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I–V characteristics of foilless diodes*

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Some physical characteristics of foilless diodes are obtained and analysed by numerical simulations. Relations between diode current and configuration parameters, i.e. diode voltage and external magnetic field, are investigated. Employing these relations and assuming that the external magnetic field is strong enough, the diode current can be approximately written as $I_{\rm b} = (7.5/x)(x + (0.81 - x)/(1 + 0.7L_{\rm d}^2/\delta r))(\gamma_0^{2/3} - 1)^{3/2}$, in which $L_{\rm d}$ is the Anode–Cathode (AK) gap, $R_{\rm c}$ the outer radius of cathode, and $R_{\rm p}$ the radius of drifting tube; $x = \ln(R_{\rm p}/R_{\rm c})$, $\delta r = R_{\rm p} - R_{\rm c}$. This expression is comparatively accurate for different configuration parameters and voltages; results obtained from this expression are consistent with that of numerical simulations within an error of 10%.

Keywords: foilless diode, I–V relation, intense electron beam
PACC: 2925B, 4180D

1. Introduction

For the generation of intense relativistic electron beams, foilless diodes have several advantages over conventional foil diodes. The foilless configuration eliminates distortion, shatter, vaporization of the foil and beam scattering due to the foil. As a result, intense thin hollow relativistic electron beams could be produced. Besides, foilless diodes are capable of long-pulsed and repetitive operations, therefore they are widely employed in wave–beam interaction devices, microsecond pulse electron accelerators and high current transportation fields. Meanwhile, they also have disadvantages compared with foil diodes, such as strong external guiding magnetic fields must be applied, the intensity of the acquired beam is relatively low, and the generation and application of electron beams must be under the same vacuum circumstances, etc.

Studies of foilless diodes started at the beginning of the 1970s. There are two types of models adopted in the study of foilless diode theories in the early period. One is the space charge limited current model based on infinite strong guiding magnetic fields and extreme approximation, e.g. the Ott, Antosen, and Lovelace (OAL) model. The diode is supposed to be a "corner diode" (Fig.1) in the OAL model. The potential of the cathode, which is an end surface of the drifting tube, and that of the anode, which is a half of an infinitely long conducting tube, are maintained at V and 0 respectively. Electron beams are emitted, with the inner radius $R_{\rm c1}$ and the outer radius $R_{\rm c}$, from the annular cathode, and move along the axis with no transverse movements as constrained by the external axial guiding magnetic field which is infinitely strong. The beam is assumed to be thin compared with its distance to the anode wall, that is, $(R_{\rm p} - R_{\rm c}) \gg (R_{\rm c} - R_{\rm c1})$. By solving the Poisson equation under the above conditions, the diode current can be acquired:[1]

$$I_{\rm OAL} = \frac{17(\gamma_0^{2/3} - 1)^{3/2}(r_{\rm b}/\delta r)}{\ln(8\delta r/\Delta)} \quad ({\rm kA}) \quad \text{(relativistic case)}, \tag{1}$$

in which $\gamma_0 = 1 + eV/m_0c^2$ is the relativistic factor, V the potential of the cathode; $r_{\rm b} = (R_{\rm c1} + R_{\rm c})/2$ and $\Delta = R_{\rm c} - R_{\rm c1}$ are mean radius and mean thickness of the electron beam; $\delta r = R_{\rm p} - R_{\rm c}$ is the distance from beam to the anode wall.

The other model used in developing foilless diode theories assumes that the diode current can be determined by the equilibrium the beam reaches in the hollow drift tube.[2] Then the diode current can be approximately given by

$$I_{\rm equ} = 34\left\{\left[\frac{\gamma_0}{1 + 4\ln(R_{\rm p}/R_{\rm c})}\right]^2 - 1\right\}^{1/2} \quad ({\rm kA}). \tag{2}$$

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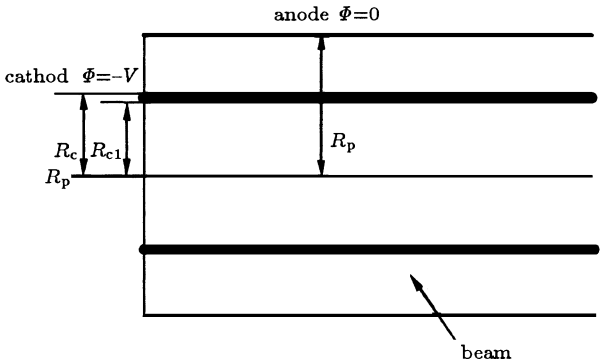


Fig.1. Geometry of the "corner diode" in OAL model.

