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Space-charge limiting current in spherical cathode diodes*

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The results of the investigation on the space-charge limiting current for a spherical-cathode diode in the non-relativistic situation are presented in this paper. The results show that the current enhancement factor equals the square of E-field enhancement factor on the cathode surface. The generated space-charge limiting current is deduced. In the case of a pin-shaped-cathode diode, the space-charge limiting current is also obtained, indicating that the current is independent of the geometric parameters of the diode. Analyses of the shielding effects and the conditions for generation of the uniform space-charge limiting beam show that, for pin-arrayed cathodes, the distance between pins should be in the range from $1.2D$ to $1.5D$, where D is the distance between the two electrodes.

Keywords: diode, space-charge limiting current, relativistic electron beam
PACC: 5290

1. Introduction

The spherical and pin-arrayed cathode diodes with a planar anode are widely used to generate high current electron beams or serve as a part of the pulsed power devices, but the analytic solutions to their space-charge limiting current are not attainable. In this paper the particle in cell (PIC) simulation code is employed to calculate the space charge limiting current for spherical cathode diodes. Meanwhile, an experiment is also carried out to verify the results of simulations and theoretical analyses. The results show that the current enhancement factor is approximately equal to the square of the E-field strength enhancement factor.

2. The space-charge limiting current for a spherical cathode diode

The schematic figure of the diode structure is shown in Fig.1. Firstly, the electromagnetic simulation code "Superfish/Poisson" is used to calculate the E-field distribution in the diode.[1] It is supposed that the field enhancement factor, β, equals the ratio of the maximum field intensity in the cathode surface, $E_{\max}$, and V/D, where V is the voltage and D is the distance between the two electrodes. For the case that the cathode radius R=1.0, 2.0, 3.0 and 5.0 cm respectively, the field distributions in the diode for different ratios of D/R are calculated. The calculated results show that $E_{\max}$ is at the top of the cathode sphere. The dependence of the field enhancement factor β on D/R is shown in Fig.2. From the fitting, we can obtain

$$\beta = 0.9 + 0.9\frac{D}{R}. \tag{1}$$

Therefore, the maximum field $E_{\max}$ over the surface of the spherical cathode is

$$E_{\max} = \beta\frac{V}{D} = V\left(\frac{0.9}{D} + \frac{0.9}{R}\right). \tag{2}$$

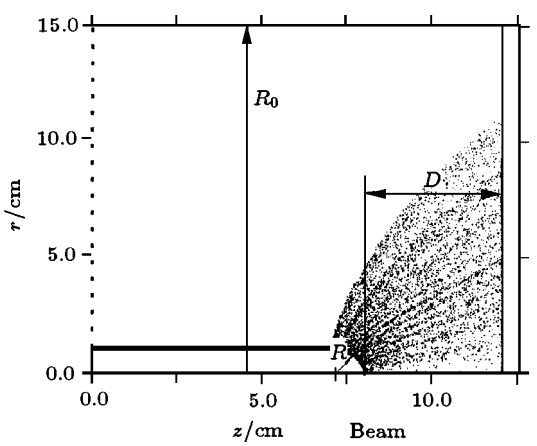


Fig.1. The schematic figure of the diode with spherical cathode.

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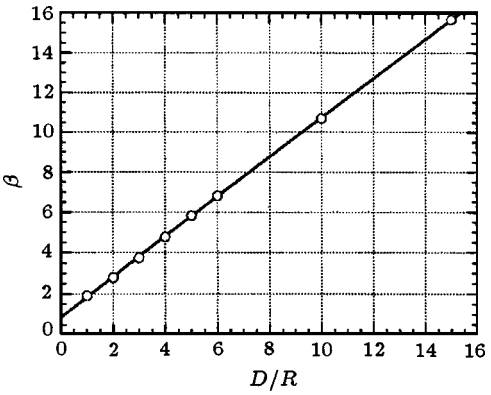


Fig.2. The curve of β versus D/R.

