Study of electron beam uniformity in large-area multi-aperture diode with arc plasma cathode

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Abstract. The use of plasma emission cathode in the conjunction with a multiple apertured electron optical system (EOS) is promising for the multi-MW class electron beams of a large cross-sectional area. In a multi-aperture source, the beam parameters could be raised simply due to increase of the number of apertures (i.e. an effective emission area), if a uniformity of the electron emission over a large-area plasma cathode is ensured. In the presented paper, the cross-sectional distribution of the emission current density was investigated using the X-ray diagnostic technique for two versions of the diode-type EOS, with electrodes performed as flat molybdenum "grids". The first one had 241 apertures arranged hexagonally inside a circle with a diameter of 8.3 cm and the second had 499 apertures within a circle of 11.8 cm diameter. The emission plasma is produced using a single arc-discharge plasma generator placed on the axis at 20 cm from the EOS. It was demonstrated that multi-aperture systems with a single on-axis plasma generator can be effectively employed to obtain large-area beams, even in the presence of the guiding magnetic field. All apertures are emitting in the 499-apertured EOS. The beam current density is quite uniform up to the radius 2.5 cm and gradually decreases to the periphery.

1. Introduction
The high-power beams of subrelativistic electrons with a cross-sectional area ~ 10^2 cm^2 are used in a number of scientific and technical applications, particularly, in a material science and engineering, for surface modification of solids, modeling of high thermal fluxes on plasma facing components in fusion reactors, etc. The use of a plasma electron emitter is very promising for the large area beam application due to a lack of engineering issues inherent to the large area thermionic cathodes.

An electron beam source based on the plasma cathode and the multi-aperture electron optical system (EOS) has been developed at Budker Institute, Novosibirsk. The beam parameters (non-simultaneous) are as follows: the energy up to 120 keV, the total current up to 250 A, the pulse length up to 1 ms. The beam extraction/acceleration needs a multi-aperture diode optics. The cathode and the anode are as flat molybdenum “grids” with multiple round openings, which are drilled in a hexagonal order. The emission plasma is produced with a single arc discharge plasma generator placed at an axis. Details of the beam source design are given elsewhere [1].

The concept of the multi-aperture diode is well suited for generation of the beam with a large cross-sectional area. An increase of the emission current here can be achieved, in general, simply by increasing the number of grid openings (i.e., an effective emission area). However, in the scheme with
a single on-axis emission plasma generator, this approach faces the challenge of radial uniformity of the emission plasma, in other words, the efficiency of use of the peripheral apertures in the EOS with a large cross-section. The problem becomes exacerbated, as the guiding magnetic field is applied to transport and to compress the electron beam, producing a required current density on a target. The experiments performed earlier have shown that the presence of the magnetic field leads to the contraction of an arc discharge in the near-axis region.

This paper presents an experimental study of the emission current density distribution over the multi-aperture EOS for two versions of various sizes. The first one had 241 round aperture arranged in a hexagonal order inside a circle with a diameter of 8.3 cm and the second had 499 apertures within a circle with a diameter of 11.8 cm. A diameter of the emission openings was 0.3 cm and 0.26 cm, and an effective emission (open) area was ca. 17 cm² and ca. 26 cm², respectively. The diode gap was 1 cm in both cases.

An X-ray imaging diagnostic technique was developed to measure the beam profile on a flat metal target. The diagnostic system allows obtaining a 2D-picture of the cross-sectional distribution of the beam current density in every single shot. The spatial resolution of this diagnostic was found using special tests: 4 pairs of lines per 1 cm at a 10% contrast level.

2. Experimental setup

The experiments have been carried out employing an electron beam test facility designed for the simulation of pulsed high heat loads effect on the construction materials [2]. The schematic of the experimental setup is shown in figure 1. The beam source is installed inside the vacuum barrel. It is immersed in an axial magnetic field produced by external magnetic windings on the barrel. The field typical value is 7 - 10 mT at the diode region and increased by 1.7 times at the beam collector located at 0.85 m downstream of the diode. The accelerating voltage is applied to the diode cathode which is performed as a hollow cylinder, made of a stainless steel. An emission grid, through which electrons are extracted, is mounted at the end face of the cylinder. The emission plasma is generated by an arc discharge source of a washer-gun type [3, 4] placed at a distance of 20 cm from the emission grid.

![Figure 1. Schematic layout of the experimental setup: 1—hollow high-voltage electrode with emission grid (cathode); 2—washer gun plasma source; 3—feedthrough insulator; 4—extracting grid (anode); 5—magnetic coils; 6—beam collector with attached phosphor screen; 7—45°-mirror; 8—fast CCD-camera.](image-url)
An emission plasma generator is equipped with a small magnetic coil, which provides a magnetic field up to 800 mT in the arc channel (the initial segment of the arc discharge path). Thus, the magnetic field lines are strongly divergent in a space between the arc generator and the emission grid. In this way, in principle, the conditions for spreading the discharge plasma over the emission grid, providing a better emission uniformity across the wide-area EOS, are created.

2.1. X-ray diagnostic system

The beam collector is designed as a thin metal plate and serves as an X-ray converter. The phosphor screen (Gd$_2$O$_2$S:Tb phosphor on a thin plastic film) is attached directly to the back side of the collector plate for imaging the beam X-ray footprint. The phosphor glow is registered with the use of a 45° mirror and a fast CCD camera. It should be noted that the luminescence decay time for Gd$_2$O$_2$S:Tb is of ca. 0.6 ms, whereas a typical beam duration in the presented experiments is of ca. 0.2 ms. Thus, the image current density distribution on the collector integrated over the beam period could be imaged.

