Electrostatic-Instabilities as a Source of Picosecond Termination of Runaway-Electrons Beam in High-Voltage Gas-Filled Ultra-Fast Diode

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The fast disruption of the runaway electrons-beam in a high-voltage picosecond atmospheric-discharge [G. A. Mesyats and M. I. Yalandin, IEEE Trans. Plas. Sci. 37 785 (2009)] is considered. The plasma electrostatic instabilities are proposed as a mechanism of such disruption. Strong over-voltage (more than 1 MV/cm at gas pressure 1 atm) provides an intense electrons-acceleration in the runaway regime. It is shown that neither collisions nor a static potential profile could deliberately prevent this runaway regime. Whereas, the cathode-anode bridging impossible within tens of pisoseconds. It is obtained that the characteristic times of a simplest electrostatic-instabilities build-up are consistent with the observed runaway-electrons beam-duration at the certain plasma density, which was considered as a parameter. The agreement our estimation results and the measurements [G. A. Mesyats, V. G. Shpak, S. A. Shunailov and M. I. Yalandin, Technical Phys. Lett. 34 169 (2008); Mesyats et al., ibidem. 32 18 (2006)] confirms that collective plasma processes indeed can provide the observed picosecond termination of the fast-electrons beam in a high-voltage gas-filled diode within the tens of picoseconds.

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1. Inroduction

Recent progress in high-power picosecond electronics gives an ability to generate unique-properties chargedparticles beams and radiation sources [1–6]. The voltage pulse up to 1 MV with sub-nanosecond duration allows receiving of a picosecond sub-relativistic electrons beam in vacuum diode (duration of the beam and pulse is the same: $t_b \approx t_{pulse} \ge 300 \text{ ps}$). If the same diode is filled by atmospheric gas the beam duration t_b is much less than the voltage pulse: $t_b < 50 \text{ ps} \ll t_{pulse} \ge 300 \text{ ps}$ [2].

The present work is intended to consider possible mechanisms of such runaway-electrons beam shortening. The runaway conditions for the electron motion are satisfied. Hence we have to consider collisionless mechanisms governed by fast self-consistent fields evolution due to the space-charge motion.

2. Discharge Parameters

The power source provide the voltage growth rate $\sim 10^{15}$ V/s [2, 3]. Maximal voltage is several ~ 100 kV, the pulse length several ~ 100 ps. The gas pressure is atmospheric. Air and hydrogen were used (Fig. 1). Axial magnetic field up to ~ 1 T is applied.





Fig. 1 Fast-electrons current temporal evolution [3], 1 - vacuum diode, 2 and 3 - air and hydrogen at 760 Torr.

The amplitude of fast-electrons current I_b is in the range ~ 0.1-10 A depending on conditions (whereas in vacuum diode I_b is up to ~ 10 kA). The fast-electrons energy is equal to the applied voltage (i.e. > 100 keV). Therefore, fast-electrons are accelerated in the gas-filled diode in the "runaway" regime. Runaway regime, as it's known, implies that particles acceleration in electric field gives to particle more energy, than can be dissipated by its collisions. In neutral gas critical electric field for runaway can be estimated as $E_g \sim 10 \text{ eV}/e\lambda_{\text{ion}}$, where λ_{ion} - inelastic (ionizing) collisions length. The last one can be esti-

mated as $\lambda_{\rm ion} \sim 1/(n_a \sigma_{\rm ion}) \approx 10^{-4} \,\mathrm{cm}$ (at neutral density $n_a = 2.78 \cdot 10^{19} \,\mathrm{cm}^{-3}$, $\sigma_{\rm ion} \approx 3 \cdot 10^{-16} \,\mathrm{cm}^2$). Hence critical field is about $E_g \sim 10^5 \,\mathrm{V/cm}$. More accurate analysis gives: $E_{\rm cr} = (4\pi e^3 n_0 Z)/(2.72I)$ [7], where Z - electrons value, I - average energy of inelastic losses. For atmospheric air and hydrogen $E_{\rm cr, N2} \approx 4.5 \cdot 10^5 \,\mathrm{V/cm}$ and $E_{\rm cr, H2} \approx 1.8 \cdot 10^5 \,\mathrm{V/cm}$ accordingly. Both values are the same order of magnitude as E_g .

