Gun Design and Emittance Measurement for High Brightness Electron Sources

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Abstract

A high brightness gun with a small thermionic cathode has been designed and manufactured to produce a low emittance beam. To study the beam we have developed an emittance measurement system based on the "pepper-pot" method. We find a normalized rms emittance of order π mm·mrad, and a normalized brightness of order 10^{10} $A/m^2 \cdot rad^2$.

Introduction

In recent years the demand for a high-brightness electron linac has increased dramatically, for applications such as the free-electron laser, coherent synchrotron radiation, a slow-positron source, and others. In these applications, high beam brightness is crucial and in order to obtain high-brightness beam, it is very important to transport and accelerate the beam emitted from the cathode with negligible emittance growth. We therefore need to understand the beam behavior in each component of the conventional rf linac. As a first step, a high brightness electron gun and an emittance measurement system for a low emittance beam have been developed.

High brightness gun

The lower limit of the normalized emittance from a thermionic electron source is governed by the size and the temperature of the cathode. For an azimuthally symmetric beam, the normalized rms emittance at the surface is[1]

$$\varepsilon_n = 2\pi r_c \sqrt{\frac{kT}{m_0 c^2}} \qquad (1)$$

where r_c is the cathode radius, and T is absolute temperature of the cathode surface. The normalized brightness is defined by[1]

$$\begin{aligned} B_n &= I/{\varepsilon_n}^2 \\ &= \frac{m_0 c^2}{4\pi kT} J \end{aligned} \qquad (2)$$

where I and J are the peak values of beam current and beam current density. Thus high brightness requires low emittance and high current. This favors a small cathode size and a high accelerating diode voltage. An electron gun with a 1 mmϕ cathode has been designed using computer simulation code EGUN[2]. The cathode is two orders of magnitude smaller in area than that used in the present 2.5 GeV linac at KEK[3]. The cathode material is barium-impregnated dispenser tungsten, which is popular as a thermionic cathode and has a high current density[4]. The gun is a diode, and the anode-cathode gap is 31 mm, the anode is 3 mm thick, with a hole of 4 mm diameter, and the wehnelt is parallel to the anode. In the simulation, the beam current in the space charge limiting regime is 611.0 mA for a diode voltage of 150 kV . The normalized emittance is 0.71 π mm·mrad (I_{peak} = 611 mA) at 5 mm from the anode exit from the calculation in which the thermal motion of electrons is not included.

In experiments, the cathode-surface temperature was measured with an optical pyrometer. The beam current upon applying a voltage of 151.3 kV versus the cathode temperature is shown in Fig.1. Vacuum pressure with the cathode hot was 1.2 × 10^{-5} Pa.

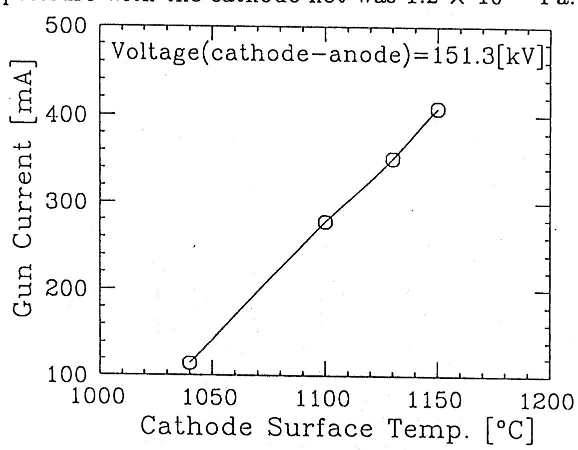

Fig.1 The beam current versus the cathode surface temperature (V_{peak} = 151.3 kV).

We have obtained a maximum current of 408 mA with 30.4 W heater power and about 1150 °C cathode-surface temperature. The gun is used in the temperature limiting regime as show in Fig.1. The beam was 5 μs pulse width and 1 Hz repetition rate, and the beam current density of the cathode emission was 51.9 A/cm^2.

