DEVELOPMENT OF ELECTRON GUN OF CARBON NANOTUBE CATHODE

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Abstract

We have been developing a high brightness electron gun utilizing carbon nanotube (CNT) cathode since 2001. Recently we succeeded to achieve a realistic-size cold cathode which could stand comparison with current densities of oxide cathodes conventionally used in accelerators all over the world. The anode current was obtained to 0.48 A from the CNT-cathode of 2.6 mm diameter, which current density reduced from the anode current was about 9.1 A/cm^2 with 128 kV-DC acceleration voltage in pulse operations of 50 pps using about 8 ns pulses. The emission current was very stable in the long term period operation of about 3 weeks under about 10^{-6} Pa vacuum pressure.

INTRODUCTION

In search for CNT-cathode emitting high density current, joint researches were performed by KEK (Ohsawa et al.) and some companies during 2001 to 2003 [1]. Field emission current up to 3 A/cm^2 was obtained in a triode type gun with 8 kV-DC low accelerating voltage in 2003 [2]. In these studies, grid pulses of about 200 ns and 5 kV were applied in 0.25 mm distance between the grid and cathode electrodes, which produced a high field of 20 MV/m. On the other hand, the field between the grid and anode electrodes was 1.6 MV/m, which was produced by 8 kV applied in 5 mm distance. The measurements were performed in vacuum pressure about 10^{-6} Pa.

In order to investigate the CNT-cathode characteristics in a practical field-emission gun with 100 kV-DC accelerating voltage, we constructed a gun test stand in February 2004, and installed a grid-cathode assembly that was newly designed for field emission CNT-cathodes. We designed the dimension so as to be compatible with the EIMAC-Y796 grid-cathode assembly which is widely used all over the world currently. The beam tests have been performed for about a year [3], [4], by using pulses of 50 to 300 ns, but sufficient cathode-current densities could not be got on account of discharge occurred between the grid and cathode electrodes.

FIELD EMISSION TEST

Equipments

The overall view of the apparatus used in present experiments is illustrated in Fig.1. The emitted electrons are accelerated by DC high voltage of 100 kV between the anode and grid electrodes, and then emerging from the electron gun through an anode hole. These electron beams are adjusted by a magnetic lens to focus on the beam catcher in solenoidal fields. The values of beam currents are measured by monitors such as a wall current monitor (WCM), a core monitor and a beam catcher (BC) which is set along the beam line. Furthermore, a fluorescence screen is available, if necessary, by inserting in the beam line instead of beam catcher at the same place.

In this way, the beam tests were done and wave shapes were obtained at the WCM and BC as shown in Fig. 2. The pulse width is about 8 ns, as is seen in Fig. 2.

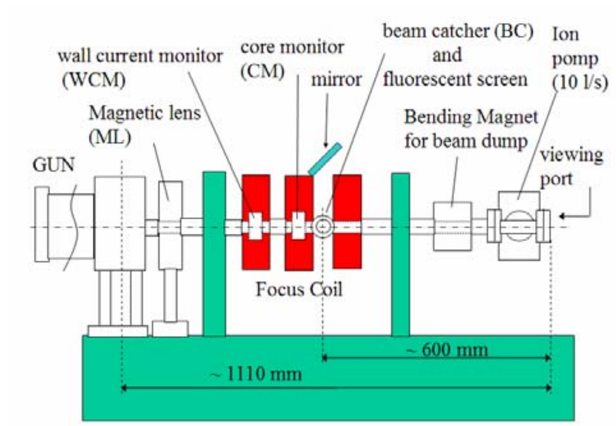

Figure 1: The main components of this test stand. The electron beams are adjusted by a magnetic lens to focus on the beam catcher in solenoidal fields.

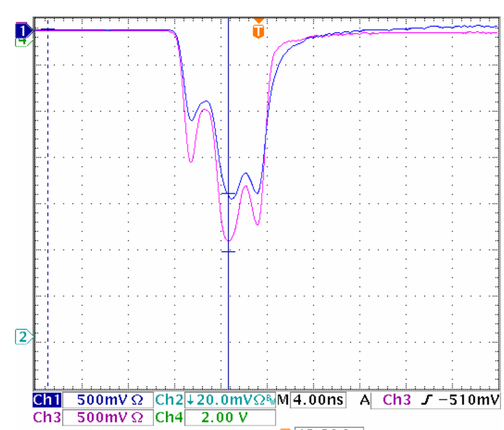

Figure 2: Beam pulses observed by wall current monitor (CH1) and beam catcher (CH3).

