Angular distribution of beam electrons in a source with arc plasma emitter

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Abstract. Results on studying the angular characteristics of an electron beam, generated in a multi-aperture diode with an arc-discharge plasma emitter are reported. The main beam parameters were as follows: the electron energy up to 120 keV, the emission current up to 100 A, the pulse duration 0.1 - 0.3 ms, and the initial diameter ca. 8 cm. The beam was formed and transported to a metal target in an adiabatically converging magnetic field. The diagnostic technique based on an X-ray imaging of the profiles of individual beamlets passed through the pepperpot-like mask was developed and used to investigate an angular distribution of the beam electrons. The spatial resolution of the diagnostic was evaluated in a special test experiment and found to be not worse than 4 lp/cm at a 10 % contrast level. It was demonstrated that an angular distribution of the beam electrons fits well by the Gaussian function with the RMS width ~ 0.067 rad. The data on the angular distribution measured with pepperpot diagnostic are in a good agreement with those obtained in the experiments on the beam passage through a magnetic mirror.

1. Introduction
The electron beam source has been developed in Budker Institute, Novosibirsk. It is based on an arc-discharge plasma cathode and a multi-aperture electron optical system (EOS) [1]. The diode-type EOS assembles two plain molybdenum electrodes with 241 round apertures drilled in a hexagonal grid. An efficient diameter of EOS was ca. 8 cm. The main beam parameters were as follows: the electron energy up to 120 keV, the emission current up to 100 A, and the pulse duration of a sub-millisecond range. The beam was transported and compressed adiabatically in the converging magnetic field. A metal target was exposed to a power density of 1-10 GW/m² that is necessary for some material science and engineering applications. To achieve such power density, the 30-fold or more compression of the initial beam current density is required. Assuming the adiabatic invariance of the magnetic moment, a high degree of compression needs some requirements to the initial pitch angles of electrons. Thus, the information about the beam angular characteristics is of a paramount importance.

In the presented work, we study the angular distribution of electrons in a beam generated in a multi-aperture, plasma-emission diode. For this purpose, the diagnostic system based on pepperpot technique was developed. It allows us to measure the angular distribution of electrons over the beam cross-section in a single shot. The spatial resolution of the diagnostic system was evaluated in a...
special test experiment and was found to be not worse than 4 line pairs per centimeter at the 10% contrast level. The algorithm of experimental data processing is also described. The experimental results are compared with those obtained in the experiments on the beam transportation through a magnetic mirror.

2. Experimental layout

The experiments were carried out using the electron beam test facility designed for the simulation of high thermal loading on the construction materials [2]. A layout of the experiments is shown in Figure 1. The hollow high-voltage electrode (1) was mounted inside a vacuum tank on a PMMA bushing (3). The inner surface of the high-voltage electrode serves as the distributed anode of an arc discharge that creates an emission plasma (2). The molybdenum plate at the face end of the hollow electrode with 241 round openings of 3 mm diameter is a cathode of an accelerator diode. The grounded anode electrode of the diode (4) employed 4.4 mm openings aligned precisely with their cathode counterparts.

![Figure 1.](image)

An accelerated beam was transported in a guiding magnetic field to the Faraday cup located at 2 m from the beam source. The field of mirror configuration was produced using coils placed at the vacuum tank exterior (5) and at the solenoid section of the facility (6). The pepperpot system was installed at 0.85 m from the beam source on a movable holder. The beam was received onto a stainless steel mask with an array of pinholes of 2 mm diameter, arranged with a pitch of 14 mm horizontally and vertically, covering the square of 120x120 mm. As a result, the number of beamlets were cut out from the initial beam. These beamlets were absorbed in a thin metal plate placed downstream of the pepperpot mask and served as the X-ray converter. The phosphor screen (Gd₂O₂S:Tb phosphor on the plastic substrate) was attached directly to the back side of the converter plate for imaging the beam X-
ray footprint. The luminous spots on the screen were viewed via a 45° mirror using a fast CCD camera. The luminescence decay time for Gd:O:2:Tb was about 0.6 ms, whereas a typical beam duration in the experiments was 0.1 – 0.3 ms. Thus, the time integrated measurements were realized.

