CARBON FIELD EMISSION STRIP CATHODE ELECTRON SOURCE

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Abstract

Over the recent years carbon nanostructure cathodes have become promising high brightness field emission electron sources with large working area. Results of a carbon based field emission strip-shaped cathode simulations and the design of set-up for its investigation are presented in the article. Experimental setup has been designed for cathode emitting properties measurement and determination of emitted electrons initial parameters used as input data for electron beam computer simulation. The setup consists of the high-voltage triode electrode system and allows to investigate the voltage-current characteristics of the cathode and to estimate the electron distribution of the beam on the anode surface. Evaluation of electrons distribution on the anode will be processed by measurement of the emitted X-ray focal spot on the anode using CCD camera. Verification of the electron beam dynamics simulations will be based on the experimentally acquired data.

INTRODUCTION

The carbon nanostructure cathodes nowadays are manufactured using a large number of different techniques providing all kinds of carbon morphologies: single-walled and multi-walled nanotubes, nanowalls and so on [1]. Most of them are also known under different names. A number of works were dedicated to description of the cathodes volt-ampere characteristics investigations and structure growth methods, especially concerning carbon nanotubes [2]. At the same time generation of electron beams for X-ray devices - one of the main aspects of the carbon nanostructure cathodes applications – was inspected not so detailed. Designed set-up discussed here incorporates the electron source and is focused on investigation of the carbon nanostructure cathode operation in terms of X-ray source applications.

Two main process characteristics will be measured using the presented unit: VI-characteristics and electron beam dynamics in the system. The first characteristic is traditionally measured by the volt-meters and ampere-meters. The second can be measured using the faraday cups or other elements implying the electron beam profile measurements. But taking into account the fact that the cathode will be used as an electron source for X-ray generation devices, it is more relevant to perform the measurement of the anode X-ray focal spot because this particular size will characterize the efficiency of the X-ray generator.

Strip shape of the cathode was chosen to get more information about the initial parameters of the electrons emitted from the cathode surface. While along a narrow cathode side the focusing electrical field is applied to electrons, along the broad side there is no transverse electrical field presented.

The system is designed to provide 2 A/cm^2 emitted current density with 100 keV final electrons energy (on the anode) and 50 μm anode beam spot in the narrow direction. In the broad direction anode beam spot should have the distorted edges not larger than 5% from the whole spot size to observe uniform beam distribution. The 50 μm narrow size of the anode spot is dictated by the focal spot size requirements for next generation of high power microfocus X-ray sources.

COMPUTER SIMULATION

The first step for building the unit was to design the triode system that can generate electron beam of high current density and form the corresponding electron spot on anode. Design of the triode unit is shown on the figure 1. The system was designed to provide current density as high as 2 A/cm^2 for 8 V/μm cathode extracting field (for 20 kV extracting electrode potential) typical for investigated type of the carbon cathode material. In vertical direction the electrode system can generate the focusing electrical field that reduces the beam size in ~1:2 proportion vs. the cathode size. Due to this fact the cathode vertical size was chosen to be 100 μm. For such system the vertical $2\cdot\sigma$ size of the cathode electrons distribution is 60.4 μm and the anode $2\cdot\sigma$ equals 27.5 μm.

High value of the extracting E field on the cathode surface leads to even higher fields on the surface of the electrodes due to blending radii and lower distances and can lead to breakdown issues. The electrode shape was optimized to provide maximum electrodes surface electrical field on the level of 18.5 V/μm for 8 V/μm on the cathode surface. This demand accounts for a drawback of only 2 times of beam transverse size reduction, even more reduction could be obtained for higher surface field values.

The electron beam dynamics was investigated for the case of 0.2 eV mean initial beam energy with 100% energy spread and ±45^o angular spread. The energy values

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were chosen according to measured spectrums of the CNT emitted electron beams [3, 4].

The anode space phase distributions in vertical and horizontal transverse directions are presented on the figure 2. Distributions reveal that the horizontal direction has tails due to edge fringing effects of the cathode emitting surface. They do not exceed 3%, most part of the beam lies on the horizontal plane that means that there is no impact of the focusing or defocusing fields. All the calculations were processed including the space charge effects of the electron beam with CST Particle Studio suite.

