m}, h > 0.5 \text{ keV}, I_{\text{Be}} = 0.56 I_o; \text{PP} (\text{C}_2\text{H}_4\text{-polypropylene}) d = 4 \mu \text{m}, 0.1 \leq h \leq 0.293 \text{ keV}, (124 \text{ Å} \leq \lambda \leq 42.4 \text{ Å}) I_{\text{PP}} = 0.66 I_o \). Here the \( I_o \) is an integral intensity measured in absence of the filters, i.e. in the region of quanta of the energies \( 10^{-2} \text{ keV} \leq h \leq 10 \text{ keV} \) (1.24 \( \text{ Å} \)).

The results of this measurement allow us to estimate the spectral composition of the studied radiation using the database on the x-ray transmission spectra of different materials [13]. The results of this estimation are presented in table 1. The dependencies of the energy spectral densities of the radiation on the photon energies in the region \( 10^{-2} \text{ keV} \leq h \leq 10 \text{ keV} \) evaluated based on the table 1 data are presented in figure 3.

Table 1. Energy fractions of the generated beam.

| Energies of photons \( h \) | Radiation intensity |
|-----------------------------|---------------------|
| \( h > 10^{-2} \text{ keV} \), (\( \lambda \leq 1240 \text{ Å} \)) | 100% |
| \( 10^{-2} \text{ keV} \leq h \leq 0.1 \text{ keV} \), (124 Å \( \leq \lambda \leq 1241 \text{ Å} \)) | 10% |
| \( 0.1 \text{ keV} \leq h \leq 0.293 \text{ keV} \), (42 Å \( \leq \lambda \leq 124 \text{ Å} \)) | 22% |
| \( 0.293 \text{ keV} \leq h \leq 0.5 \text{ keV} \), (25 Å \( \leq \lambda \leq 42 \text{ Å} \)) | 7% |
| \( 0.5 \text{ keV} \leq h \leq 1 \text{ keV} \), (12.4 Å \( \leq \lambda \leq 25 \text{ Å} \)) | 10% |
| \( 1 \text{ keV} < h \leq 4 \text{ keV} \), (3.1 Å \( \leq \lambda \leq 12.4 \text{ Å} \)) | 26% |
| \( 4 \text{ keV} < h \leq 10 \text{ keV} \), (1.2 Å \( \leq \lambda \leq 1.2 \text{ Å} \)) | 25% |

The measurement error (electrical noise and possible background radiation) is the same for all angles and does not exceed 10%.

Independent estimation of the angular distribution of the investigated radiation was done using the energy distribution over the cross-section of the generated beam. Fuji BAS TR imaging plates were used, placed at a distance \( L = 26 \text{ cm} \) from

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| \( 4 \text{ keV} < h \leq 10 \text{ keV} \), (1.2 Å \( \leq \lambda \leq 1.2 \text{ Å} \)) | 25% |
Figure 3. The intensity spectral density dependence on the energy of electromagnetic quanta for the studied radiation.

Figure 4. (a) Image of the cross-section of the generated x-ray beam obtained by Fuji BAS TR plate coated with an aluminum filter \(d = 15 \mu m\) and positioned at the distance \(L = 26\) cm from the end of the ferrite prism with the working length \(l = 4.5\) cm; (b) The angular dependence of the plate darkening coated by the aluminum filter \(d = 15 \mu m\) along with the image; (c) The angular dependence of the plate darkening coated by the aluminum filter \(d = 15 \mu m\) across the image; (e) The spectral densities of the studied radiation behind the aluminum filter: \(d = 4 \mu m\)—solid curve and \(d = 15 \mu m\)—dashed curve.

