Vol 15 No 3, March 2006
1009-1963/2006/15(03)/0600-04

Chinese Physics

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Effect of longitudinal applied magnetic field on the self-pinched critical current in intense electron beam diode*

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(Received 4 March 2005; revised manuscript received 18 July 2005)

The effect of applied longitudinal magnetic field on the self-pinched critical current in the intense electron beam diode is discussed. The self-pinched critical current is derived and its validity is tested by numerical simulations. The results shows that an applied longitudinal magnetic field tends to increase the self-pinched critical current. Without the effect of anode plasma, the maximal diode current approximately equals the self-pinched critical current with the longitudinal magnetic field applied; when self-pinched occurs, the diode current approaches the self-pinched critical current.

Keywords: intense electron beam, diode, self-pinched current
PACC: 5290

1. Introduction

An intense electron beam diode serves in most pulsed power systems as an electron beam generator as well as a power conversion carrier. Generally, the beam current generated by the diode with a certain voltage applied should be estimated and predicated before experiment for pre-optimization of experiment configuration. Hence, it is vital to obtain the current–voltage relationship under different external parameters for designing a practical pulsed power system.

Usually, the electron beam pinch occurs when the diode current is high enough. In the case of diode gap D being relatively small, viz. $D \ll R$, the self-pinched critical current I_c is given by[1−3]

$$I_c = 8.5\gamma_0\beta_0\frac{R}{D}(\mathrm{kA}), \qquad (1)$$

where γ_0 and β_0 are relativistic mass and velocity factors respectively, $\gamma_0 = 1+eV_0/m_0c^2$, $\beta_0 = \sqrt{1-1/\gamma_0^2}$, and e, m_0, and c, the electron charge, rest mass and speed of light; V_0 is the diode voltage at anode. R is the cathode radius, R and D are expressed in centimetres, and I_c is in kilo amperes.

Considering the state of pinch, electron beam generated by the diode is generally non-homogeneous and cannot be directly applied in the systems requiring large-area uniform electron beams. In this case, applying a longitudinal magnetic field can alleviate the pinching as well as slack the expansion of electron beam. Generally it is assumed that when the applied magnetic field is greater than a critical value, the self-pinching of the electron beam will be suppressed.[3,4] Namely, an applied magnetic field can increase the self-pinched critical current.

In Section 2, the self-pinched critical current of a planar diode with a longitudinal magnetic field applied is derived. The pinch process and the self-pinched critical current of a planar diode are studied by using the numerical simulation method for cases of different applied magnetic fields in Section 3. Finally, the conclusions and discussion are given in Section 4.

2. Self-pinched critical current of planar diode with longitudinal applied magnetic field

According to the method employed in Ref.[5], for $D \ll R$, the effect of the radial electric field can be

*Project support by National High Technology 863 Program of China (Grant No AA834060).

neglected. Then the transverse balance equation of a boundary electron can be approximately expressed as

$$\frac{m_0\gamma v^2}{r} = -ev_{\theta m}B_z + ev_zB_\theta, \tag{2}$$

where, m_0, γ and v are respectively electron rest mass, relativistic factor and velocity; e, the electron charge; v_θ and v_z, the azimuthal and axial velocities; B_θ and B_z, the azimuthal and axial components of magnetic field.

Supposing that diode pinching will occur when the relativistic Larmor radius of the electron emitted from cathode is smaller than or equals to the diode gap, namely., $r \le D$, Eq.(2) can be written as

$$\frac{m_0\gamma v^2}{D} = -ev_{\theta m}B_z + ev_zB_\theta, \tag{3}$$

where

$$v_0^2 \approx v_t^2 + v_z^2 = \beta_0^2c^2, \quad v_t^2 = v_r^2 + v_\theta^2 \approx v_{\theta m}^2 \tag{4}$$

with v_t, v_r, v_θ and $v_{\theta m}$ respectively being the transverse, angular, radial electron velocity and the approximate transverse velocities.