For the case of the voltage V <500kV (e.g. non-relativistic condition), 2.5D PIC simulation code KARAT[2] is used to calculate the space-charge limiting current, I_s, for different D/R. The electron profile is shown in Fig.1, where the number of macro particles is about 5000. The current enhancement factor, η_b, is defined as the ratio of space-charge limiting current between the spherical cathode diode and the planar diode with the same projective cathode area and the gap between cathode and anode,

$$\eta_b = I_s/I_{c1}, \tag{3}$$

where $I_{c1} = 2.33 \times 10^{-6}\frac{V^{3/2}}{D^2}\pi R^2$ (see Refs.[3] and [4]).

The calculated results are shown in Table 1 and Fig. 3. The results indicate that η_b can be approximately represented as β^2, that is

$$\eta_b \approx \beta^2. \tag{4}$$

Therefore, under the non-relativistic conditions ($V <$ 500kV), the space-charge limiting current of the spherical cathode diode is

$$I_s = 7.13 \times 10^{-6}\left(0.9 + 0.9\frac{R}{D}\right)^2 V^{3/2}, \tag{5}$$

where V is the diode voltage in unit of volt, and I_s the space-charge limiting current in unit of ampere.

The PIC simulation shows that Eq.(5) is not suitable for $D/R < 1$, i.e. electron beam pinching occurs.

Table 1. The dependence of β and η_b with D/R.

D/R	β	V/kV	I_s/kA	I_{c1}/A	η_b
1.0	1.9	142	1.2	391	3.0
2.0	2.8	224	1.4	194	7.2
3.0	3.8	243	1.3	97	13.3
5.0	5.8	255	1.2	37.7	30.5
10	10.7	265	1.1	10	110
25	24.6	270	0.7	1.6	420

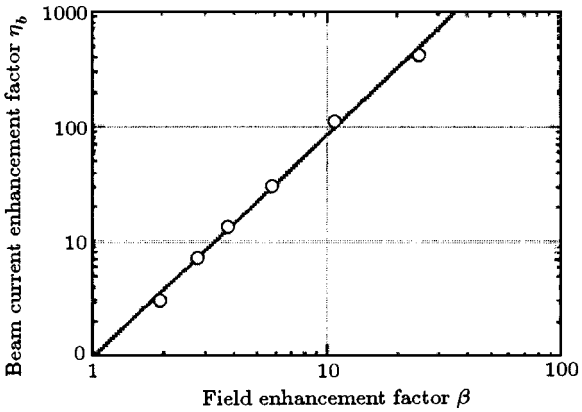


Fig.3. The beam current enhancement factor η_b as a function of the field enhancement factor β.

3. Space-charge limiting current for the pin cathode

Equation (5) shows that, when $D \gg R$, the space-charge limiting current generated by the diode is approximately independent of D and R, and only dependent upon the diode voltage. Therefore, the space-charge limiting current, I_{sn}, is

$$I_{sn} = 5.8 \times 10^{-6} V^{3/2}. \tag{6}$$

Based upon the above results, we have explored the characteristics of the space-charge limiting current produced by pin-arrayed cathode, and calculated the optimal pin-separation, ΔL, when the pins are uniformly distributed.

According to the Child–Langmuir law, for a large aspect-ratio diode, when the applied voltage V is less than 500kV, the density of the space-charge limiting current can be approximately described as[3,4]

$$J = 2.33 \times 10^{-6}\frac{V^{3/2}}{D^2}, \tag{7}$$

where J is the current density (A·cm^{-2}), V is the diode voltage in unit of volt and D is the diode gap in unit of centimetre.

Therefore, from Eqs.(6) and (7), we can obtain the maximum separation between the pins[5]

$$\Delta L = 1.58D, \tag{8}$$

where ΔL is the upper limit for the pin separation for generating the space-charge limiting current.

Practically, for a uniform beam, the separation should be a little less than that. However, much smaller separation between the pins would result in the generation of the nonuniform electron beam due

to shielding effects caused by the electrons emitted from the pins. According to Ref.[6], the radius of the shielding area around the emitting point, r_s, is[6]

$$r_s = 5 \times 10^2 \sqrt{I_{sn}} D V^{-3/4}. \quad (9)$$

Inserting I_{sn} in Eq.(6) into Eq.(9), we have

$$r_s = 1.2D, \quad (10)$$

where r_s is the radius of the shielding produced by the electron beam from a single pin.