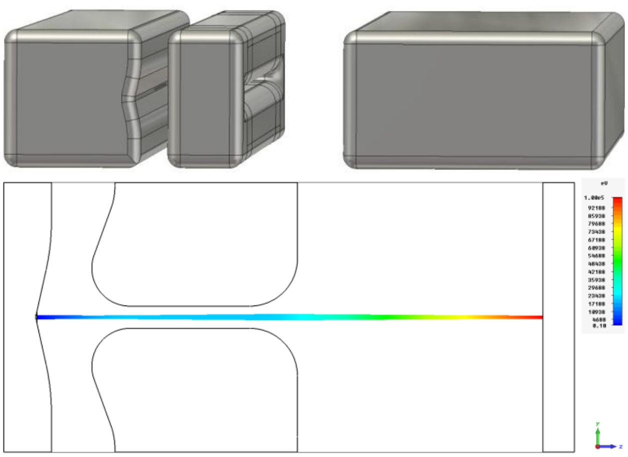

Figure 1: Triode unit and electron trajectories with the energy colour ramp.

The emitted current values were calculated using the Fowler-Nordheim emission equation:

$$J = aE^2 \exp(-b/E),$$

here E is the electrical field magnitude, a=6.3·10^{-6} and b=7.3·10^{7} are the emission linear and exponential factors measured for one of the carbon emission cathodes examples.

Another important issue is the anode heating by the electron beam because the beam has a thin strip shape with 50 µm x 20 mm with high power. This effect depends on the depth of the electrons penetration path inside the anode material. The Penelope code [5] calculations were made to estimate the penetration depth for two refractory metals used in X-ray tubes: W and Mo. Results shows that the penetrating depth (width) for the electrons in W equals 5.2 (4.0) µm, in Mo – 9.7 (7.5) µm that was confirmed with the analytical expression [6]:

$$x = \frac{0.1 \cdot E_0^{1.5}}{\rho}, \quad y = \frac{0.077 \cdot E_0^{1.5}}{\rho}$$

here E_0 - electrons energy (eV), ρ - material density (g/cm^3) and x is perpendicular to surface penetration depth, y is penetration width measured in µm.

Temperature estimation with 5 ms pulse length and 4 kW beam power absorbed in the penetrating volume has shown that anodes with both materials are not heated up higher than ~2000 K within the pulse length that keeps the surface operating temperature away from the meltdown issues.

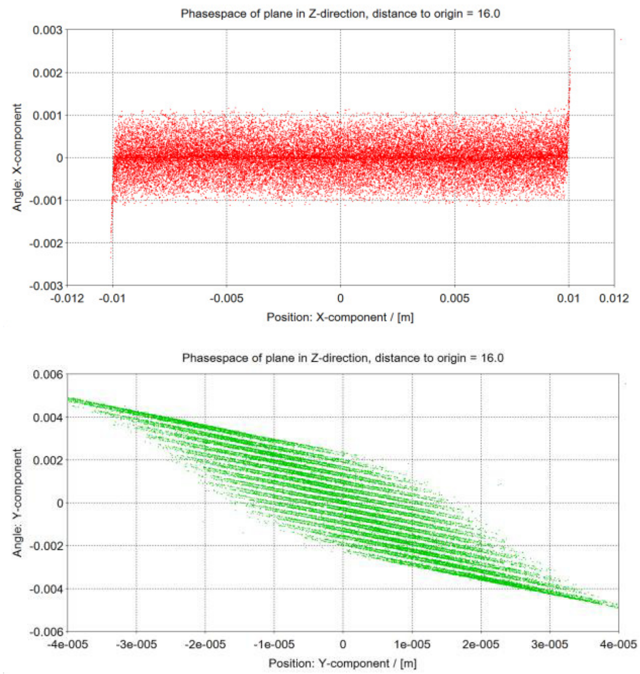

Figure 2: Phase space of the beam on anode surface.

X-RAY FOCAL SPOT MEASUREMENTS

To measure the size of X-ray focal spot the standard pinhole method is applied. The triode unit is tilted along the vertical axis for an angle less than 10 degrees to make the effective focal spot dimensions ratio adequate for measurements (e.g. 50 µm x 1 mm for ~2.9 degrees tilt).

The X-ray focal spot is visualized via the X-ray FSD camera from Photonic Science. It has high precision 6.5 µm pixel size matrix and 8.9x6.7 mm active area that is widely used to control the X-ray tubes in the medical application devices. To measure 50 µm focal spot the enlargement factor (ratio between focal spot-pinhole (FPD) and pinhole-camera (PCD) distances) must be larger than 1 to have a large focal spot size for easier measurements. Another issue is unsharpness of the image that arises due to finite pinhole aperture size. Pinhole with minimal market available aperture size of 10 µm from Fluke Biomedical was chosen for measurements to make the unsharpness of the image as small as possible.

