Runaway electron flows in magnetized coaxial gas diodes

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Abstract. This paper presents the experimental results on applying a strong magnetic field ($B$) to increase the uniformity and density of a picosecond runaway electron flow (RAEF) formed in an air coaxial diode with a tubular cathode. A uniform longitudinal field $B_z$ allows to confine RAEF similarly to the electron beam in a magnetically insulated coaxial vacuum diode. Dependence of the spatial discreteness of RAEF emission and the transverse size of the emitting plasma regions on $B_z$ has been demonstrated. For the cathode diameter of 8 mm, a current density was significantly increased from 40 A/cm² (at $B_z = \text{const}$) to 100 A/cm² by applying $B$-field with converging field lines. In the region of $B$ maximum (5 T) the RAEF diameter was squeezed by $\approx 4$ times.

1. Introduction

According to natural and numerical experiments, picosecond runaway electron flows (RAEFs) in gas electrode gaps with inhomogeneous electric field [1-6] could be described as a thin diverging layer [7]. These flows are of practical interest for various situations where the interaction of fast electrons with an interelectrode medium of a large volume or area is required. For a number of applications [8-10], a uniformity of RAEF and its increased density can be provided by application of a guiding magnetic field ($B$).

A uniform longitudinal field $B_z$ has been already used in [11] to transport RAEF for time-of-flight measurements. With that, RAEF emission and accelerating unit (coaxial gas diode, CGD) had analogy with vacuum, magnetically insulated coaxial diodes (MICD) [12]. Magnetization of RAEs in $B$-field with a field lines density rising along longitudinal axis toward a collector is similar to the processes in special electron guns [13] and in open plasma traps [14].

In Section II we describe the devices with different coaxial gas diodes. The first one operates at $B = B_z = \text{const}$, and the second one at the nonuniform field $B = B(z,r)$ of a magnetic-mirror configuration. Also, details of the diagnostics used in the experiments are described. In Sections III, we present the main experimental results on RAEFs confinement and compression.

2. Experiments arrangement

For the experiment with $B = B_z = \text{const}$, the MICD unit was used, which was developed for studying an amplifier of high-current electron beam noises [15]. That is, approaches to the beam formation in the MICD [16] and magnetized RAEF in the CGD are close. Magnetic field was created by a pulsed solenoid. Tubular stainless steel cathodes were used. With the cathode diameter of $2R_c = 22$ mm (1 in...
figure 1 (a)), a collector probe could be used to register RAEF current. However, large diameter of the collector (25 mm) and the time resolution of a built-in capacitive voltage divider did not allow recording the real amplitude and duration of a picosecond RAEF. Observed signal gave the "ampere-second" integral, that is, charge of the RAEF. Collector of the current probe was always shielded with aluminum foil (15 μm) transparent for electrons with energies above 40 keV [17]. At $2R_c = 8$ mm and the anode constriction (neck) of 13 mm, configuration of the CGD in figure 1 (b) is close to the MICDs of relativistic microwave generators [18]. When a converging $B$-field was required, the cathode was positioned outside the solenoid (figure 1 (c)). This magnetic system was borrowed from the experiment [19]. When the RAEF current was recorded by the collector with diameter of 13 mm [11], the pulse leading edges < 30 ps were observed.

![Figure 1](image)

**Figure 1.** Geometry of CGDs with homogeneous $B_z$-field for RAEF imprints visualization (a) and for the current measurements (b). The case of $B$-field lines density rising toward the collector (c).

Voltage pulse $U_{in}$ (figure 2 (a)) was applied to the CGD cathode via transmission line (TL) from the RADAN-303 source [20] accomplished by the pulse compression device [21] equipped with an adjustable cutoff spark gap [22]. With the TL diameter equal to $2R_c$ (cathode 1 in figure 1 (a)), and due to the absence of inhomogeneities in the TL duct, a slightly distorted reflected pulse $U_{ref}$ can be observed. Then, with the $U_c$ full width at half maximum (FWHM) < 0.5 ns, to estimate the voltage at the cathode ($U_c$), the dynamic [23] or conventional reflectometry are suitable.

To visualize the RAEF transverse structure, the luminescence of CPG400 screen (Gd2O2S: Tb phosphor) was photographed by an open shutter. When the image brightness was varied by the lens diaphragm, neutral filter or camera sensitivity, details of the glow structure were observed. The screen and collector recording the current were installed at the beginning of the anode constriction in a certain, fixed cross-section. Here $B ≈ B_z = 5$ T in the case shown in figure 1 (c), and the $B$-field gain with respect to the cathode positions reached 10-20.