The increase of the distance between the pepperpot mask and X-ray converter allows us to obtain a better resolution of the diagnostic. However, in this case, an overlapping of the luminous spots may occur, that complicates the results of interpretation. The electron trajectories are also affected by the guiding magnetic field, if the following condition is not met:

\[ L \ll \lambda = \frac{V_e 2\pi}{B}, \]  

where \( L \) – the distance between the mask and the x-ray converter, \( \lambda \) - a step of Larmor spiral. In our case \((B \sim 0.01 T, E_e \sim 80 keV)\), the Larmor step is \( \lambda \approx 587 \) mm. Thus, the distance between the mask and the X-ray converter was chosen as 2 cm.

The material and thickness of the beam converter are crucial for the amount of light emitted by the phosphor screen. The number of emitted photons \( S \) can be calculated as:

\[ S = k \cdot \int E N(E) T(E) A(E) EdE, \]  

where \( E \) – the X-ray photon energy, \( N(E) \) – the spectral response of the X-ray converter, \( T(E) \) – the converter transmittance, \( A(E) \) – the absorption coefficient of the phosphor layer and \( k \) is the light yield of the phosphor \((k =35 \text{ photon/keV})\). The spectral response of the collector was determined using the model reported in [3, 4]. The phosphor absorption coefficient was calculated, taking into account the surface density of the active substance – 55 mg/cm2. The number of photons was calculated for various materials: W, Ta, and a stainless steel with the beam parameters as follows: \( E_b = 100 \) keV, \( I_b = 100 \) A, \( \tau_b = 0.15 \) ms. All calculations use the material properties specified in the NIST database [5].

The number of photons vs. the collector thickness is shown in the Fig. 3. Over the entire range of the converter thickness, tantalum produced the highest light yield. Thus, tantalum was chosen for the X-ray converter as the most optimal and the easiest material for processing. The thickness of the converter was taken as 0.01 cm.

![Figure 2](image)

**Figure 2.** Dependence of light yield on x-ray converter thickness for different materials.

3. Experiments and results
A typical pepperpot image is shown in figure 3 for the beam with the following parameters: 80 keV, 70 A, 0.1 ms. In the upper part of the figure, an image intensity profile is depicted. It was measured
along the horizontal dotted line. As it is seen in the figure, the X-ray footprints of separate beamlets are clearly distinguishable. Due to non-uniformity of the beam current profile, the brightness of the footprints has a maximum in the center of the beam and decreases to the periphery. A visible dark strip in the image is a result of the converter design, which comprises two overlapping pieces of the tantalum foil. The pepperpot image reveals a substantial non-uniform background glow that complicates the recovery of angular beam characteristics. This background may be caused both by the electrons with large angles and the X-rays, that were generated at the pepperpot mask and passed onto the phosphor screen directly through the mask material.

Figure 3. Typical X-ray image of the beamlets, and intensity profile measured along horizontal dashed line crossing the center of the beamlet.

Figure 4. Image of background, and intensity profile measured along horizontal dashed line.

To evaluate the background origin, a special experiment was carried out, where the major part of pepperpot pinholes was covered with a stainless steel foil of 100 µm thick. An example of the resulting image is shown in figure 4. The luminescence intensity profile was measured along the horizontal line crossing the center of image. It can be seen, the profile of the background light did not change indicating that it was caused only by the X-rays passing through the pepperpot plate material. Under further image processing, this background should be subtracted from the signal.

