PARTICLE SIMULATIONS OF A THERMIONIC RF GUN WITH GRIDDED TRIODE STRUCTURE FOR REDUCTION OF BACK-BOMBARDMENT

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Abstract

We have investigated the use of triode structure in a thermionic rf gun in order to minimize the inherent back-bombardment of electrons onto the cathode. By using an rf powered extractor grid in the triode structure, the electric fields in the vicinity of the cathode surface can be controlled independent from the phase of rf field in the main accelerating cells. Significant reduction of back-bombardment power up to 99% is shown with rf input powers of ~40 kW to the extractor grid, using a two-dimensional particle simulation code. Also, preliminary refinement of the triode configuration has shown reasonably acceptable emittance degradation at the first cell exit in a 4.5-cell structure and a rather higher peak current than the conventional rf gun.

INTRODUCTION

A high brightness electron beam with a long pulse length is preferred for high power free-electron lasers (FELs). Thermionic rf guns can produce such high brightness electron beams in a compact system using resonance cavities, as shown in Fig. 1. These properties make the thermionic rf guns well suited for the use in high averaged power FELs. In a conventional thermionic rf gun, however, the back-bombardment of the electrons causes the heating of the cathode surface, which destabilizes the electron beam generation by changing the thermal electron emission, and accordingly degrades the output beam properties [1,2]. Several methods such as the use of transverse magnetic fields [3,4] and the temporal control of rf input for compensating time-varying beam-loading [5,6] have been proposed to mitigate this problem with limited successes. As a result, the maximum pulse duration of the rf gun operation is limited to several microseconds, while a longer pulse duration would be desired for the FEL operation.

A method is proposed to reduce the back-bombardment using a triode structure driven by rf power, employing a cut-off drift space structure [7]. In this work, we investigate the use of a grid based coaxial rf structure [8.9] instead, which is easy to implement as it requires only a modest rf power supply of several tens kW.

We investigated the modification of thermionic rf gun with a gridded triode structure. Using 1D and 2D particle simulations, we studied the electron dynamics in the rf gun and evaluated the back-bombardment power as well as the essential beam properties such as, peak current, and beam emittance as a function of triode configuration and its operating parameters. Preliminary modification has been conducted for minimizing degradation in beam properties at the first cell exit rather than the gun exit in order to focus the discussion on the triode structure.

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TRIODE STRUCTURE

In order to evaluate the reduction of back-bombardment in a triode structure using an extractor grid, we compared the electron trajectory in an S-band 4.5-cell thermionic rf gun [1] with a conventional cathode and rf triode system. The schematic view of the rf gun with a triode system is shown in Fig.1. As seen in the figure, the triode rf gun is the rf gun equipped with a small coaxial rf gun, which is driven by the same rf frequency as the main accelerating cells.

In a conventional rf gun, electrons are extracted from the cathode by accelerating fields of standing waves in the 1st accelerating cell (see Fig.2(a)). In a triode system using a grid, a highly transparent (>80%) mesh grid is installed between the cathode and the 1st accelerating cell (Fig.2(b)). Using the same frequency rf power as the main accelerating fields, additional standing waves are formed in the space between the cathode and the grid (KG space) and extract the electrons from the cathode surface. By

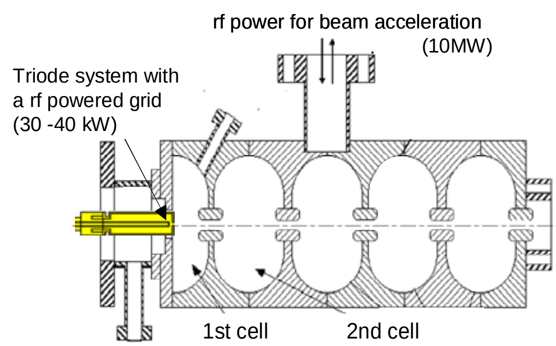

Figure 1: Schematic view of an rf gun with an rf powered triode.