Measurements were done with the use of 4 \(\mu m\) and 15 \(\mu m\) thick aluminum filters. The result is shown in figure 4. The darkening of the imaging plate corresponds to the time-integrated radiation energy emitted in the given direction. It is seen from figure 4, that the beam cross-section behind the aluminum filter \(d = 15 \mu m\) is characterized by the angle size \(\Delta \theta \sim 2.2^\circ\) (the corresponding linear size is \(a \sim 1.2\) cm). The cross-section longitudinal length of the beam behind the aluminum filter with the thickness \(d = 4 \mu m\) is nearly not changed while the transverse length is grown up to \(\Delta \alpha \sim 1.4^\circ\) (figure 4(d)). The corresponding linear length is \(b \sim 0.75\) cm. A comparison of energy spectral densities for radiation behind the aluminum filters with the widths \(d = 4 \mu m\) and 15 \(\mu m\) (figure 4(e)) shows that the radiation behind the filters at \(d = 4 \mu m\) a part of low-energy quanta is much more than at \(d = 15 \mu m\).

The energy characteristics of the radiation were studied. The total energy registered by the detector is determined as follows.
The average radiant flux was 0.3 MW.

of the radiation was with the thickness (this size was found to be the smallest behind the aluminum filter).

The crystalsizesofthediamonddetectorswere \( \sim 0.5 \text{ cm} \) and the height \( \sim 1.2 \text{ cm} \) (this size was found to be the smallest behind the aluminum filter with the thickness \( d = 15 \mu \text{m} \)). The maximal radiant energy of the radiation was \( \sim 0.6 \text{ mJ} \) at the discharge gap of 7 cm and the average radiant flux was 0.3 MW.

\[
\varepsilon = \frac{1}{CR} \int_{-\infty}^{t} V(t) \, dt.
\]  

Here, \( R = 75 \text{ \( \Omega \)} \) is the detector load resistance, \( V(t) \) is the instantaneous value of the signal, measured in Volts, at time \( t \), \( C = 5 \times 10^{-4} \text{ A W}^{-1} \) is the detector sensitivity. The duration of the radiation pulse may turn out to be significantly less than the time resolution of the recording channel (\( \sim 2 \text{ ns} \)), and the pulse duration and shape cannot be obtained by electrical measurements only. Nevertheless, since the signal spectral width (see table 1) is scarcely beyond the region of the detector spectral sensitivity (\( 10 \text{ eV} \ldots 10 \text{ keV} \)), relation (1) can be used to estimate the total energy incident on the detector.

The value of \( \int_{-\infty}^{t} V(t) \, dt \) was determined as the area under the curve \( V(t) \) (see figure 2(a)).

During measurements, the length of the ferrite working part \( l \) was varied from 1.5 cm to 7 cm by changing the length of the negative electrode. In several series of experiments, the length of the working part was first increased (2, 3, 5, 6, and 7 cm), and next decreased (6.5, 5.5, 4.5, 3.5, 2.5, and 1 cm). At each length in each series, 2 or 3 consecutive shots were made, with the total length of the ferrite sample being constant.

The crystal sizes of the diamond detectors were \( r_0 \sim 0.3 \text{ cm} \) (\( S_0 = 3 \times 10^{-2} \text{ cm}^2 \)) in the lateral direction. These sizes were almost half as much as the smallest cross-sectional dimension of the beam measured behind the aluminum filter with a thickness \( d = 15 \mu \text{m} \). Thereby, the signal measured by the detector is proportional to the spatial energy flux \( P \) of the studied radiation:

\[
P = \frac{\varepsilon}{S_0}. \quad (2)
\]

The energy flux dependence on the working length of the ferrite surface is depicted in figure 5 by squares.

This figure shows that the energy flux \( P \) is the nonlinearly-growing function of the ferrite surface working length. A solid line in figure 5 shows a fit of the experimental data by a quadratic dependence. For the case under consideration, the pure quadratic dependence is statistically significant at the probability level \( W > 0.87 \). It was found that the maximal energy flux \( P \) at the discharge gap of 7 cm was \( \sim 1 \text{ mJ cm}^{-2} \). To estimate the total energy \( \varepsilon \) of a single pulse of the studied radiation, we calculated a relation

\[
\varepsilon = P \cdot S,
\]  

where \( S \) is the beam cross-section, which was regarded as a rectangle with the widths \( a = 1.2 \text{ cm} \) and the height \( b = 0.5 \text{ cm} \) (this size was found to be the smallest behind the aluminum filter). The maximal radiant energy of the radiation was \( \sim 0.6 \text{ mJ} \) at the discharge gap of 7 cm and the average radiant flux was 0.3 MW.