3. Experiments on RAEF confinement and compression

3.1. CGD closure at various axial magnetic fields

Figure 2 (a) presents voltage reflectograms for the cathode 1 in figure 1 (a) at $d = 30$ mm for different fields $B_z$. Before runaway electrons emission the CGD is open, and initial part of the reflection $U_{ref}^{(-)}$ is not inverted during no-load operation interval. According to estimates by the method [23], the voltage amplitude at the cathode near this negative peak is $U_c ≈ –150$ kV [24, 25]. When electric field at the emissive edge exceeds critical value for runaway of thermal electrons in an air ($E_{cr} ≈ 450$ kV/cm), the particles starting from the cathode region, as their energy increase, could be continuously accelerated in the entire gap $d$, where $E < E_{cr}$ [26, 27]. After passing the RAEF, a tubular ionized channel appears.

In the field $B_z < 0.5$ T, the radial thickness of the conducting channel is large, which is confirmed by the glow of the phosphor (figure 2 (b)) and the geometry of electron flow in a model simulation in
the vacuum approximation (particle-in-cell code KARAT [28]). In this case, the particles are accelerated to the anode for \( \approx 200 \) ps, and plasma enters the anode constriction in the region \( 2R > 25 \) mm (figure 2 (c)) before the pulse \( U_{in} \) terminates. For the clarity, the pulse \( U_{in} \) is repeated in figure 2 (a) as a half-tone curve. Under such conditions, inverted lobe \( U_{ref}^{(\ast)} \) of the maximum amplitude (1) indicates the mode which is close to the short circuit. According to the estimate by the method [23], the current in CGD exceeded 6 kA, which is close to the short-circuit current (\( \approx 7.5 \) kA).

With an increase in the magnetic field, the "vacuum" electron flow does not short to the grounded anode constriction (see simulations in figure 2 (d) and 2 (e)). The phosphor luminescence, especially in the strongest field \( B_z \), would seem to confirm such a regime for the RAEP in air. However, we see in figure 2 (a) that inverted reflection (2 and 3) persists, although its amplitude decreases with the growth of \( B_z \). To clarify the situation, the brightness and contrast of the photographs at \( B_z = 1.1-4.3 \) T were increased. This showed that electron illumination presents up to the phosphor boundary at \( 2R = 25 \) mm, that is, the ionized channel partially shorts the anode constriction even in a strong field \( B_z \). The physical reason for the increase in the diameter of a magnetized electron flow in a gas can be determined by the drift of a part of the runaway electrons across magnetic field, including the path interval where they accelerate towards the anode. Recall that the difference between the radial dimensions of the cathode and the anode constriction is not large: \( (25-22)/2 = 1.5 \) mm, but this is much larger than the possible broadening of the RAEP plasma emission region at the cathode during the action of the runaway conditions (\( < 10^{-11} \) s, [7]).

![Figure 2](image.png)

**Figure 2.** (a) Incident voltage pulse \( U_{in} \) and reflections \( U_{ref} \) from CGD with the cathode 1 in figure 1 (a) obtained for RAEP emission and propagation at various fields \( B_z; 1 \rightarrow 0.18 \) T; 2 \( \rightarrow 1.1 \) T; 3 \( \rightarrow 4.3 \) T. (b) RAEP imprints at luminescence screen at various \( B_z \). (c-e) Geometry of electron flow accelerated at a constant cathode potential -130 kV simulated in a vacuum approximation.

### 3.2. Emission spatial discreetness and temporal structure of a magnetized RAEP

Judging by RAEP imprints in figure 2 (b), azimuthal flow discreetness is expressed already at \( B_z \approx 0.18 \) T. In the \( B_z \) field, the RAEP jets transmit the discreetness of the emission zones at the cathode edge to the phosphor. The dependence of the spatial discreetness on \( B_z \) is analogous to the vacuum MICDs [29]. In the MICD, a magnetized electron flow from the leading emission centers screens neighboring micro-protrusions, preventing development of the field emission (FE) on them and its subsequent transition into explosive electron emission (EEE). With an increase in \( B_z \), the Larmor radius of electrons (screening scale) decreases, and active EEE centers turn out to be closer to each other. In a gas diode with magnetic field, the source of shielding electrons is the impact ionization of gas by FE electrons and subsequent avalanche multiplication of thermal ones. With a sufficiently large \( B_z \), one can see that the number of emission zones is approximately equal to
2\pi R_c / \delta R_c$. Here $\delta R_c$ is observed thickness of the tubular RAFF. Indeed, both the quantity $\delta R_c$ and the screening scale of the cathode emission edge are values of the same order of magnitude given by the range of transverse oscillations of particles in $B_z$ field.