For $v_t \approx v_z \approx \dfrac{\beta_0 c}{\sqrt{2}}$, the beam radius approaches $\dfrac{R}{\sqrt{2}}$. And the self-magnetic-field at beam fringe can be approximately given by

$$B_\theta \approx \frac{\mu_0 I_\mathrm{b}}{2\pi R/\sqrt{2}} = \frac{\mu_0 I_\mathrm{b}}{\sqrt{2}\pi R}. \tag{5}$$

According to Eq.(5), the self-pinched critical current I_BC with a longitudinal magnetic field applied is obtained as

$$I_\mathrm{BC} = \frac{2\pi m_0 c}{e\mu_0}\gamma_0\beta_0\frac{R}{D} + \frac{\sqrt{2}\pi}{\mu_0}RB_z, \tag{6}$$

$$I_\mathrm{BC} = 8.5\gamma_0\beta_0\frac{R}{D} + 35RB_z, \tag{7}$$

with I_BC in kiloamperes, R and D in centimetres, and B_z in teslas. If B_z goes to zero, Eq.(7) reduces to Eq.(1).

The effect of longitudinal applied magnetic field on the self-pinched current of intense electron beam diode is similar to that of it on the self-magnetic-field-limited current.[5] Equations (1) and (7) are obtained by discarding the effects of radial electric fields; hence they should be comparatively accurate for $D \ll R$. In fact, the electric fields (including the self-electric-field and the applied electric field) should not be wholly neglected. It tends to increase the self-pinched critical current.

3. Numerical simulations

In this section, for different cathode radii, diode voltages and anode–cathode gaps, the currents and the radii of electron beams at the anode are studied with and without longitudinal magnetic field applied by using the numerical simulation code-KARAT.[6]

Here, we define the ratio of the diode current to the self-pinched critical current as $\zeta_\mathrm{I} = I_\mathrm{b}/I_\mathrm{c}$. In the absence of an applied magnetic field, the beam radius r at the anode versus ζ_I is shown in Fig.1(a), from which it can be seen that, when ζ_I is less than unity, r decreases slowly with the increase of ζ_I; when ζ_I is approximate to unity and approximately keeps constant, r decreases rapidly. The ζ_I versus I_b is given in Fig.1(b). It shows that the maximum ζ_I is close to unity.

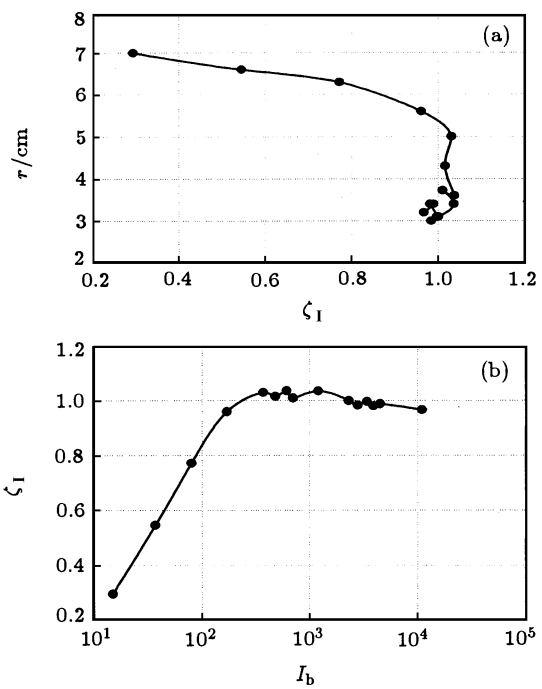


Fig.1. (a) Beam radius r versus $\zeta_\mathrm{I} = I_\mathrm{b}/I_\mathrm{c}$ for R=7cm, D=2cm, B=0.0T. (b) $\zeta_\mathrm{I} = I_\mathrm{b}/I_\mathrm{c}$ versus the diode current I_b for R=7cm, D=2cm, B=0.0T.

The beam radius r at anode versus the parameter $\zeta_\mathrm{I} = I_\mathrm{b}/I_\mathrm{c}$ with a longitudinal magnetic field applied is shown in Figs.2(a) and 2(c). If ζ_I is less than a critical value (this value increases almost linearly with the increase of magnetic field, as shown in Fig.3, which is consistent with Eq.(7)), the radius r decreases slowly with ζ_I increasing. If ζ_I is close to the value, the radius r falls sharply. And then ζ_I decreases with the increase of diode current and the cathode voltage [Fig.2(e)].

