THE INFLUENCE OF INITIAL CURRENT DENSITY DISTRIBUTION ON THE EMITTANCE REDUCTION

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Abstract

In this study, the influence of current density distribution on the cathode surface on the beam emittance evolution was investigated. The emittance evolution with different beam profiles (flat-top, peak and hollow distribution) have been compared. The modification of the current profile was shown to affect the axial distance of the point of minimal emittance over wide range. The hollow profile allows extending the axial distance of the point of emittance minimum keeping its value extremely low. Further the parameters of a peak profile, which give the smallest emittance were determined. This work demonstrates the significance of initial current density distribution for the emittance evolution.

INTRODUCTION

Generation of electron beam with extremely small transverse emittance is decisive for accelerators being used in Free Electron Laser (FEL) facilities. Since emittance growth is caused mainly at the electron source, further improvement of electron gun performance is important. In recent studies, the mechanism of emittance evolution and the possibility for the emittance reduction by self-induced space charge forces were reported [1-3]. According to these studies, emittance takes maximal value in the vicinity of cathode surface and then decreases to its minimal value which tends to be extremely low or almost same with the thermal emittance of the cathode.

Figure 1 shows an example of the calculated emittance evolution. The thermal emittance was neglected, so the emittance at the point A is 0 mm-mrad. After acceleration, the emittance takes maximal value due to the image charge and the space charge effect at the point B. The current density profile is distorted by these effects. The distorted current density distribution generates nonlinear electric fields. At the point C, the emittance decreases due to the nonlinearity. The emittance keeps decreasing to an extremely low value at the point D. After the point D, the nonlinear field increases the emittance. In order to make use of this phenomenon for the real electron gun a booster has to be placed slightly before the point D. The booster would conserve the beam emittance for the further acceleration. In Figure 1, the point D has an axial distance of 580 mm from the cathode. For a real electron gun, this point is too close to the gun exit, which makes it mechanical impossible to place an additional booster. From this point of view, we are interested to find conditions with longer axial distance for the point D.

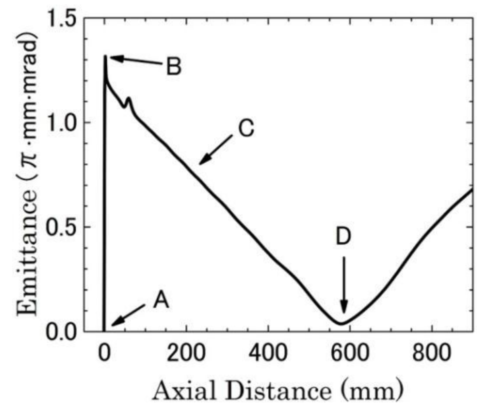

Figure 1: Calculated emittance evolution for the SCSS thermionic gun. The point A, B, C and D correspond to the cathode surface, the emittance maximum, the emittance decreasing point and the emittance minimum.

The axial distance of the emittance minimum can be varied by changing the beam current and applied voltage. It is pointed out that the position of the emittance minimum strongly depends on the current density profile at the emittance maximum [4]. These studies were carried out under assumption of a uniform current density distribution on the cathode surface. However, the real thermionic cathode might have a non-uniform temperature distribution. In this work, we have investigated the influence of current density profile on the cathode surface on the beam emittance evolution numerically. The emittance evolution with different beam profiles have been compared and discussed.

SIMULATION METHOD

The calculation in this study is performed by the two dimensional axial symmetric code KUAD2 [5], which is a code for calculating trajectories in static fields.

The SCSS thermionic gun was taken as the model for this study [6]. The SCSS is assumed to be ideally axial symmetric. The diameter of the CeB_6 cathode of the SCSS gun is 3 mm and the distance between the cathode and the anode is 5 cm. The investigated axial distance from the cathode surface is 935 mm. The electron beam is continuously accelerated by a uniform DC electric field.