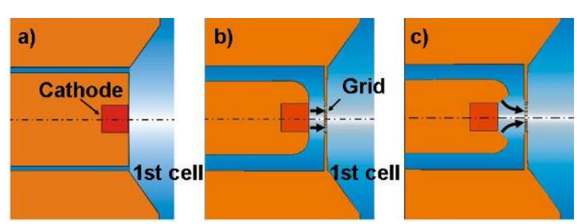

Figure 2: Schematic of the cathode structure in thermionic rf gun: a) conventional cathode, b) a triode system using a grid extractor, and c) a triode with a recessed cathode and a grid extractor.

varying the phase and the amplitude of the rf fields in the KG space with respect to the rf fields in the 1st accelerating cell, the trajectory of the electron beam in the 1st cell can be controlled to reduce the back-bombardment. In addition, we can further control the beam emittance and the peak current by modifying the triode structure using a recessed cathode configuration, as shown in Fig 2(c). In any case in this paper, the diameter of the cathode is 2 mm and the current density on the surface of the cathode is 30 A/cm^2.

METHOD OF PARTICLE SIMULATION

In this study, we have used a number of 1D and 2D codes for calculating the electron dynamics in the rf gun, as follows. Electromagnetic fields of standing waves in the 4.5 cells and in the KG space are calculated by a 2D cylindrical eigenmode solver [10] (see Figs. 3(a) and (b)). The field results are used as input parameters in the particle simulations.

Preliminary investigation of the gridded triode operation was conducted using a 1D particle tracking code which utilizes on-axis field values of the calculated eigenmodes and neglects the space charge effects. The back-bombardment power was calculated as a function of the input rf power to the grid and the relative phase between the main accelerating fields and the grid rf fields. In addition, 2D particle simulations were carried out by the use of KUBLAI code [11], which simulates the electron dynamics in a cylindrically symmetric geometry. The KUBLAI code takes into account the space-charge effects by simultaneously solving Maxwell's equations and Lorentz equation. We have evaluated the beam emittance and the peak current of the output beam as well as the back-bombardment power onto the cathode.

As of numerical treatment of the grid in the triode structure, it is assumed to be a solid metal plate in the field calculations on one hand. On the other hand transparency of electrons through the grid is assumed to be 100 % in the dynamics simulations, though practically it may be around 80 % or higher.

RESULT OF PARTICLE SIMULATION

Figures 4 and 5 show electrons' motions calculated by the 1D code, showing electrons' axial distances from the cathode surface as a function of time. In the figures, pink and blue backgrounds indicate accelerating and decelerating phases, respectively. In the conventional 4.5-cell rf gun, as seen in Fig. 4, more than half of the extracted electrons (classified by red color in the figure) tend to back-stream to the cathode. In contrast in the triode rf gun in Fig. 5(a), almost all electrons are seen to reach the 4.5-cell gun exit. In the magnified view in the vicinity of the cathode and the grid in Fig. 5(b), one can see how the triode scheme reduces the back-streaming electrons. Though a few electrons are seen to back-stream and to hit the cathode, their energies and accordingly the total back-bombardment power may be much lower than

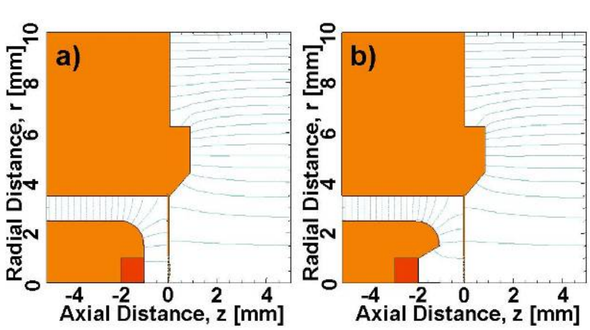

Figure 3: Electric fields of standing waves: a) a triode system using a grid extractor, and b) a triode with a recessed cathode and a grid extractor.