As a matter of fact, the internal mechanism of actual foilless diodes, especially the physical process in the accelerating region near the cathode, is so complex that no accurate analytic solutions can be obtained. For instance, the Anode–Cathode (AK) gap exerts a great influence on the diode current and thus cannot be neglected, but this influence is not expressed out in Eq.(1), nor in Eq.(2). In addition, according to Eq.(1), the emitting area of the cathode will greatly affect the diode current, whereas numerical simulation results show that the influence of the area is approximately neglectable.[3] These differences or errors appear mainly due to the fact that most current theoretical analyses about foilless diodes have been made in a way of simplification under assumed limit conditions, so simplified that some important factors (such as the AK gap) have been ignored. In this article, physics of foilless diodes are examined both numerically and theoretically, and I–V relations of foilless diodes applicable in larger parameter ranges are acquired.

2. Numerical study on foilless diodes

Foilless diodes of various parameters are simulated with the full electromagnetic PIC code KARAT.[4] Influence of these parameters upon diode current is examined. The diode configuration is shown in Fig.2, where L_d is the AK gap, R_c is the outer radius of emitting region of the cathode, $\delta r = R_p - R_c$ is the distance from the beam to the drift tube wall and Δ is the thickness of the emitting plane of the cathode. In simulations, the emitting region is divided into about ten cells. The number of macro-particles is approximately 10 000.

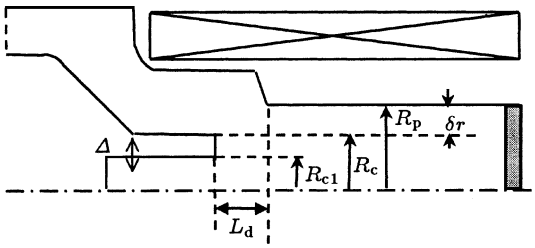


Fig.2. Configuration of simulated foilless diode.

2.1. Influence of the thickness of the emitting plane

Figure 3 shows the variation of diode current with the thickness of the cathode Δ when the diode voltage applied is 600kV, the outer radius of the cathode is 1.1cm, the external magnetic field is 3.0T and δr is 0.3cm. It is demonstrated that the diode currents remain unchanged with the variation of the thickness of the cathode. Analyses show that this is mainly due to the shielding effect of intense electron beams. On the other hand, from the point of view of beam transmission, it is required to satisfy the space charge limiting law. As is well known, the space charge-limiting current of a thin annular beam is higher than that of a solid or thick beam, therefore if the emitting beam intensity of the cathode is larger than the intensity that could transmit for a solid or thick beam in the drifting tube, the beam will become thin by the effect of space charge. Under this condition no matter how thick the cathode is, the transmitting beam will be thin. A distribution map of beam densities along radius obtained from simulation is exhibited in Fig.4.

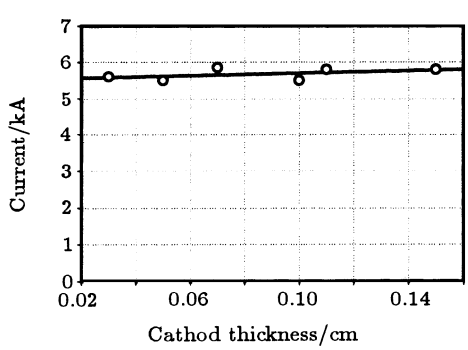


Fig.3. Current variation with thickness of the cathode at a diode voltage of 600kV, L_d=2cm.

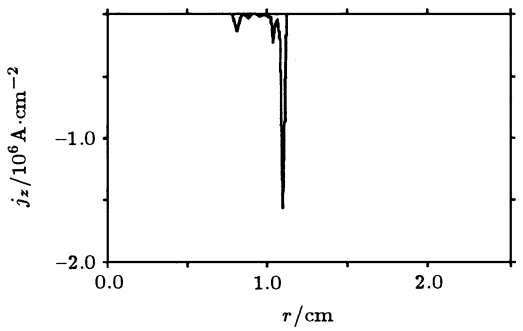


Fig.4. Radial distribution of beam density (thickness of cathode 0.2cm).