Emittance measurement system

We have developed an emittance measurement system used to evaluate such a low-emittance beam of a few π mm·mrad precisely. We want to avoid pulse-to-pulse fluctuation of beam energy. To this end, the only method which permits measurement of the beam quality in a single shot is the pepper-pot method[5].

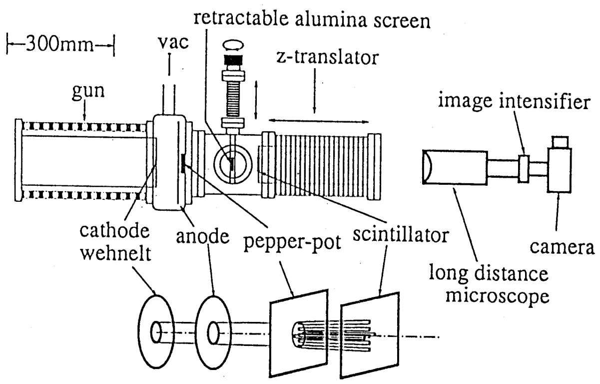

Fig.2 The diagram of the experimental setup with the pepper-pot method.

The diagram of the experimental setup is shown in Fig.2. The beamlets passed by the pepper-pot mask drift and hit a scintillator film located downstream.

The pinholes of the pepper-pot mask must be small and dense (the pinhole diameter is 30 μm and spaced by 200 μm), sufficient to measure a beam with a very small size and small divergence angle. The mask was set at 5 mm downstream from the anode. The mask pattern magnified with a microscope is shown in Fig.3. Holes arranged two dimensionally on the mask enable us to measure both (x, x') and (y, y') phase space, simultaneously.

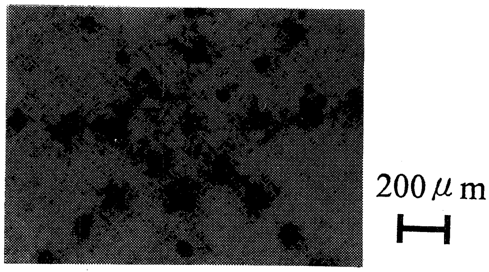

Fig.3 The photograph of the pepper-pot mask pattern (the pinhole diameter of 50 μm is shown in the figure, but in the experiments, the pinhole diameter of 30 μm was used.)

A plastic scintillator which is 10 μm thin and has a fast scintillation characteristic (the rise time is 350 ps and the decay constant is 1.6 ns) has been adopted to measure the beamlets' image with a high temporal and spatial resolution. Silver(30 Å thin) was deposited on the scintillator surface by vacuum evaporation to avoid charge-up. In order to follow beam trajectories and improve the statistical precision, it is possible to move the scintillator screen along the z-axis with a stepping motor.

The position and intensity of the spot on the scintillator are observed as transmitted light. Since the light intensity is very weak and the spot size is very small (of order several hundred μm), an image intensifier with a high gain and a microscope with a high spatial resolution must be used. Images on the scintillator are observed by using an image intensifier with a high-speed shutter (the minimum time is 3 ns). We can thus obtain time-resolved information concerning the emittance[6]. The gate pulse width applied to the image intensifier was 1 μs. The timing of the gate pulse was adjusted for the plateau of a voltage applied to the cathode. Thus the energy spread of the beams was neglected. The gain of the image intensifier was lowered not to saturate its light intensity by the gain controller of the image intensifier, and recorded as photographs. The intensity of the light spots was transformed into a digital value by a image processor. The divergence angle of the beamlets is calculated from the pepper-pot size, the area of the spot enclosed within a threshold value, and the distance from the pepper-pot mask to the scintillator screen.

Experimental results and Discussion

We measured the pepper-pot image at three different locations: 185.1 mm, 242.1 mm, and 299.1 mm downstream from the mask. A photograph of a pepper-pot image on the scintillator screen located at 185.1 mm downstream from the mask is shown in Fig.4.