For some reasons, the electrons are not emitted at the same time from the pins in a pin array; therefore, the electron beam emitted previously by a pin would produce shielding effect on the pins around it. The shielding effects decrease the electronic fields over these pins, so that the cathode plasma cannot be formed. When the distance between the pins is too small, the shielded pins would not emit electrons due to the shielding effects.

Therefore, all the pins should emit electrons during a single input voltage pulse in order to generate a uniform electron beam, and the optimal distances should be

$$\Delta L = (1.2 \sim 1.5)D. \quad (11)$$

4. Experimental study of the space-charge limiting current for a spherical-cathode diode

The theoretical results obtained from PIC numerical simulation are verified by experiments. The experiment has been carried out on the SINUS-881 accelerator, as shown in Fig.4. The output impedance under a matched condition for the accelerator is 40Ω at the operating voltage ranging from 300 to 700kV.

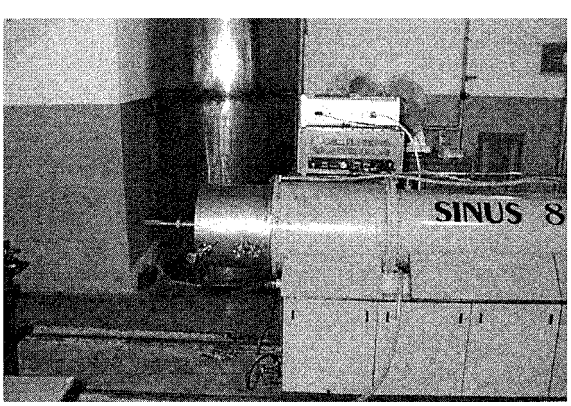


Fig.4. Experimental set-up of a spherical-cathode diode.

The radius of the spherical cathode is chosen to be 0.95cm. The A-K gap is varied from 0.5 to 17.6cm, followed by an adjustment of diode voltage correspondingly. Five or six shots have been taken for each A-K gap. The experimental data and those calculated using Eq.(5) are plotted in Fig.5. The theoretical result, I_s, is less than I_{exp}, the experimental result, and the fitting result shows that $I_{exp} \approx 0.76 I_s$. The experimental data for the diode voltage of about 0.7MV with different D/R are presented in Fig.6. The results show that, when the ratio D/R increases, the space-charge limiting current I_s decreases, approaching a constant for large D/R, which is in agreement with that deduced from Eq.(5). The difference between the theoretical values and the experimental data is considered to be due to the partial emitting area of cathode surface in experiments, compared with the hypothesis in theoretical analyses.

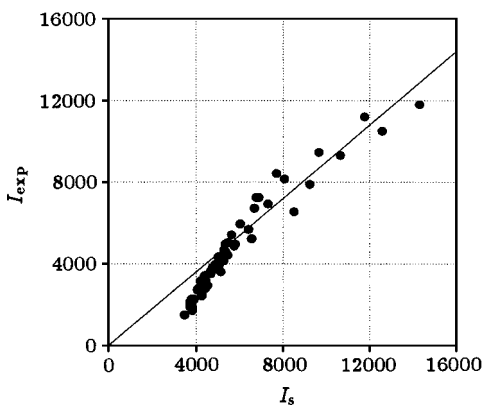


Fig.5. The experimental results of diode current versus calculated data using Eq.(5).

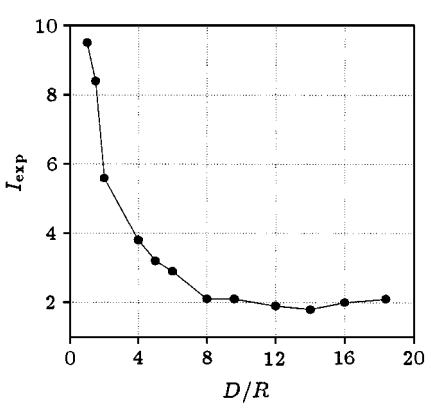


Fig.6. Experimental data for diode current versus D/R (Diode voltage is about 0.7MV).

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