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Parameters of a paraxial magnetized bunch of runaway electrons

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Abstract. The methods for diagnosing of a dense paraxial magnetized bunch of run-away electrons (RAEs) in a coaxial air-filled diode with a sharp conical cathode and elongated distance to the anode constriction are described. Spatiotemporal characteristics of the bunch are specified. Investigations tools include luminescence screen and collector-type probe of electron current. The lasts equipped with collimators to measure radial distribution of the current density. Fast response probes confirm that paraxial RAE bunch has the width of about 10 ps, and behind the collimator with diameter of 0.7 mm the current density achieves ≈1 kA/cm^2.
Keywords: runaway electrons, axial magnetic field, acceleration, bunch charge, current density.

1. Introduction

It has been recently demonstrated [1] that the flux of run-away electrons (RAEs) in an air gap with a sharp cathode represents a layer with a paraxial fraction duration <10 ps. After the collimator with a 1 mm diameter hole, the current and current density are ≈200 mA and ≈25 A/cm^2, respectively. For practical applications of RAE flow, these parameters can be increased by applying a strong longitudinal magnetic field. This has been demonstrated for magnetized tubular RAE flows [2] in gas diodes (GDs) with a design close to magnetically insulated vacuum coaxial diodes (see, e.g., [3], and references therein). Below, we detail the diagnostic methods in experiments [4], where a dense paraxial magnetized RAE bunch was obtained. A technique for recording and measuring the spatiotemporal characteristics of the bunch is described.

2. Experiment arrangement

A high-voltage pulse with a full width at half-maximum (FWHM) of ≈5 ns from the RADAN driver is fed to the converter with a short pulsed forming line (PFL). At the PFL output, there are sharpening and cutting nitrogen dischargers (up to 60 atmospheres) [5]. Spark gaps of these dischargers are smoothly regulated without depressurization of the casing by means of mechanical gears. The gears allow the breakdown voltage to be adjusted to provide the amplitude and the width (FWHM) of high-voltage pulse U_{in} in the range of –(150–160) kV and ≈250 ps, respectively. In this case, there are no breakdowns in the gas section of the transmission line (TL), through which U_{in} enters the sharp conical cathode (Fig.1). Therefore, using a single capacitive probe, U_{in} and the voltage pulse U_{ref} reflected from the cathode can be observed (Fig.2). Since U_{in} is short, and the signal delay between the probe and the cathode (≈4 ns) is much longer, then U_{ref} is relatively weakly distorted by the noise followed U_{in}.

To estimate the instant of RAE emission at the leading edge (front) of U_{ref}, we use the fact that sharpening spark gap operates in a self-breakdown mode. Its actuation is unstable with respect to the driver pulse that charges PFL, and the front formed varies in duration. Under these conditions, the instant of RAE emission is estimated by the method [6] – by the minimum dispersion of the "delay" between a variable trigger point of the oscilloscope at the front of U_{in} (see inserts in Fig.2) and the front of RAE current pulse.

The pulse U_{ref} recorded by the remote probe has a doubled amplitude at the cathode, since before the voltage collapse after RAE emission, an idle run is realized in the GD. This means that the voltage amplitude at the cathode reaches ≈ $2U_{ref}$ = –160 kV, which is close to the amplitude U_{in}, and the instant of RAE emission marked in Fig.2 by an arrow at U_{ref} front corresponds to the cathode voltage of ≈ –80 kV. At the same time, at the tip of the cathode (we interpolate its edge by a radius of 50 μm), a calculated increase in the electric field strength of >800 kV/cm is achieved, which is sufficient for the thermal electrons runaway at atmospheric pressure [7, 8].

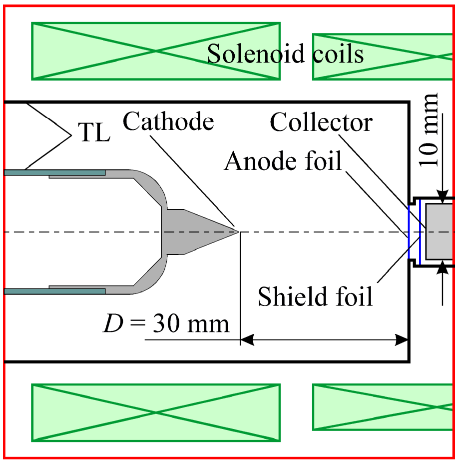

Fig.1. Magnetically insulated coaxial gas diode with a conical steel cathode.