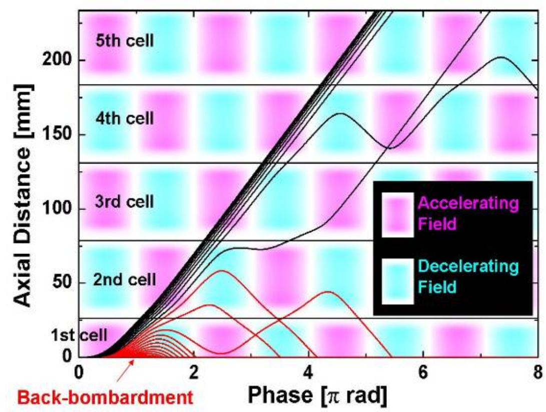

Figure 4: Electrons' motions in the conventional rf gun by 1D simulation, showing axial distances from the cathode as a function of time.

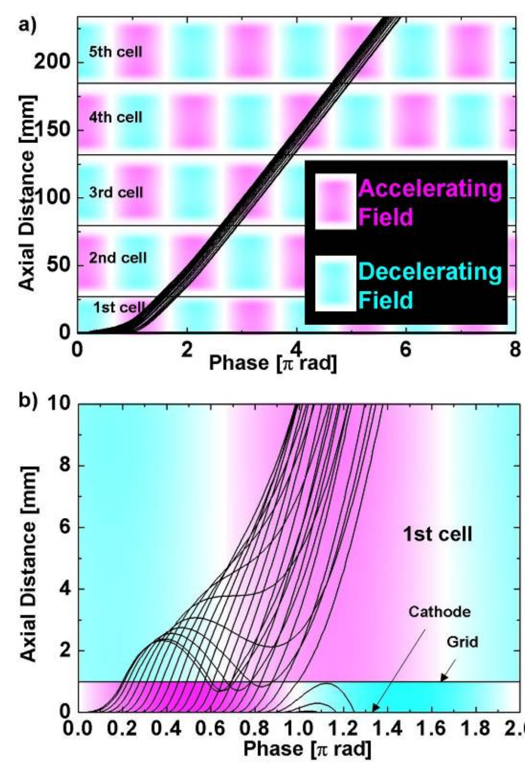

Figure 5: Electrons' motions in the triode rf gun by 1D simulation. b) shows a magnified view in the vicinity of the cathode and the grid.

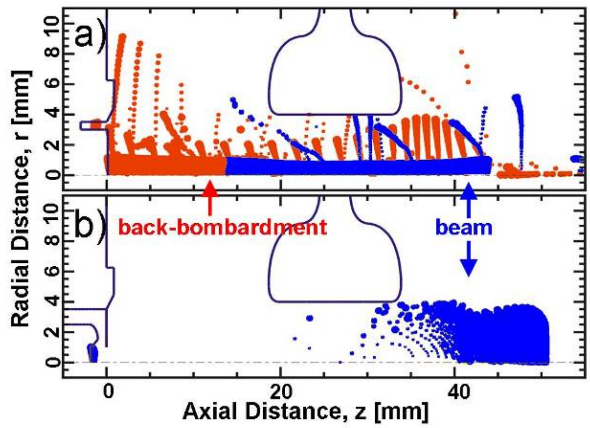

Figure 6: Snapshots of electron distributions by the 2D code, a) in the conventional and b) in the triode rf guns.

those in the conventional rf gun, which will be discussed in the following section.

Figure 6 shows snapshots of electron distributions in the 1st and 2nd accelerating cells in the conventional and triode rf guns by 2D simulations. Back-streaming electrons are indicated by the red dots. Again, one can see obviously that backward electrons are eliminated apparently in the triode gun compared with the conventional one.