The dependences of the enlarged focal spot size and unsharpness vs. the enlargement factor are presented on the figure 3 for the 50 µm effective focal spot. Enlarged focal spot is calculated as a focal spot times the enhancement factor and in experiment it is measured at the point of half intensity fall of the blurred image edge. The data shows that the enhancement of the enlargement factor reduces the relative unsharpness of the image.

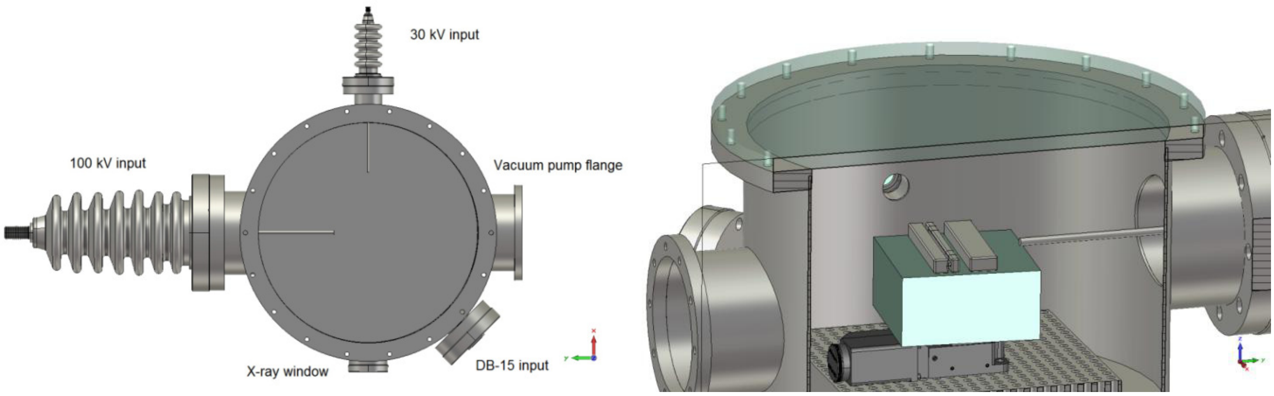

Figure 4: Vacuum chamber and experimental elements aligned inside the chamber.

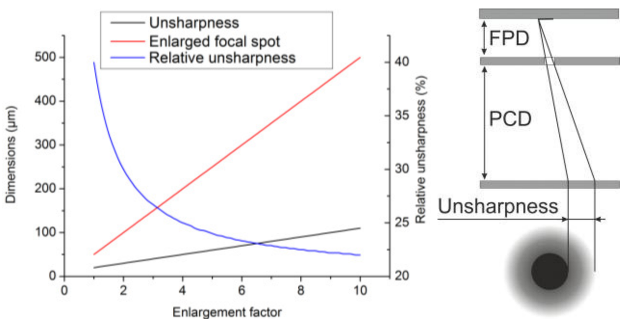

Figure 3: Dependences of the focal spot size, unsharpness vs. enlargement factor and schematic view of the unsharpness.

EXPERIMENTAL SETUP

The triode unit representing the most important part of the system must be placed on the goniometer to precisely adjust the tilt angle of the focal spot (figure 4). The goniometer is computer controlled stage placed inside the vacuum chamber. The triode unit is placed and fixed on the thick dielectric plate (Teflon, alumina oxide or other available high-density dielectric) fixed with the goniometer.

The vacuum chamber is made in a form of vertically aligned cylinder. The bottom is made blind with a metal stage for goniometer alignment. To power up the electrodes the 100 kV and 30 kV high-voltage feedthougs flanges are made in the chamber walls opposing the corresponding electrodes. The cathode is grounded and connected via the cable to the bottom stage. To feed the goniometer stage the standard DB-15 flange is made. The X-ray window is made inside the flange from beryllium and is used for observation of the focal spot and spectrum analysis of the emitted X-ray radiation. The top of the chamber is a fast entry door from the transparent dielectric material made to inspect the operating process of the unit.

The vacuum chamber is designed to perform at the 10^{-4} Pa vacuum pressure that is enough to operate with carbon field emission cathodes. The pumping system is based on the prepump and turbomolecular pump working with 110 l/s pumping speed with the flange connection to the chamber. This system can provide the pumping of the system to nominal vacuum level less than 20 min.

CONCLUSION

The presented results show the experimental unit that can be applied for different tests of the carbon nanostructure cathode. The main idea was to make the unit to provide the possibility of measuring the VI characteristics and to explore the operation of the cathode for X-ray generation devices. The system is based on strip-shape triode unit.

All theoretical estimations and computer simulations have now been processed. The experimental unit is now under construction. The first results of the measurements are foreseen to be acquired in the late 2014.

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