The modification of current density distribution on the cathode surface is done based on Eq. 1, where σ is a variable parameter. After the determination of σ, the $A(\sigma^2)$ is adjusted to keep the total current constant. The extracted current from the cathode is set to 1.0 A and the beam energy at the gun exit to 500 keV.

$$J(r) = \begin{cases} \frac{A(\sigma^2)}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{r^2}{2\sigma^2}\right) & \text{(Peak Dist.)} \\ \text{const.} & \text{(Flat} - \text{top)} \\ \frac{A(\sigma^2)}{\sqrt{2\pi\sigma^2}} \exp\left(+\frac{r^2}{2\sigma^2}\right) & \text{(Hollow Dist.)} \end{cases} \quad (1)$$

Typical current density profiles of the flat, peak and hollow distributions on the cathode surface are shown in the Fig. 2. In order to evaluate the non-uniformity of the current density, a factor f_{prof} as defined in Eq. 2 is used.

$$f_{prof} = \frac{J_{(r=1.5)}}{J_{(r=0)}} \times 100 \quad (2)$$

The factor f_{prof} gives the ratio of the current density at the edge of cathode to that at the center. For the CeB_6 cathode with radius of 1.5 mm the temperature at the center is 1773 K and work function is 2.4 eV. According to the calculation by Richardson-Dushman equation [7], f_{prof} = 57% means that the temperature at the edge is 1718 K. The factor of f_{prof} = 120% means that the edge temperature is 1792 K.

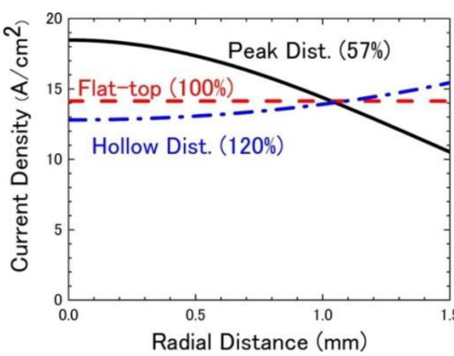

Figure 2: Radial distribution of current density profiles.

RESULTS AND DISCUSSION

Figure 3 shows the emittance evolutions for different current density profiles. The emittance reduction phenomenon is also observed in the case of peak and hollow distributions. The emittance evolutions change by varying initial current density distribution. The axial distance at the point of minimal emittance strongly depends on the initial beam profile. The emittance minimum of a flat-top beam occurs at the axial distance z = 580 mm. That of the peak distribution (f_{prof} = 57%) occurs at z = 266 mm and the one of the hollow distribution (f_{prof} = 120%) at z = 758 mm.

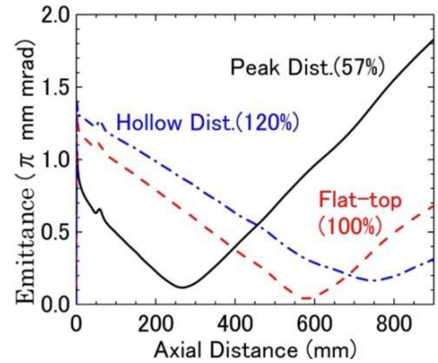

Figure 3: Emittance evolution of the three different initial beam profiles with a fixed current.

Figure 4 shows the correlation between the position of emittance minimum and f_{prof}. The higher value of f_{prof}, the longer the axial distance of the point of minimal emittance. The initial current density profile strongly affects the emittance evolution.

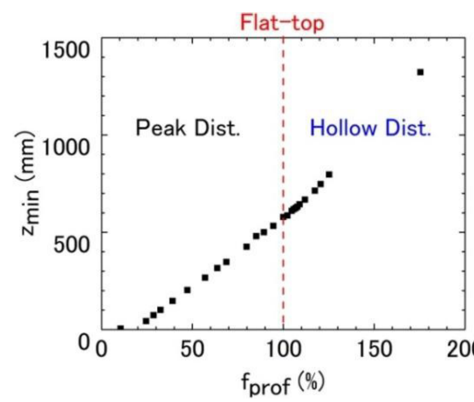

Figure 4: Correlation between the position of emittance minimum and the initial current profile modulation factor f_{prof}.

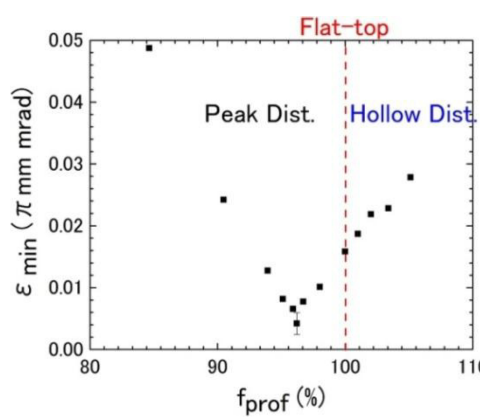

Figure 5: Emittance minimum as a function of f_{prof}.