It was found [2, 3] that the fast-electrons beam starts from the cathode when the electric field strength at the cathode reaches ~ 1.5 MV/cm. Therefore the criterion of runaway $E > E_{\rm cr}$ is satisfied. At the ionization length ~ 10⁻⁴ cm in this field an electron can receive about ~ 100 eV, what is favorable for the ionization. Thus, full ionization can be probable within the time ~ 10 ps, and the maximal plasma density can be as high as ~ 10¹⁹- 10^{20} cm⁻³. The multicharged ions influence is weak, as the beam duration is the same for air and H₂ (Fig. 1).

For runaway in plasma, when the Coulomb collisions are prevailing, critical electric field $E_{\rm cr} = 0.214e\Lambda/(L_{\rm d})^2$ ("Dreicer-field") [7–11] (where Λ - the Coulomb logarithm, $L_{\rm d} = (T_{\rm e}/4\pi n_{\rm pl}e^2)^{0.5}$ - the Debay length), i.e. $E_{\rm cr} \approx e/(L_{\rm d})^2 \approx 2.6 \cdot 10^{-13} \cdot n_{\rm pl,\,cm^{-3}}/T_{\rm e,\,eV}$ [V/cm] that gives ~ 10⁵ V/cm for 10¹⁹ cm⁻³ and 10 eV, what is close to the value for runaway in a gas.

Let's consider three model-cases of potential perturbation due to plasma influence. It is known that dense plasma does not reach the anode during the 100 ps, and anode-cathode bridging not occurs. It will be shown further that the static redistribution of potential-profile itself hardly can prevents the runaway regimes occurrence.

First case: the "most smooth" potential distribution in the average (Fig. 2, 1). The electric field E in this case is the almost the same in the whole gap $E(z) \approx E_1$ and E_1 ~ $100 \text{ kV/1 cm} \sim 10^5 \text{ V/cm}$, what is only in a few times lower than critical for runaway $E_1 \sim E_{cr}$. It should be noted that the runaway regime is observed in sub-critical field: $E < E_{cr}$ [7, 11] as well. Then the runaway conditions are satisfied for particles from the high-energy tail of the distribution function. The saturation time of quasistationary flow to the runaway region in the velocity-space is about $\tau_{\rm flux} \approx (E_{\rm cr}/E)^{3/2} \cdot \tau$ [7, 11], where τ - electronrelaxation time (τ can be estimated as $\tau \sim 1/((10^{12} \div$ 10^{13}) + $10^{-6}n_{\rm pl,\,cm^{-3}}$)[s], where gas pressure is 760 Torr, and plasma electrons have $T_e \sim 10 \text{ eV}$ (see [12])). For $E_{\rm cr}/E_1 \sim 5$, $\tau_{\rm flux} \sim 10 \cdot \tau$, namely the time $\tau_{\rm flux} \sim 1-10 \, {\rm ps}$, what is much less than runaway beam duration (50 ps).

Second case: potential inside the plasma is almost constant and is equal to the cathode potential: $U_{pl} \sim U_{cath}$ (Fig. 2, 2). In this case the most of potential fall is in front of the plasma propagating to the anode, namely "at the anode side" of plasma. Therefore 1) the electric field strength increases with plasma propagation to the anode, 2) the time of fast-electrons beam generation should be defined by this plasma propagation. Then the beam termination should be due to the gap bridging by plasma. But it is not consis-



Fig. 2 Schematic distribution of the potential: 0 - vacuum distribution, 1-3 - model-distributions: 1 - minimal average $E(z) \approx E_1 \sim 10^5 \text{ V/cm}$, 2, 3 - plasma at the cathode- and at the anode-potential accordingly.

tent with experiments [2], which show that there is no the beam duration dependence on the cathode-anode distance. At the differ cathode-anode distance (from 0.6 to 2.6 cm) the fast-electrons beam duration is the same. Moreover, the experiments with fin dielectric films [2] show that fast-electrons acceleration region is placed near the cathode. Therefore we have to consider third case, when the most of anode-cathode potential fall as well as acceleration region is placed near the cathode (Fig.2, 3). But the dense plasma size is about $100 \text{ ps} \cdot 10^9 \text{ cm/s} = 0.1 \text{ cm}$, what is much less than Coulomb collision length (for 10 keV, $10^{19} \text{ cm}^{-3} \lambda_{\text{Col}} \sim 10^{12}T^2/n \sim 10 \text{ cm}$).