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Field Emission from CNTs

As well known, CNT was discovered in 1991 in Japan [5] and attracts widely attention to use as field emitters [6], [7], since they have noteworthy features such as large aspect ratio, excellent chemical stability, high structural completeness, strong mechanical strength, high electrical conductivity, etc.. In field emission the surface potential barrier is deformed so strongly that unexcited electrons can leak out through material surfaces. The Fowlor-Nordheim theory [8] which describes the electron field emission mechanism gives following equations:

$$\ln(I / E^2) = \ln(a) + b(\phi^{3/2} / E)$$

with

$$a = 1.54 \times 10^{-6} A\beta^2 / \phi,$$

$$b = -6.83 \times 10^7 / \beta$$

where I is anode current (A), E is the field strength between the grid and cathode electrodes, A is electron emission area (cm^2). If E is measured in MV/m and the work function ϕ is assumed to be 4.4 eV as being estimated from the highly oriented pyrolytic graphite (HOPG), the non-dimensional field enhancement factor β becomes,

$$\beta = -6.3 \times 10^4 / \zeta$$

where ζ is the slope of the F-N plot.

Measurements

The experiments have been performed with pulses of 8 ns width at a fixed repetition rate of 50 pps with DC acceleration voltage (V_{acc}) of 100 kV usually.

Figure 3 shows the dependence of cathode current densities (J_c) which are reduced from anode currents measured by the beam catcher, versus the electric field strength E between the grid and cathode electrodes. In case of V_{acc} = 100 kV, the cathode current densities which are shown by blue diamond marks, raised up to 7.2 A/cm^2 at the cathode field strength of 9.1 MV/m, and then when the V_{acc} was raised up to 128 kV, J_c was increased up to 9.1 A/cm^2, which is plotted with a open diamond mark in the same figure. This dependence of J_c versus V_{acc} indicates that the present CNT-cathode has an ability to emit more highly current, if we would remove a suppressed condition from space charge between the grid and anode electrodes. It is highly expected that J_c exceeds 10 A/cm^2 by increasing V_{acc} at the same cathode field strength.

Figure 4 presents Fowlor-Nordheim plot of the same data, which are on a straight line. The linear dependence is an evidence of the tunnelling electron emissions. The non-dimensional β-factor calculated from the plot is about 1850 and dimensional one is about 5 × 10^4 (cm^{-1}). These values well agree with other data obtained from a CNT emitter [9] which thought to be done in a realistic condition. This coincidence is thought to indicates that the present electric-fields at our CNTs were ideal or in the optimum conditions.

Figure 5 shows beam current stability for 24 days. The current decrease is less than 1.3% during about 3 weeks. Remarkable lifetime is expected for the present CNT-cathode compare with other field emitters in ultra high vacuum pressures [10].

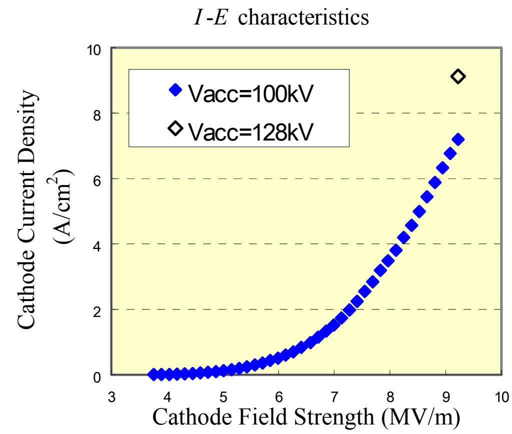

Figure 3: *I-E* characteristics of 2.6mmϕ CNT-cathode.

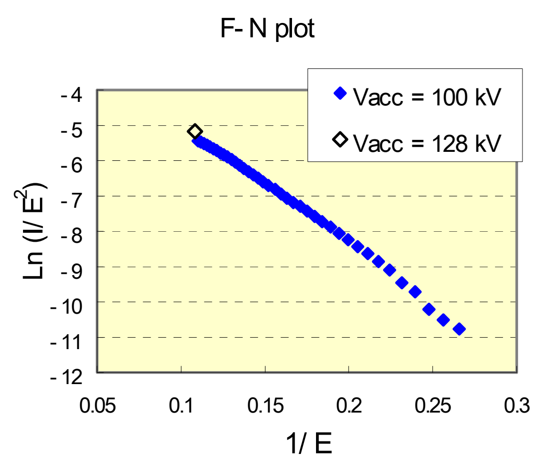

Figure 4: Fowlor-Nordheim plot of 2.6mmϕ CNT-cathode.