An additional experiment on measuring the sharp edge spread function has been performed to determine a spatial resolution of the imaging technique. In this experiment, the pepperpot mask was dismantled, and the beam was stopped directly by the X-ray converter. The edge was formed with a tungsten plate of 0.1 cm thickness, which covered a part of the converter surface and completely shadowed the X-rays. On a basis of the measured edge profile, the line transfer function and the modulation transfer function were calculated [6]. The diagnostic’s spatial resolution was found not worse than 4 line pairs per cm at the 10% contrast level.
The image intensity profile after processing is shown in figure 5. The solid curve corresponds to the intensity profile after background subtraction. For the convenience of further processing, the profile of every beamlet was interpolated with a Gaussian function:

$$F(x) = a_1 \cdot e^{-\frac{(x-a_2)^2}{2a_3^2}},$$

where $a_1, a_2, a_3$ – interpolation parameters. The experimentally observed profiles are the result of the convolution of the electron angular distribution function with the step function, which describes the pepperpot orifice and the line spread function. Thus, the deconvolution procedure was carried out, to find the angular distribution function of the beam electrons. The result is shown in figure 5 by a dashed curve. For two most bright beamlets, the RMS width of the Gaussian approximation was found (in radian terms) as 0.091 and 0.085. It should be noted that the magnetic field value at the diode and at the diagnostic location was 6.5 mT and 12 mT, respectively. Thus, assuming the conservation of the magnetic moment, the RMS width of the angular distribution function at the diode exit should be found as ca. 0.067 rad.

To verify the adiabaticity of the beam magnetic compression, a number of experiments, where the guiding magnetic field at the pepperpot location varied from 12 mT to 32 mT, while the field at the diode region was constant, was carried out. The resulting dependence of the beam angular spread vs. the magnetic field value is shown in figure 6.

**Figure 5.** Beamlets intensity profile processing: solid curve - intensity profile after background subtraction; dashed curve – resulting beamlets profile.

**Figure 6.** Dependence of the beam angular spread vs. magnetic field value.

**Figure 7.** Dependence of the beam transmission vs. mirror ratio.
The points correspond to the Gaussian RMS width measured in the experiments. The dashed curve is derived from the invariance of the magnetic moment and is given by the formula:

$$\theta(B) = \arctg \left( \frac{B}{B_0} \right),$$

where $\theta_0, B_0$ – the RMS angle and the magnetic field value at the diode location, $\theta$ and $B$ – the angle and the field at the diagnostic location. The previously obtained values, 0.067 rad and 6.5 mT, were used as $\theta_0$ and $B_0$, respectively. As it can be seen from the figure, the experimental dependence correlates satisfactorily with theoretical predictions. That proves the adiabaticity of the beam compression under our experimental conditions.

This fact allows us to compare the measured beam angular distribution with the beam transition through the magnetic mirror. In these experiments, the beam parameters were constant, while the magnetic field mirror ratio varied within the range from 7 to 60. The beam current through the magnetic mirror was measured with a Faraday cup (FC). The resulting dependence of the beam transmission vs. mirror ratio is shown in figure 7. As it can be seen, about 95% of the beam emission current passed to the FC for the mirror ratio value from 7 to 30. With a further increase of the mirror ratio, the current on the FC decreased gradually. For the mirror ratio of 60 only about 72% of the initial current passed to the FC. For higher mirror ratios, the measurements were not carried out because of the beam pulse shortening due to the electrons reflected from the mirror. The dashed curve is derived within an assumption that the beam angular distribution is described by the Gaussian function with the RMS width of 0.067 rad. Overall, the theoretical curve agrees well with the experimental data, except the highest mirror ratio values when the FC current declines faster. This difference, apparently, can be explained due to the effect of the beam space charge [7].

4. Conclusion

The angular characteristics of the electron beam generated in the source with plasma cathode and the multi-aperture diode have been studied. For this purpose, the imaging X-ray diagnostic tool based on the pepperpot technique was developed. Using this diagnostic, it was demonstrated that the beam angular distribution could be fairly good described with the Gaussian function with the RMS width of ca. 0.067 rad. The results are in a good agreement with those obtained in the experiments on the beam pass through the magnetic mirror.

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