Figure 3. (a) Randomization of RAEF jets structure for 8-mm-diameter cathode with a smooth half-toroidal edge (rounding radius of 0.5 mm). (b) Examples of RAEF integral current that can be interpreted as summation of non-synchronous elementary jets of magnetized fast electrons.

It was suggested in [7] that previously observed duration of the runaway electron flows is overestimated due to the limitations of diagnostics and asynchronous emission of elementary RAFFs from different areas of large cathodes. Both of these features took place for the cases in figure 2 (b), where decoupling of diametrically opposite emitters is $2R_c/c \approx 70$ ps ($c$ is the speed of light). To observe asynchronous emission of electron jets, we used a collector probe which recorded the pulse leading edges of $\approx 30$ ps, and the cathode of 8 mm diameter (figure 1 (b)), but with a smooth, half-toroidal edge with a rounding radius of 0.5 mm. Due to the spread in the positions of FE centers at the edge of a large area and a weak distortion of the $E$-field, the number of emission zones [29] is no longer determined by the screening effect even in a strong $B_z$ (figure 3 (a)). Indeed, the condition $E > E_{cr}$ is achieved at large $U_c$ (modulo): $> 260$ kV for the trace 1 in figure 4 (a). While $E$ is growing at the voltage pulse leading edge, FE centers (microprotrusions) with a wide microfields amplification range can be activated. As a result, a large temporal spread of elementary RAFFs is added to the chaotic spatial referencing, which is observed in figure 3 (b).

Figure 4. (a) Reflectograms obtained for the tubular cathodes of 8-mm diameter with a smooth edge (1, rounding radius of 0.5 mm) and a sharp edge (2) at $B_z = 1.1$ T. (b) Upper row: RAFF autographs for a sharp-edge cathode and the gap distance of $d = 30$ mm at various $B_z$. Bottom row – the same autographs with increased brightness. (c) Amplitude and temporal stability of RAFF emission at $B_z = 1.1$ T and a gap distance of $d = 30$ mm for a sharp-edge cathode (8-mm diameter).
In contrast to the case of a smooth edge, for a sharp-edged cathode of the same diameter (8 mm) \( E_{cr} \) is achieved at a lower (modulo) voltage \( U_c \approx 170 \text{ kV} \), that is, faster with respect to the beginning of the pulse \( U_{in} \) (trace 2 in figure 4 (a)). In this section of the voltage leading edge, where \( \text{d}U_c/\text{d}t \) is high, the spread in the jet emission moments is reduced [30]. There are many jets in a strong \( B_z \) [29], the integral RAEF is close to annular (figure 4 (b)) and quite stable (figure 4 (c)). Note that tubular RAEFs with a structure as in figure 4 (b) were recorded by the collector after anode constriction with a diameter of 13 mm. That is, taking into account the cathode diameter of 8 mm, the annular slit compared to the case shown in figure 2 was increased to \((13-8)/2 = 2.5 \text{ mm}\). Figure 4 (b) shows a pair of original RAEF imprints at some magnetic fields and the same imprints with increased brightness. Judging by the last imprints, RAEF fell on the anode constriction (diameter = 13 mm) at \( B_z < 1.1 \text{ T} \), but taking into account the limited duration of \( U_{in} \), the polarity inversion in the pulse \( U_{ref} \) was not pronounced. For the same reason, the inversion decreased with increasing gap length \( d \): \( 20 \rightarrow 30 \rightarrow 50 \text{ mm} \) (figure 5).

![Figure 5](image)

(a) Reflectograms obtained for the tubular cathode of 8-mm diameter with a sharp edge at \( B_z = 1.1 \text{ T} \) for different distance between the cathode and the anode constriction: 1 – \( d = 20 \text{ mm} \); 2 – \( d = 30 \text{ mm} \); 3 – \( d = 50 \text{ mm} \). (b) Increase in the RAEF acceleration time to the anode constriction at different \( d \) for the cathode position being unchanged.

3.3. RAEF compression in a strongly converging B-field

With a sharp-edged cathode diameter of 8 mm and the gap \( d = 30 \text{ mm} \), in the magnetic fields \( B_z > 1 \text{ T} \), the current of tubular RAEF on the collector was in the range of 9-12 A, and its charge, taking into account typical envelope in figure 4 (c), was \( \approx 0.7 \text{ nC} \). Considering the size of the glow region for the most strong \( B_z \) in figure 4 (b), the current density of RAE is estimated as \( \approx 40 \text{ A/cm}^2 \). The integral charge of RAEF from the cathode of an increased diameter of 22 mm (figure 1 (a)), all other things being equal, increased approximately proportionally to the length of the annular edge of the cathode. Despite an increase in azimuthal discreteness (an increase in the number of separate regions emitting RAE), with a decrease in the field \( B_z \) from 1 T to a certain limit (figure 2 (b)), the tubular structure of the RAEF is generally preserved. This was the reason for the experiment [31] on the compression of a tubular electron beam in a strongly converging magnetic field (figure 1 (c)).