Therefore neither collisional dissipating of the beamenergy nor the static redistribution of potential is not sufficient to provide the beam termination and we have to consider collisionless mechanisms [13–21].

3. Collective Electrostatic Processes

1. Virtual cathode oscillations. The "3/2-law" gives a limitation of a current density $j_{3/2}$ that can be estimated for 100 kV and 1 cm as $j_{3/2} \sim 100$ A/cm². In fact this value is consistent with observation, as the total cathode area $\sim 10^{-2}$ cm², 0.1 A < $I_{\rm b}$ < 10 A and because the emission-centers area is much less than 10^{-2} cm² [4–6].

The virtual cathode oscillations have a period ~ $1/\omega_{\rm pe}$ [18], where $\omega_{\rm pe}$ is the plasma Langmuir frequency: $\omega_{\rm pe} = (4\pi n_{\rm pl}e^2/m_{\rm e})^{0.5} \approx 0.57 \cdot 10^5 \cdot (n_{\rm pl, \, cm^{-3}})^{0.5}$ [s⁻¹], where $n_{\rm pl}$ is equal to the beam density. The last one can be estimated as 10^{11} cm⁻³- 10^{12} cm⁻³. Corresponding to this density the plasma-frequency is: $2 \cdot 10^{10}$ s⁻¹- $0.6 \cdot 10^{11}$ s⁻¹ (see Fig.3, 1). Thus, the time of a "beam reflection" by a virtual cathode $1/\omega_{\rm pe}$ for a given beam density is rather close to the measured range of the fast electrons beam duration $t_{\rm b}$.

2. Buneman-instability and ion-acoustic one. The two-stream or Buneman-instability [19,20] occurs if electron-flow velocity is higher than its thermal one $u > v_{\text{Te}} \equiv (2T_{\text{e}}/m_{\text{e}})^{0.5}$, the ion-acoustic instability - if u exceeds the velocity of ion-sound $u > (T_{\text{e}}/M_{\text{i}})^{0.5}$ [15–17]. The maximal linear increment γ for the Buneman-



Fig. 3 Langmuir frequency (1), 2-6,8-9 - increments of the Buneman-instability (2), the ion-acoustic one (3,4) and the beam-instability (5-6,8-9), 7 - electron-ions collision frequency ($T_e = 10 \text{ eV}$). 3 and 4 - ion-acoustic increment $\gamma_{i.a.}$ for $u/v_{Te} = 1$ and 0.1 accordingly. 5,8 and 6,9 - are the beam instability increments γ_0 (5,6) and γ_{coll} (8,9) for the beam-density $n_b = 10^{11} \text{ cm}^{-3}$ (5,8) and $n_b = 10^{12} \text{ cm}^{-3}$, (6,9).

Table 1 The beam-instability increments.

	$\nu < \gamma_0$	$\nu > \gamma_0$
$\omega_{\rm pe} \cdot v_{\rm Tb}/u > \gamma_0$	$\gamma_{\rm kin} \approx \omega_{\rm pe} \cdot \frac{n_{\rm b}}{n_{\rm pl}} \cdot \frac{u^2}{v_{\rm Te}^2}$	Beam is stable
$\gamma_{\rm coll} < (\omega_{\rm pe} \cdot v_{\rm Tb}/u) < \gamma_0$	()1/3	
$\omega_{\rm pe} \cdot v_{\rm Tb}/u < \gamma_{\rm coll}$	$\gamma_0 \approx \omega_{\rm pe} \cdot \left(\frac{n_{\rm b}}{n_{\rm pl}}\right)^{1/3}$	$\gamma_{\rm coll} \approx \omega_{\rm pe} \sqrt{\frac{n_{\rm b}}{n_{\rm pl}} \frac{\omega_{\rm pe}}{2\nu}}$