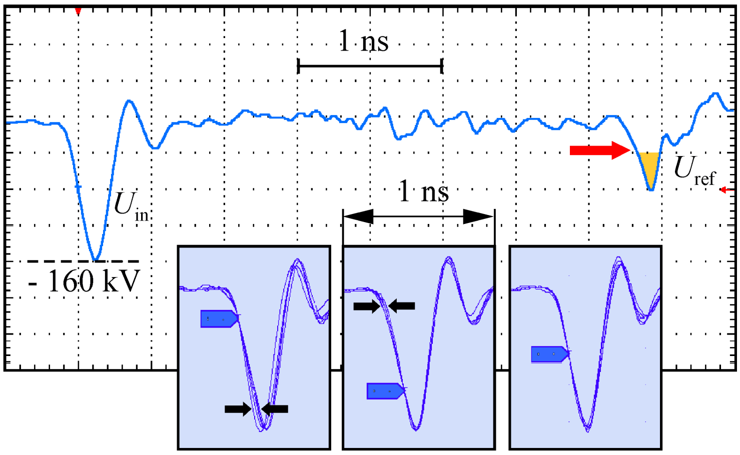

Fig.2. Incident voltage pulse U_{in} and the pulse U_{ref} reflected from the cathode. Inserts show variations of the oscilloscope triggering point.

The pulse width of U_{ref} by the RAE emission voltage level is $\delta t \approx 180$ ps (Fig.2), and the cathode voltage during acceleration varies (shaded area U_{ref}) in the range from –80 kV to –160 kV. The calculation of the electron acceleration time from the cathode to the anode in the vacuum approximation gives the values ranged from 200 to 165 ps for those voltages, respectively. Although RAE energy decreases due to inelastic collisions in the gas, the effect of electric field compression between the plasma front of the ionization wave and the anode leads to an increase in the particle energy compared even with a vacuum approximation [1]. This means that U_{in} width in our case is sufficient for an accelerated motion of RAEs from the cathode to anode.

3. Measurement results

A single-pulse RAE flow is visualized by the glow of AGFA CPG400 luminescent screen with a Gd_2O_2S:Tb phosphor (Fig.3a), which is installed instead of an anode aluminum foil (Fig.1) and photographed by an open shutter. This gives approximate data on the transverse size of the bunch, since the phosphor glow intensity (Fig.3b) is not calibrated with respect to the bunch current (charge) and electron energy. However, visualization of RAE bunch structure is necessary when alignment electron flow to determine the radial current/charge distribution using the collimators.

In the experiments, collector sensors are used, the design of which is shown in Fig.4a, Fig.4b. Observed duration and amplitude of electron current pulse differs from the real one and is determined by the processes on the collector, the quality of transition (stepped line) from collector to the cable (Fig.4c), as well as frequency response of the cable and recording bandwidth of the oscilloscope. The last factor is demonstrated in Fig.4d for experimental conditions [1], where diameters of collector and paraxial collimator (hole in the disk) are $d_1 = 5$ mm and $d_2 = 1$ mm, respectively. An oscilloscope with a bandwidth of f = 59 GHz and a sampling rate of 160 Gs/s observed the RAE current with a duration (FWHM) of $t_{1/2} \approx 11$ ps. This pulse (*1* in Fig.4d) transformed (broadened) as f decreased to 33 and 20 GHz (*2* and *3* in Fig.4d, respectively). In the latter version, it turns out to be symmetrical, and represents mathematical interpolation – a response to an ultrashort (δ – function) pulse under conditions of insufficient f. Note that the fronts were close to the oscilloscope transient response (t_{tr}) for any given f. For example, at f = 59 GHz, observed front at levels 0.1–0.9 had a duration $t_r \approx 7$ ps, and then we obtain the ratio $(t_{1/2}/t_r) \approx 1.57$.