For the RAEF compression option with a cathode diameter of 22 mm, there is a fundamental limitation associated with the reflection of particles from a magnetic mirror - the area of thickening of the magnetic field lines. A very small part of the RAEF passed to the collector in the “loss cone” through the magnetic mirror with a field gain of \( \approx 20 \). As a result of differences in the dynamics of electrons with different initial pitch angles, the current pulse became significantly longer (trace 2.3 A in figure 6 (a)), and the integral charge (0.4 nC) was no more than in figure 4 (c) for 8-mm cathode in a uniform field \( B_z \). Azimuthal structure of the compressed RAEF on the collector at \( B_z = 5 \text{ T} \)
(figure 6 (b)) generally corresponded to autograph from a 22-mm cathode in a weak uniform field $B_z \approx 0.3$ T \textit{(ibid.)}. Analysis of the RAEF compression problem showed [31] that transmission coefficient of the particles through magnetic mirror depends on the combination of factors. First of all, this is the difference in the magnetic field from emitter to collector. Other factors include an absolute value of magnetic field at the emitter, as well as angle of inclination of the $B$-field line in this region ($\alpha$ in figure 1 (c)), which determines efficiency of the electron cyclotron oscillations buildup at the initial stage of acceleration. For a 22-mm cathode, the field difference was (0.25-5) T. If magnetic field is enhanced to $\approx 0.5$ T in the emitter region of 8-mm cathode (due to the smaller distance to the solenoid, $d = 14$ mm, figure 1 (c)), then for the smaller angle $\alpha$ and the field difference (0.5-5 T), the reflection from magnetic mirror is greatly reduced. As a result, the RAEF with an average original diameter of 8 mm (figure 6 (c)) was compressed at the collector to 2.5 mm \textit{(ibid.)}. Its current represented a narrower peak (trace 7.3 A in figure 6 (a)). Here, the current amplitude is slightly less than in the case of 8-mm cathode in a uniform field $B_z = 0.5$ T. Photographing a compressed RAEF autograph with a light filter (figure 6 (c)) made it possible to estimate, judging by the area of the most intense glow, the collector current density as $\approx 100$ A/cm$^2$.

![Figure 6.](image)

**Figure 6.** (a) Currents of the RAEFs compressed in a convergent $B$-field for the cathodes of diameter 22 (2.3 A) and 8 mm (7.3 A) positioned as in figure 1 (c, b) Imprint of the RAEF emitted from 22-mm cathode and the same flow squeezed by a nonuniform $B$-field. (c) Like previous, but for 8-mm cathode. The imprint image obtained using a dark optical lens filter is shown

4. Conclusion
The transportation and compression of tubular magnetized fluxes of runaway electrons in coaxial gas diodes has been demonstrated. When runaway electrons passed a long gap “cathode-anode constriction” (50 mm) in a uniform field $B_z$ for a time exceeding the duration of applied high-voltage pulse, the effect of the emerging ionized channel on the diode closure was not pronounced. In shorter gaps, inverted reflections appeared, indicating the onset of a short circuit. With a sufficient voltage duration and a tubular electron flux hitting the anode, the short-circuit regime was practically achieved, but its efficiency decreased with an increase in the guiding magnetic field that reduced the RAEF diameter, which in this case passed into the drift channel through the anode constriction. According to time-of-flight estimates, the particles at the RAEF current peak had a significantly higher energy than is determined by the voltage amplitude across the gap. This is explained by an increase in the electric field at the front of the ionization wave due to the displacement of the field from the dense plasma [32]. In the case of a magnetized RAEF, this effect will be more pronounced than in the absence of a magnetic field [33, 34] for two reasons. First, in the presence of a magnetic field, the gas ionization efficiency increases due to the lengthening of the RAE trajectories, which provides more favorable conditions for plasma generation. Secondly, an additional, geometrical factor for the amplification of the electric field at the boundary of the plasma region will be its narrowing due to the RAEF magnetization. Note also that in a magnetic field with converging lines of force, it was possible
to compress tubular RAESs by 3-4 times in diameter. This ensured an increase in the azimuthal uniformity of the RAES and an increase in its current density by about 2.5 times.

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