instability is $\gamma_{\text{bun}} \approx (m_{\text{e}}/M_{\text{i}})^{1/3} \omega_{\text{pe}}$. The ion-acoustic instability increment is $\gamma_{\text{i.a.}} \approx \omega_{\text{pe}} (m_{\text{e}}/M_{\text{i}})^{0.5} u/v_{\text{Te}}$. From Fig. 3 it can be seen that the increments of both the Bunemaninstability and the ion-acoustic one corresponds to the observed beam duration ($t_{\text{b}} \sim 50 \text{ ps}$ [2]) for a certain plasmadensity values (i.e. $\gamma(n_{\text{pl}}) \sim 3/50 \text{ ps}$).

3. Beam-instability. The beam-instability is subdivided into four cases by velocity dispersion in the beam and by collision frequency in the plasma [14, 16, 17, 21]. These cases are: mono-energetic beam or "kinetic" beam (with wide velocity spread), and rare or frequent collisions in plasma (see table 1). The notation is as follows, $n_{\rm b}$, $n_{\rm pl}$ - the beam and plasma density, $v \equiv 1/\tau$ plasma-electrons collision-frequency, *u* and $v_{\rm Tb}$ - beam velocity and beam thermal-velocity.

The runaway-electrons beam density n_b was taken as a parameter equal to 10^{11} cm^{-3} and 10^{12} cm^{-3} . The collisional beam-instability increment γ_{coll} is presented at Fig. 3 by curves 8 (for $n_b = 10^{11} \text{ cm}^{-3}$) and 9 (for $n_b = 10^{12} \text{ cm}^{-3}$) as a function of a plasma density.

From Fig. 3 it can be seen that the dependence of the collisional-beam-instability increment $\gamma_{coll}(n_{pl})$ from the plasma density is weaker than that for a Langmuir-frequency (and γ_{bun} , $\gamma_{i.a.}$). Therefore γ_{coll} is consistent with the measured time range (tens of ps) in a more wide plasma-density range than ω_{pe} , γ_{bun} and $\gamma_{i.a.}$.

Due to the large collision-frequency ($\nu > \gamma_0$) even a small beam-velocity spread is high enough for achieving beam stability according to the linear theory (see. Table 1). But the detailed analysis of resulting turbulent state exceeds the frames of our work.

4. Discussion

As it can be seen from Fig. 3, each collective mechanism occupies the certain plasma density range, in which its build-up time is close to the observed range - tens of ps. Therefore, some kind of the turbulent "evolution" of



Fig. 4 Schematic picture of collective plasma processes evolution during the charged particles density growth.

collective processes can take place during the beam propagation and charged particle density growth (see Fig. 4).

It is clear that the developing of all the discussed collective mechanisms depends on the density. The faster plasma and beam densities increase, the faster an instability build-up will occur. Therefore, the lower/bigger the neutral gas pressure, the longer/shorter the beam duration. Similarly, the use of more easily ionizing gas (e.g. Csvapor 3.89 eV) will lead to the fast-electrons beam shortening, and vise versa. Both these suggestions can be examined experimentally.

It should be noted that the stronger the electronemission from the cathode the faster the density growth, and therefore the shorter the beam.

The magnetic field application isn't necessary for the picosecond runaway-electrons beam generation [3] that is why we have considered only the electrostatic instabilities. Generally, the magnetic field influence leads to a lower threshold for the discussed instabilities [17].

5. Conclusion

We have considered the simplest plasma electrostatic instabilities as a probable mechanism of the runawayelectrons beam-disruption in a picosecond atmosphericdischarge.

Strong over-voltage provides an intense electronsacceleration in the runaway regime. It was shown that neither collisions nor a static potential profile could deliberately prevent this runaway regime.

It was shown that the characteristic times of electrostatic-instabilities build-up are consistent with the observed runaway-electrons beam-duration at the certain plasma density, which was considered as a parameter.

The agreement our estimation results and the measured data confirms that collective plasma processes indeed can provide the observed picosecond termination of the fast-electrons beam in a high-voltage gas-filled diode within the tens of picoseconds.

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