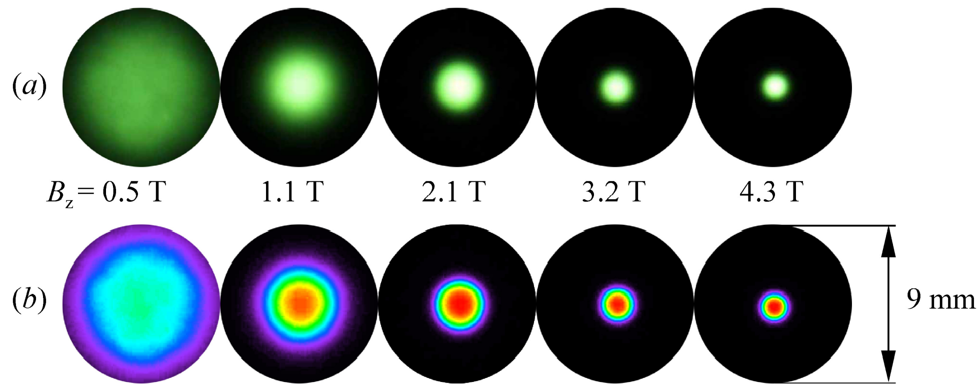

Fig.3. Autographs of RAE bunches on luminescence screen obtained at different magnetic fields in GD (a); Development of the same autographs using colors gradation (b).

As follows from the RAE flow autographs shown in Fig.3, to analyze the transverse bunch structure in a magnetic field in the range of (0.5–4) T, it is necessary to record electron current in paraxial region with a diameter of up to 9 mm. With such collector and bunch diameters, even an extremely short δ – current pulse (an infinitely thin disk) will give a response on an "ideal" oscilloscope no shorter than the charge drain time from the collector $t_0=d_1/2c$ = 15 ps. Here c is the speed of light. In the case of a thin paraxial bunch in a strong magnetic field, the current pulse broadening will be less pronounced. Table 1 shows the minimum parameters of RAE current pulses obtained (without the use of collimators) with an open collector with a diameter of 9 mm at various B_z. In the case of B_z = 4.3 T, the pulse width $t_{1/2} \approx$ 21.1 ps (FWHM) is approximately 5.5 ps shorter than at B_z = 1.1 T. The front t_r depends on B_z to a lesser extent than $t_{1/2}$.

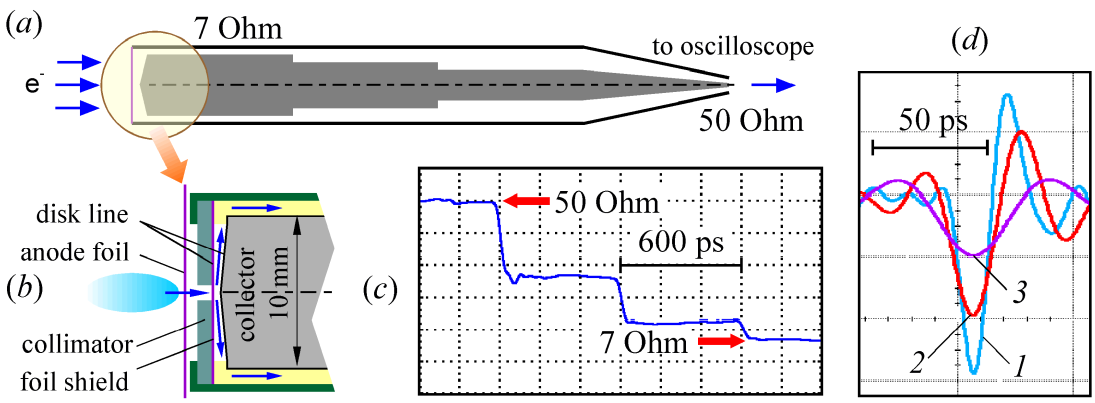

Fig.4. (a) General design principle of a fast-response RAE current probe and its collector unit (b); (c) Reflectogram of a stepwise line connecting 7-Ohm coaxial section adjoined to the edge-type collector with a 50-Ohm SMA connector; (d) RAE current pulses recorded by oscilloscope at different bandwidth: *1* – 60 GHz; *2* – 33 GHz; *3* – 20 GHz.