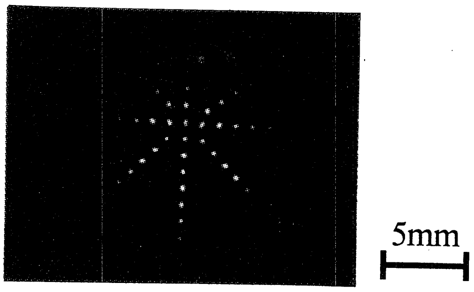

Fig.4 The photograph of a pepper-pot image at 185.1mm downstream from the mask.

For this data, the applied voltage was 150 kV and the peak current was 200 mA. Since the beamlets are cut out by the pepper-pot mask, the measured beam radius has an ambiguity determined by the hole separation of 200 μm. As the radius of the beam is in the range from 1.0 to 1.2 mm, the error is less than 20%.

Numerical solution of the envelope equation confirmed that space-charge is negligible for these parameters[7]. Approximating each spot as a circle, we obtained phase space plots for both (x, x') and (y, y'), as shown in Fig.5.

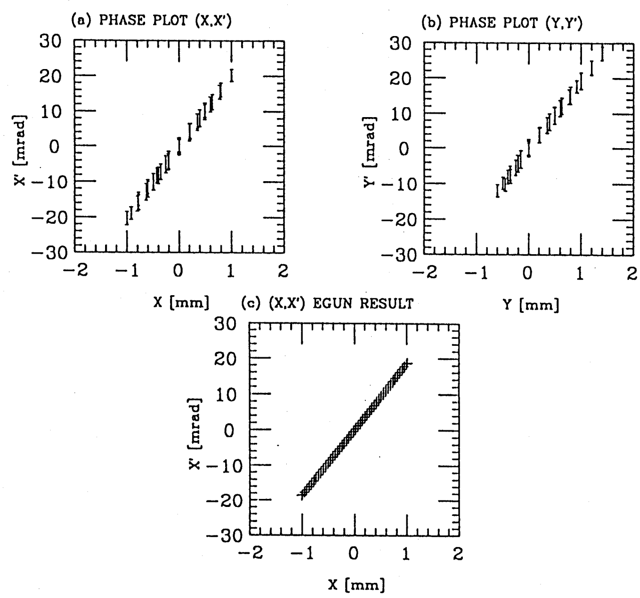

Fig.5 The diagram of the phase plots. (a) (x, x'), (b) (y, y') in this experiments. (c) the result simulated by EGUN.

The normalized rms emittance was calculated from the phase space plots. The definition of the rms emittance is[8]

$$\varepsilon_{rms} = 4\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle x \cdot x'\rangle^2} \qquad (3)$$

where the brackets $\langle\cdots\rangle$ represent averages.

The comparison between the experimental results and the simulation results of EGUN in which the current is limited at 200 mA are shown in Table.1.

	experiment	simulation
ε_n [mm·mrad]	$\varepsilon_{xn} = 0.81\pi$ $\varepsilon_{yn} = 0.91\pi$	$\varepsilon_n = 0.42\pi$
B_n [A/m^{2}rad^2]	2.8×10^{10}	1.2×10^{11}

Table.1 Comparison between results of experiment and simulation at $I_{peak} = 200$ mA.

The normalized rms emittance of the cathode surface (diameter is 1mm) at 1050 °C is estimated as 0.48 πmm·mrad from equation (1). In experiments, the normalized rms emittance of the gun is increased twice as large as that of the cathode. The emittance obtained in the simulation is about half of the experimental value. This discrepancy may arise from the fact that thermal motion of the electrons was not included in this simulation.

Summary

We have developed a high brightness electron gun with a small thermionic cathode (the diameter is 1 mm), and an emittance measurement system based on the pepper-pot technique. The normalized emittance of our electron gun was measured as $\varepsilon_{xn} = 0.81\pi$ mm·mrad and $\varepsilon_{yn} = 0.91\pi$ mm·mrad, corresponding to a normalized brightness of 2.8×10^{10} $A/m^2{\cdot}rad^2$. We have been trying to investigate the emittance growth due to the electron gun components, in particular the grid and anode, as well as in the linac, bunching system, beam transports, an accelerator tube, and so on.

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