We define the ratio of the diode current to the self-pinched critical current with an applied magnetic

field as $\zeta_{BI} = I_b/I_{BC}$. The variation of r with the ratio ζ_{BI} in Fig.2(b) or 2(d) is consistent with that of r with the ratio ζ_I with no magnetic field applied [Fig.1(a)], viz. in the absence of the anode plasma, the maximum ζ_{BI} is also close to unity.

The maxima ζ_{BI} for different applied longitudinal magnetic fields, cathode radii and anode–cathode gaps are given in Fig.4, where it is shown that the average of the maxima ζ_{BI} is approximate to 1.07, which approaches unity. Note that the maxima ζ_{BI} for different applied magnetic fields are discrete, which is mainly caused by the insufficient datum points chosen for numerical simulations. Actually, every maximal ζ_{BI} is a maximum obtained among the data for about 10 voltages at the diode and is only one approximation. However, more datum points will cost too much computing time, and present data are sufficient to explain the problem under consideration.

The simulation results all support Eq.(7). The self-pinched critical current is a linearly increasing function of an applied magnetic field. Additionally, in the absence of the anode plasma, the maximal ζ_{BI} is approximate to unity, which is the same as the maximal ζ_I in the case of no magnetic field applied.

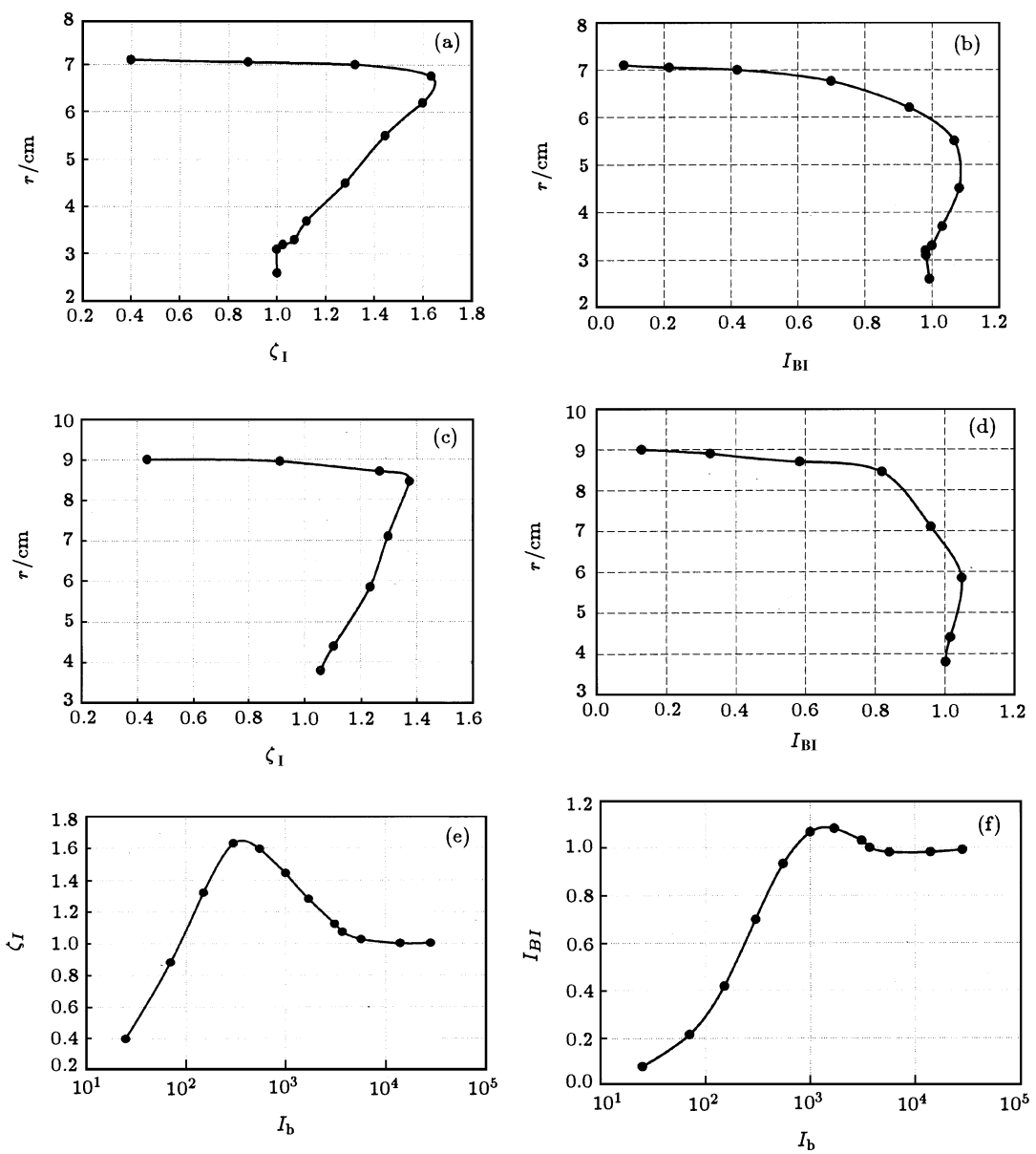


Fig.2. (a) Beam radius r vs ζ_I for R=7 cm, D=1.5 cm, B=1T. (b) Beam radius r vs ζ_{BI} for R=7 cm, D=1.5 cm, B=1T. (c) Beam radius r as a function of ζ_I for R=9 cm, D=2 cm, B=0.5T. (d) Beam radius r vs ζ_{BI} for R=9 cm, D=2 cm, B=0.5T. (e) ζ_I vs the diode current I_b for R=7 cm, D=1 cm, B=0.5T. (f) ζ_{BI} vs the diode current I_b for R=7 cm, D=1 cm, B=0.5T.

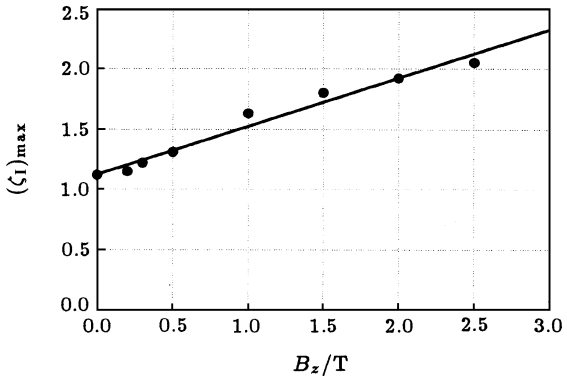


Fig.3. Maximum of ζ_I vs the applied longitudinal magnetic field B_z for D=7 cm, R=1.5 cm.

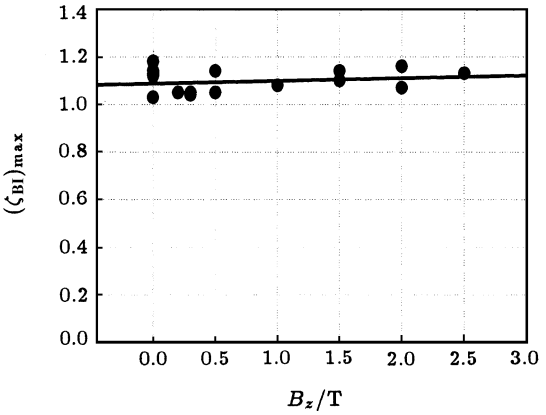


Fig.4. Maximum of ζ_{BI} vs the applied longitudinal magnetic field B_z.

4. Conclusions

The self-pinched critical current with longitudinal magnetic field applied is derived and its validity is tested by numerical simulations. The result shows that with a longitudinal magnetic field applied externally, the electron beam pinching is alleviated, and the self-pinched critical current increases. Without considering the presence of the anode plasma, the maximal current generated by a diode equals the self-pinched critical current. For the diode voltage being greater than a critical value, which corresponds to the self-pinched critical current, the diode current is obtained explicitly.

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