2.2. Influence of diode voltages

Figure 5 shows the variation of diode currents with different diode voltage under the condition that the outer radius of cathode is 1.1cm, the external magnetic field is 3.0T, and δr is 0.3cm for different AK gaps. Results show that the diode current is directly proportional to $(\gamma_0^{2/3}-1)^{3/2}$ in a diode voltage range of 0.2 to 2MV: that is,

$$I \approx h(\gamma_0^{2/3}-1)^{3/2}, \tag{3}$$

in which h is a coefficient related to diode configuration parameters.

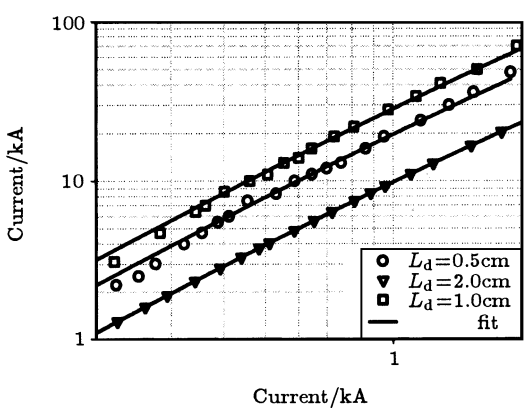


Fig.5. Current variation with diode voltage at different AK gaps (R_c=1.1cm, δr=0.3cm, Δ=0.1cm).

2.3. Influence of A-K gap

Figure 6 shows the variation of diode currents with different AK gap, provided that the diode voltage is 600kV, the outer radius of cathode is 1.1cm, the external magnetic field is 3.0T, Δ is 0.1cm, δr is 0.3cm for different radii of the drift tube. It is noted that if the cathode is in the drift tube (AK gap $L_d \leq 0$) or the gap is large enough, the total diode current does not change with the AK gap obviously. But the ratio of the two currents is related to the radius of the drift tube. By fitting the simulation data, it is seen that the diode current is approximately in direct proportion to $1+a/(1+(bL_d)^2)$, where a and b are coefficients related to the diode voltage, the radius of drift tube and the outer radius of the cathode.

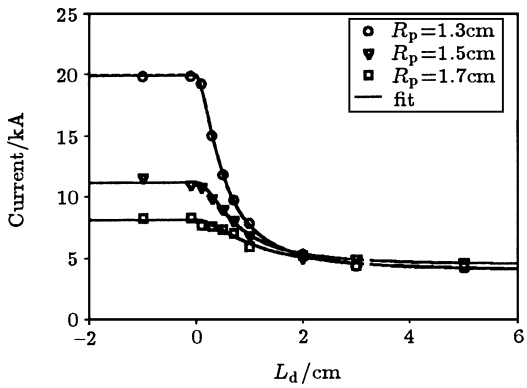


Fig.6. Current variation with AK gap for different radii of drift tube (V=600kV, R_c=1.1cm, Δ=0.1cm.

2.4. Influence of radius of drift tube

Figure 7 shows the variation of diode currents with different radius of drift tube when the diode voltage is 600kV, the outer radius of cathode is 1.1cm, the external magnetic field is 3.0T, Δ is 0.1cm for variable AK gaps. It is proved that the diode current changes linearly with $1/\ln(R_p/R_c)$, that is

$$I_b \approx c + d/\ln(R_p/R_c), \tag{4}$$

in which c and d are coefficients related to the diode voltage and AK gaps.

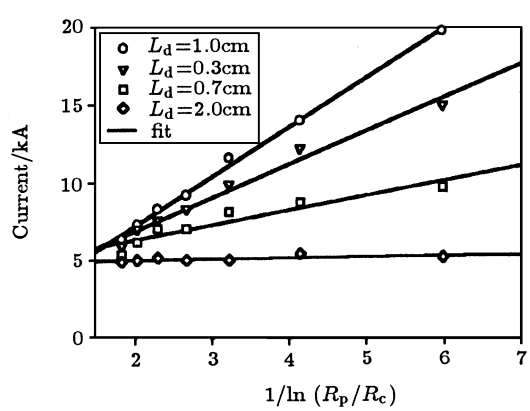


Fig.7. Current variation with $1/\ln(R_p/R_c)$ at different AK gaps (V=600kV, R_c=1.1cm, Δ=0.1cm).