4. Results discussions

What is the physical nature of the observed radiation? The sharp asymmetry in the angular distribution of the radiation intensity in the absence of focusing and limiting devices can be explained only by the interference phenomena. This in turn means that the observed radiation is coherent. We encounter a similar phenomenon when Cherenkov radiation occurs. This radiation is a coherent radiation of optically transparent media caused by a charged particle moving in a medium at a speed exceeding the speed of light propagation in this medium [14–16]. The Cherenkov radiation condition can be derived considering the interference phenomena and Huygens–Fresnel principle.

What happens in our case? We assume that at the prebreakdown stage of the discharge when a high voltage is applied to the cathode, a longitudinal electric field \( E \) appears in the interelectrode gap (a bias current with the spatial density \( J_{\text{off}} = \frac{1}{\pi R} \frac{\partial E}{\partial r} \) arises), which causes the magnetic field in the direction perpendicular to both \( J_{\text{off}} \) and the normal \( n \) to the ferrite surface. Thus, a high-power magnetic field pulse passes through the discharge gap. This pulse induces short-lived magnetization of the ferrite surface layer so that every infinitesimal part of it becomes a source of coherent electromagnetic radiation. All the induced magnetic dipoles are oriented in the same direction as the forming magnetic field. In the geometry of the present experiment, the symmetry of the system leads to the emission of interfering cylindrical elementary waves forming the resultant radiation.

The diagram explaining the formation of the radiation as a result of the coherent addition of unit electromagnetic waves is presented in figure 6. The excitation pulse and the radiation it generates move in the same direction at the same speed. The envelope of the wavefronts of the unit waves exists only in a small region near the ferrite surface where the
the electromagnetic excitation pulse passes over the surface, speed, medium with a refractive index of the considered phenomenon: no optically transparent medium is involved. In conclusion, we emphasize the important feature and novelty of the observed radiation.

![Diagram explaining the formation of the coherent radiation region.](image)

**Figure 6.** Diagram explaining the formation of the coherent radiation region.

According to the Huygens–Fresnel principle, the elementary waves are mutually canceled except for their common envelope. Thereby, the emitted radiation has low angular divergence and propagates parallel to the ferrite surface towards the anode. The coherence of the radiation is analogous to the Cherenkov radiation, due to the equivalent excitation conditions for all emitters. In a first approximation, one can be assumed that the longitudinal electric field strength \( E \) is proportional to the applied voltage \( U \). Thereby, a highly directional electromagnetic pulse is formed when the bias current \( J_{\text{off}} = \frac{1}{4\pi} \frac{dE}{dt} \) achieves its maximal value (see figure 2, curve 3).

It can be shown that the energy flux \( P \) of the studied radiation in a case of the coherent interference of cylindrical unit waves can be calculated by the following expression:

\[
P(y, l, L) \sim \frac{(l)^2}{L} \left( \sin \left( \frac{\pi y^2 l}{2 \Lambda L^2} \right) \right)^2.
\]

In this formula \( y \) is the spatial coordinate in the detector plane, \( l \) is the length of the ferrite surface working part, \( L \) is the distance between the end of the ferrite prism and the plane where the detectors are installed. The expression (4) was obtained using the approximation based on the relation \( L \gg l, y \). The conclusion from (4) is that the energy flux \( P \) is proportional to the second order of the ferrite surface working length if the radiation is coherent. This dependence was experimentally observed (figure 5), which confirms the coherent nature of the observed radiation.

### 5. Conclusions

In conclusion, we emphasize the important feature and novelty of the considered phenomenon: no optically transparent medium with a refractive index \( n \) and no charge moving at a speed \( v > cn \) are involved. The studied radiation is formed as the electromagnetic excitation pulse passes over the surface of the ferrite prism. This pulse and the radiation it generates move in the same direction at the same speed, and the radiation region is formed as a result of the coherent addition of unit electromagnetic waves. Consequently, the resulting radiation is concentrated in a narrow spatial region which translates into high radiant intensity being emitted.

**Data availability statement**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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