The fastest front ($t_r \approx$ 13.8 ps) was observed in a strong magnetic field and slightly exceeded the transient response of the used oscilloscope (t_{tr} = 13 ps for f = 33 GHz). It is known [9] that in this case the actual pulse front duration can be estimated as $t_r^* = [(t_r)^2 - (t_{tr})^2]^{1/2} = 4.6$ ps. Let us assume that the "duration/front" ratios are approximately equal for the observed and real parameters: $(t_{1/2} / t_r) \approx (t_{1/2}^* / t_r^*)$. Then $t_{1/2}^*$ are estimated from the values of t_r^*. As can be seen, these values differ significantly with the variation of magnetic field. Their range is 7–17 ps, which does not contradict the data in [1, 4, 10]. The reason for this may be the specificity of the near-cathode plasma formation, from the boundary of which electrons runaway. As shown in [4], the cross section of a magnetized RAE flow increases (at the collector) with the growth of the plasma region covering the cathode tip. Its radial expansion with decreasing B_z is accompanied by an increase in the axial dimension of emission boundary. This can lead to a spread in the emission start time and propagation of RAE fractions to the anode, that is, to an elongation of the current pulse.

Table 1. RAE bunch current pulses registered by an open 9-mm diameter collector at various magnetic fields

B_z [T]	Pulse width $t_{1/2}$ (FWHM) [ps]	Pulse rise time t_r [ps]	Pulse rise time t_r^* [ps]	Ratio ($t_{1/2}$ / t_r)	Expecting $t_{1/2}^*$ [ps]
1.1	26.5	17.0	10.9	1.56	17
2.1	22.2	14.3	6.0	1.55	9.3
4.3	21.1	13.8	4.6	1.53	7

*Parameter reconstructed taking into account transient response of the oscilloscope

Fig.5a, Fig.5b demonstrates an open-collector current pulse shape, which is quite conservative for each value of B_z, despite the amplitude spread from shot on shot. Accounting relatively small spread of the measured current pulse duration $t_{1/2}$ (typical standard deviation was about 200–500 fs), an adequate characteristic for analyzing the transverse structure of RAE bunch is its charge (Q) – the integral of the current over time. In our experiments, Q was well described by the product of the current pulse amplitude and its duration $t_{1/2}$ (FWHM). Therefore, the real current amplitudes can be estimated as ($Q/t_{1/2}$*).

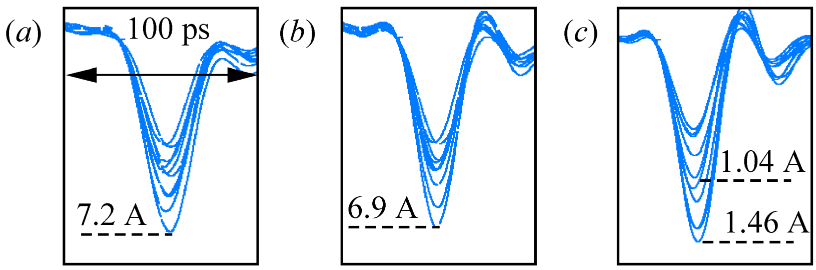

Fig.5. (a, b) The RAE current pulses recorded by an open-collector probe at magnetic fields of 1.1 T and 2.1 T, respectively; (c) Stored current pulses of RAE bunch propagated through collimator of 0.7 mm diameter at B_z = 4.3 T.