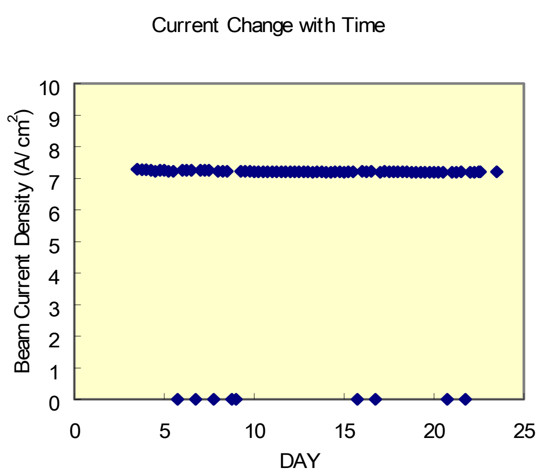

Figure 5: Current stability with time of 2.6mmϕ CNT-cathode.

FE-SEM INVESTIGATION OF THE CNT-CATHODE SURFACES

Recently our CNT-cathode improvements are advanced considerably. We obtained fine results since September 2004 after we selected a different kind of CNT, which were produced by arc-discharging method, and have high purity, large aspect ratio and highly-crystallized of CNT. Renovations were seen, especially, in the emission current density and the discharge tolerance, which means the CNT-cathode became tough against discharge in 50 to 300 ns pulse operations.

Figure 6 shows the field emission scanning electron microscope (FE-SEM) observation of the pre-improve cathode surface produced by screen-printing method on a Cu1011B substrate. This study was done in the secondary electron detection mode, at a working distance of 8.1 mm, with a probe current of 10.6 μA at 5 kV accelerating voltage. Figure 7 is an image of the improved CNT-cathode which has been deposited on a Cu1011B substrate by using arc-discharging method. The observation was done at a working distance of 8.2 mm, with a probe current of 11 μA at 5 kV accelerating voltage. Purity difference is apparent in these figures.

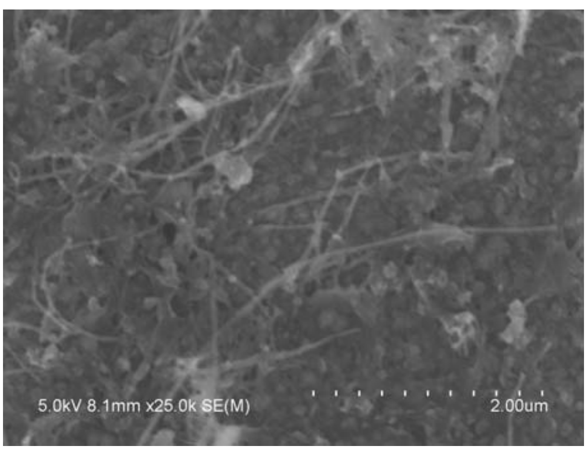

Figure 6: Pre-improved CNT-cathode surface image.

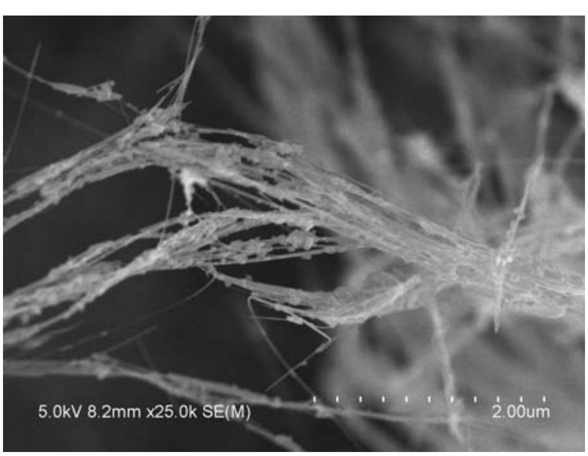

Figure 7: Improved CNT-cathode surface image.

SUMMARY

We could find a CNT-cathode which has promising characteristics by virtue of former investigations [1], [2], [3], [4]. This study went well to develop a practical field-emission gun by using improved CNT-cathode which could stand comparison with current densities of oxide cathodes. The anode current was obtained to 0.48 A from the CNT-cathode of 2.6 mmϕ, which current density reduced from the anode current is about 9.1 A/cm^2 with 128 kV-DC acceleration voltage. We are preparing to increase a V_{acc} in order to make a test in higher density region. These tests were carried out in electron gun which is set up inside our test stand, applying pulses of 8 ns at repetition rate of 50 pps. The emission current has been very stable during more than 3 weeks: the emission degradation was less than 1.3 % during about 3 weeks.

FUTURE PLAN

We would like to precede studies on field emissions from different kinds of CNT-cathodes using pulses, for instance, by means of impregnating other materials on CNTs such as RuO_2 or OsO_2, and intend to measure beam emittance to diagnose beam qualities. And it is very important to study a CNT emitter-substrate contact effect that may be suppressed emission current in the higher current test near the future in our testing.

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