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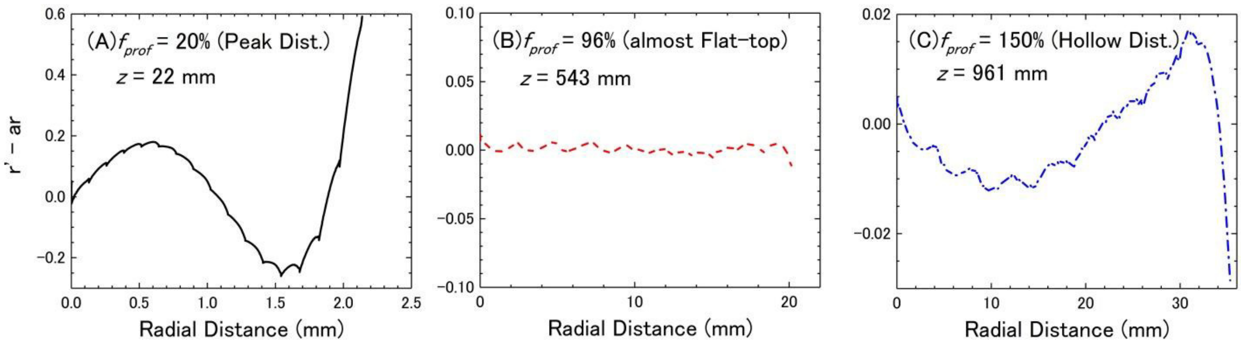

Figure 6: *r'*-*ar* plot at the emittance minimum as a function of the radial distance. Electron beam with (A) Result of peak initial distribution at the axial distance of 22 mm. (B) Result of almost flat-top initial distribution at the axial distance of 543 mm. (C) Result of hollow initial distribution at the axial distance of 961 mm.

Figure 5 shows the value of emittance minimum as a function of f_{prof}. It indicates that the value of emittance minimum also depends on f_{prof}. The smallest emittance is obtained around f_{prof} = 96% (almost flat-top initial distribution). Nevertheless the emittance minimum remains lower than 0.05 π-mm-mrad within the range of f_{prof} = 85% - 110%.

For better understanding of emittance minimum behaviour for different f_{prof} values, we consider phase space plots at the emittance minimum. Figure 6 shows the difference plot of $r'(r)$ and the linear approximation straight line ar at the emittance minimum in phase space. The parameter a is determined by the least squares method. As shown in Fig. 6, the phase space plot at the emittance minimum forms an S-shaped curve in case of the hollow initial distribution and an inverted S-shaped curve with the peak initial distribution. The emittance takes its minimal value for the f_{prof} = 96% (almost flat-top initial distribution) by transition of from the S-shaped curve (peak distribution) to the inverted S-shaped curve (hollow distribution).

SUMMARY

In this study, we have investigated the influence of initial current density distribution on the emittance reduction. The emittance reduction was verified for three different initial current density profiles (flat-top, peak and hollow distribution). The axial distance of the point of minimal emittance can be varied over wide range by changing the current density distribution on the cathode surface. The shortest axial distance of emittance minimum was obtained for peak profile. The hollow profile allows extending the axial distance of the point of the minimal emittance. The value of emittance minimum also depends strongly on initial current density distribution. The smallest emittance was obtained for f_{prof} = 96% (almost flat-top initial distribution). An electron beam with hollow current density distribution has the point of minimal emittance further than that with a flat-top distribution, whereas the value of emittance minimal becomes worse.

CONCLUSIONS

The initial current distribution affects strongly the value and the position of the emittance minimum. Thus in order to understand the emittance evolution the information about initial current is indispensable. However the usage of these properties for designing of a low emittance injectors do not bring merits technically, since the extension of axial distance of the emittance minimum and its low value in comparable range can be achieved by variation current density and cavity voltage as reported in [4].

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