2.5. Influence of external magnetic fields

Figure 8 shows the variation of diode currents with different external magnetic field, with the outer radius of cathode being 1.1cm, Δ being 0.1cm for variable AK gaps. It is seen that the diode current changes

linearly with the reciprocal of the intensity of external magnetic fields in the range from 0.5 to 2.0T, that is

$$I_{\rm b} \approx n + m/B_z, \tag{5}$$

where n and m are parameters related to the diode voltage and configuration parameters. However, the variation is slow, namely, the value of m is small. When the external magnetic field is strong enough (e.g. greater than 2T), the diode current remains almost constant. That is because the thickness of beam reduces slightly with increasing external magnetic field. When the magnetic field is intense enough, the thickness remains almost constant. Since the space-charge-limited current generated by the diode increases slightly with increasing thickness in a certain range, the diode current changes in the way described above. The results are obtained under the condition that the external magnetic field is strong enough to prevent electron beams from striking the wall of the drift tube. It is obvious that there exists a certain critical magnetic field, when the external magnetic field is weaker than this, electron beams will strike the wall of the drift tube. So, with the weakening of the field, more and more electron beams will strike the wall, that is, the diode current will be reduced. Here we mainly focus our researches on the condition that the external magnetic field is stronger than the critical field, that is, with no electron beams hitting the wall of the drift tube.

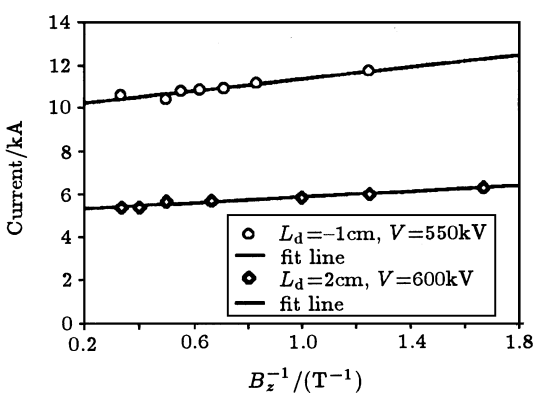


Fig.8. Current variation with external magnetic field.

3. I–V relation of foilless diodes

By analysing the above numerical simulation results, the I–V relation of foilless diodes, provided that external magnetic field is intense enough, can be expressed approximately as

$$I_{\rm b} \approx c_0 \left(x + \frac{a_0 - x}{1 + bL_{\rm d}^2/\delta r} \right) \frac{(\gamma_0^{2/3} - 1)^{3/2}}{x}, \tag{6}$$

where $x = \ln(R_{\rm p}/R_{\rm c})$, $\delta r = R_{\rm p} - R_{\rm c}$. The constants a_0, b and c_0 are approximately determined to be 0.81, 0.7 and 7.5 respectively by simulations with different voltages and configuration parameters. Therefore, the current of foilless diodes at intense external magnetic fields can be approximately written as

$$I_{\rm b} = 7.5 \left(x + \frac{0.81 - x}{1 + 0.7L_{\rm d}^2/\delta r} \right) \frac{(\gamma_0^{2/3} - 1)^{3/2}}{x}. \tag{7}$$

Results obtained from this expression for different AK gaps, cathode radii and diode voltages are consistent with that of numerical simulations within an error of 10% (Fig.9), and it is the same as the simulations carried out with another PIC code Magic. Therefore, Eq.(7) gives a relatively accurate expression of I–V relation of foilless diodes for different configuration and voltage parameters. This conclusion is of great significance for theoretical study, design and experimental analysis of foilless diodes.

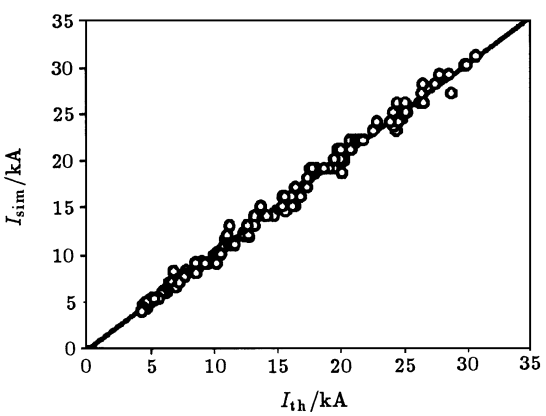


Fig.9. Comparison between results of Eq.(7) and simulations, for different configuration parameters and voltages.

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