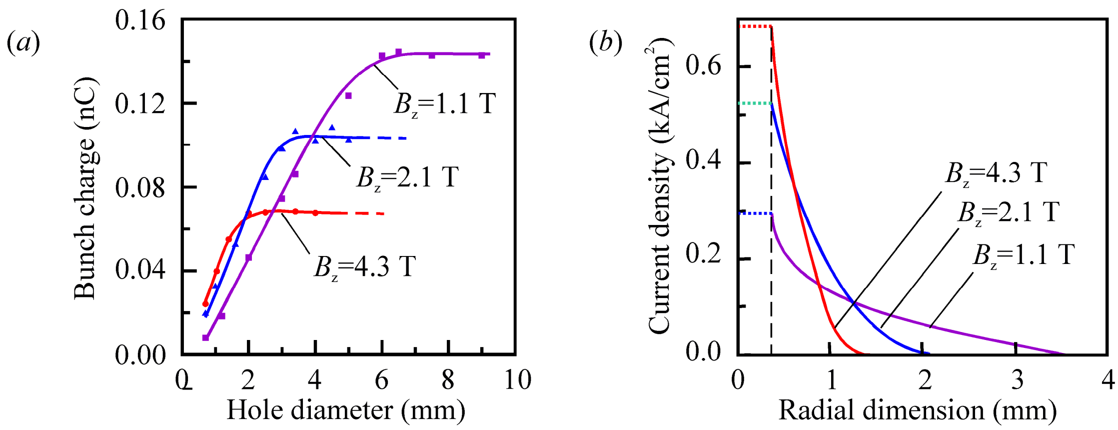

Fig.6. RAE bunch charge recorded at different B_z and collimator holes diameter. Each point was averaged over ten shots (a); Radial distribution of the RAE current density recovered accounting (a) for approximation of $t_{1/2}^*$ = 10 ps (b).

Data on the charge of the bunches that have passed through collimators of various diameters are presented for a number of magnetic fields in Fig.6a. In [4], when calculating the radial distribution of the bunch current density, it was assumed that $t_{1/2}$* = 10 ps for all B_z values and collimator diameters. These distributions are shown in Fig.6b. Taking into account the data shown in Table 1, the results of [4] can be considered relatively accurate for B_z = 2.1 T. If for the case of B_z = 4.3 T and a collimator diameter of 0.7 mm we use measured value $Q \approx 0.025$ nC (this corresponds to an average current of 1.04 A in Fig.5c, then for $t_{1/2}$* = 10 ps, the current density $J \approx$ 650 A/cm^2 is reached in the paraxial part of the bunch (diameter 0.7 mm). This value rises to ≈ 900 A/cm^2 if $t_{1/2}$* = 7 ps is assumed (see Table 1). Taking into account current/charge spreads in Fig.5c it can be seen that for the maximum amplitudes, $J \approx$ 880–1260 A/cm^2 will be reached, depending on the chosen value of $t_{1/2}$* (10 and 7 ps, respectively).

4. Conclusion

The presented diagnostic methods and devices made it possible to refine spatiotemporal and energy characteristics of a paraxial magnetized bunch of runaway electrons formed in a coaxial atmospheric diode with a conical pointed cathode placed 30 mm away from the anode foil. Taking into account features and limitations of the recording system (collector probe and oscilloscope), the difference between observed and real parameters of picosecond electron current pulses was analyzed. The data obtained show the possibility of controlling the transverse size of electron bunch by varying longitudinal magnetic field. In the limit of strong fields (≈4 T), the current density in the central part of the bunch is estimated from an average statistical amplitude of the current pulse in the range of ≈ 650–900 A/cm^2. In the case of peak current bursts, this value reached ≈1260 A/cm^2. In the measurements with foil filters, it was shown that after acceleration to the anode, the bunch contains the leading fraction of electrons with energies up to ≈340 keV. This indicates that the electric field is compressed by the plasma front (ionization wave) that follows the bunch of runaway electrons.

Detailing the parameters of a paraxial bunch of magnetized runaway electrons opens up the possibility of using a source of such particles in experiments on radiative nonthermal effects on objects and media, as well as using bunches as a temporary δ- trigger for various processes. The use of such short current bursts for calibration of the probe* developed for time-domain registration of electron bunch trains accelerated by strong Ka-band microwave fields has already been demonstrated.

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