Back-Bombardment Power and Energy Spectrum

Back-bombardment power in the triode rf gun was calculated by the use of the 1D and 2D codes, as a function of relative phase of the rf field in the KG space with respect to the main accelerating rf field. The results are shown in Fig.7, for the flat cathode configuration shown in Fig. 3(a) with an rf voltage in the KG space, V_{KG} of 20 kV. The back-bombardment power in the conventional rf gun are shown by the black straight lines for comparison. Either 1D (dotted lines) or 2D (solid lines) result indicates a greatly reduced power of 2 order of magnitude with an optimal phase difference around 1 π, though the absolute value by 1D differs from that by 2D due to neglect of beam divergence. The 2D result shows,

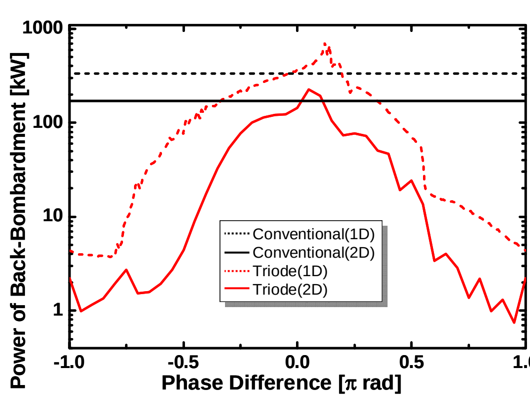

Figure 7: Back-bombardment powers by the 1D and 2D simulations as functions of relative rf phase in the KG space.

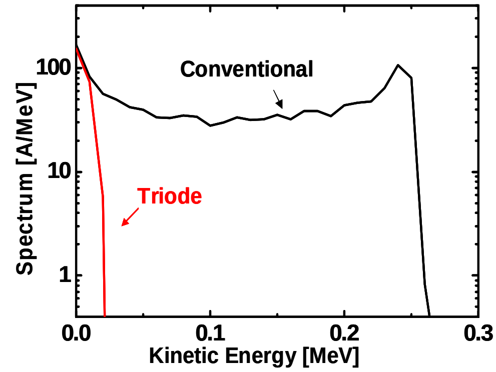

Figure 8: Electron energy spectra of back-bombardment by the 2D simulations, comparing the conventional and the triode rf guns.

at a phase difference of –0.9π, a minimum back-bombardment power of 1.0 kW corresponding to 0.6 % of that by the conventional gun. Also, the 3D simulation calculates required rf input fed to the KG space as 38 kW on neglect of wall loss and rf reflection.

Figure 8 compares energy spectra of back-streaming electrons in the conventional and the triode rf guns, for the optimal phase difference of –0.9π. It is seen that low energetic electrons still tend to hit the cathode inherently, while highly energetic electrons back-streaming from downstream cells are removed completely by the triode scheme.

Emittance and Peak Current

We then evaluate the beam properties, namely the emittance and peak current. In order to focus the discussion hereafter on influences by the triode structure, we rather look at beam properties at the exit of the 1st accelerating cell than those at the gun exit. Also, in the emittance and peak current calculations, electrons of energies less than 95 % of the maximum energy are neglected, since in practical use of a thermionic rf gun an energy analyzer is used preferably to cut away low energetic tail.

For the case shown in the previous section using the flat cathode with V_{KG} = 20 kV, the emittance is found to 11 π mm mrad, which is much higher than 0.5 π mm mrad by the conventional rf gun. In order to compensate this degradation, two kinds of modifications were adopted in the triode scheme. First one is to recess the cathode as is shown in Fig. 3(b) for better convergence of the beam in the vicinity of the cathode. We varied the depth of recession, d, ranging from d = 0, i.e. the flat shape shown in Fig. 3(a), to d = 1.25 mm. The other is to optimize the amplitude of the rf field in the KG space. The rf voltage there, V_{KG} ranges from 10 to 30 kV.

As a result, we found an optimal point at d = 0.875 mm and V_{KG} = 20 kV for both low emittance and high peak current as follows. Figure 9 shows emittance and peak current at the 1st cell exit as functions of d for V_{KG} = 20 kV, and Fig. 10 shows their dependence on V_{KG} for d = 0.875 mm. The beam properties are found to depend

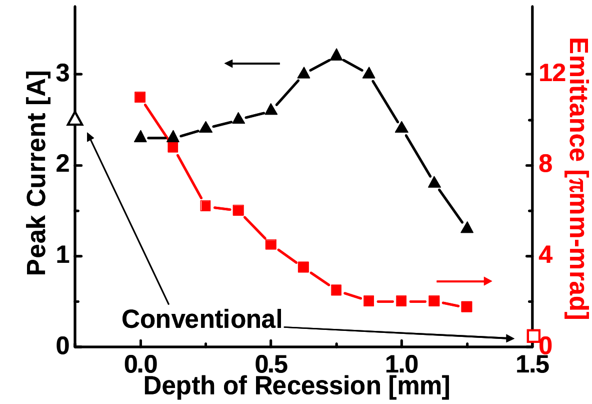

Figure 9: Peak current and emittance at the 1st cell exit as functions of d for V_{KG} = 20 kV.

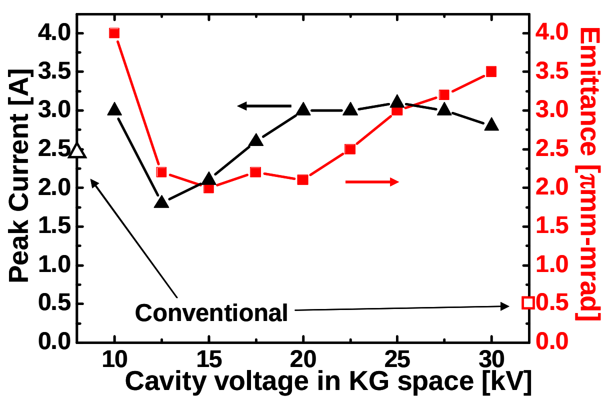

Figure 10: Peak current and emittance at the 1st cell exit as functions of V_{KG} for d = 0.875 mm.

Table 1: Comparison Summary Between the Conventional and Triode RF Guns.

	conventional	triode
back-bombardment power	170 kW	0.8 kW
peak current	2.5 A	3.0 A
normalized emittance	0.5π mm mrad	2.0π mm mrad

strongly on both d and V_{KG}. Especially the emittance is found to be improved greatly by the recessed shape as is seen in Fig. 9, while too large d results in rapid degradation in the peak current. For the optimal d = 0.875 mm and V_{KG} = 20 kV, the beam properties and the back-bombardment power are summarized in Table 1, together with those by the conventional rf gun for comparisons. The emittance is found to be compensated by the refinement by changing d and V_{KG} down to an acceptably low value of 2.0 π mm mrad, though it is still higher than the original 0.5 π mm mrad by the conventional. No degradation is seen in the peak current. At the same time, by the refinement, the back-bombardment power is found further slightly reduced down to 0.8 kW, which is again very encouraging compared with that of 170 kW by the conventional rf gun.

SUMMARY

In this study, we evaluated the reduction of the back-bombardment in a thermionic rf gun using a gridded triode structure with particle simulations. It is shown that the back-bombardment can be greatly reduced while the beam quality is reasonably maintained. With an rf power of 38 kW fed to the grid in the triode, the back-bombardment power is reduced to 0.8 kW from 170 kW, compared to the conventional rf gun. Furthermore, the output beam propeties such as the beam emittance and the peak current at the 1st cell exit remains comparable to the conventional rf gun if the triode geometry is optimized by recessing the cathode surface with respect to the grid. At the next stage further modification needs to be conducted to minimize the emittance at the gun exit for practical application to the 4.5-cell rf gun in KU-FEL facility at Kyoto University.

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