For ~100 keV beam electrons, an angular distribution of X-rays produced in the target is nearly isotropic. Therefore, to achieve a better spatial resolution of the image, the phosphor screen should be placed as close to the collector surface as possible, which in its turn requires a minimum thickness of the collector plate. A small thickness is needed also to reduce the attenuation of the X-rays passing through the collector material onto the phosphor screen. However, the use of a thin collector is complicated by its high heating under the electron beam load. The phosphor screen will be damaged if a temperature of the backside of the beam collector exceeds 80°C. The heating of the collector plate has been calculated for various materials (W, Ta, and a stainless steel) for the beam parameters as follows: $E_b = 100$ keV, $I_b = 100$ A, $t_b = 0.15$ ms and the beam diameter of 7 cm. It is assumed that the absorbed heat is uniformly distributed over the beam footprint. The electron backscattering factor for all materials was taken into account in the calculations. The temperature curves versus the collector thickness are shown in figure 2. As it can be seen, an acceptable backside collector temperature is attained for the material thickness of 0.1 cm or more.

The material and the thickness of the beam collector also affect the amount of the light emitted by the phosphor screen. The number of emitted photons $S$ can be calculated as:

$$S = k \cdot \int E N(E) \cdot T(E) \cdot A(E) \cdot E \, dE$$

where $E$ stands for the X-ray photons energy, $N(E)$ is a spectral response of the collector, $T(E)$ is the collector transmittance, $A(E)$ is the absorption coefficient of the phosphor layer, and $k$ is the light yield of the Gd$_2$O$_2$S:Tb phosphor ($k = 35$ photon/keV). The spectral response of the collector is
calculated using the model outlined in [5, 6]. The absorption coefficient calculations based on the surface density of the phosphor active substance: 55 mg/cm$^2$. All calculations use the material properties specified in the NIST database [7], the electron beam parameters and the collector materials were taken the same as for the heating calculations.

The number of light photons versus the collector thickness are shown in figure 3. With the collector thickness of over 0.1 cm, a difference in the emitted light is inessential for all considered materials. Thus, the stainless steel was taken as an inexpensive and easy-to-process material. Ultimately, the 0.1 cm thickness of the collector plate was chosen.

3. Experimental results
A typical X-ray image of the beam (80 keV, 70 A, 0.1 ms) produced with the 241 aperture EOS is shown in figure 4. The beam cross-section is very close to a circle. The image shape and the center of mass are stable from shot to shot. In the upper part of figure 4, the beam current density profile, which is measured along the dotted line crossing the center of the image, is shown. The profile is quite flat, with a steep fall at the edge. The beam current density reaches 3.2 A/cm$^2$ at the center of the beam. An effective beam diameter on the target, defined as a diameter of a circle, which encloses 90% of the beam current, is found to be ca. 7 cm.

To obtain the spatial resolution of the imaging diagnostics, special experiments on measuring the sharp edge spread function have been performed. The edge is formed with a tungsten plate of 0.1 cm thickness imposed upon the converter, the overlapping part of the beam footprint, and completely shadowing the X-rays. The resulting image is shown in figure 5. The normalized intensity profile is measured along the line perpendicular to the edge and crossing the center of the beam footprint. On the basis of the edge profile, the modulation transfer function of the diagnostic was calculated (e.g. [8]). The limiting spatial resolution was found as 4 line pairs/cm at 10% level.

![Figure 4. Typical X-ray image of the beam and current density profile measured along dotted line crossing the center of the beam.](image1)

![Figure 5. Image of the edge response and intensity profile measured along dotted line crossing the center of the beam.](image2)
Since the diagnostic measures the current density distribution on the collector at a distance of 0.85 m downstream of the beam source, it is possible to evaluate the current density distribution directly in the multi-aperture diode.

Originally, the beam consists of many separate jets (beamlets). In a guiding magnetic field, the beamlet envelope oscillates radially due to transversal velocities of the electrons. That leads to a periodic focusing of the beamlet, ultimately, to its initial radius. Thus, varying the magnitude of the accelerating voltage and the magnetic field it is possible to reproduce the initial beam structure in the collector footprint and evaluate the emission yield of every single aperture. An example of such image is shown in figure 6. As we can see from the picture, the beam structure completely resembles the EOS structure, all of the 241 apertures are utilized in the beam generation. An emission is quite uniform all over the EOS, the current density decreases by 20% of the maximum at a radius of 2.5 cm and falls almost twice at the EOS periphery (at the radius of 4 cm). It should be noted that the discrete structure of the beam on the target disappears with a change of the magnetic field and the energy of electrons, which is also confirmed by the melting imprint at the collector.

At the next experimental step, the number of apertures was nearly doubled (499 vs. 241) and the EOS diameter increased ca. 1.4 times (11.8 cm vs 8.3 cm). This step allowed to increase the maximum beam current and the emission current of 250 A at the 0.25 ms pulse was achieved. The beam structure in the 499-apertured EOS is shown in figure 7. All of 499 apertures are employed, as with the previous EOS, the current density decreases by 20% of the maximum at the radius of ca. 2.5 cm and falls to ~0.25 of the maximum in the peripheral apertures (at the radius of 5.5 cm).

**Figure 6.** Image of the beam structure for 241-apertured EOS and intensity profile measured along dotted line crossing the center of the beam.

**Figure 7.** Image of the beam structure for 499-apertured EOS and intensity profile measured along dotted line crossing the center of the beam.

### 4. Conclusions

An electron beam current density distribution in the multi-aperture diode with the plasma cathode have been studied with the help of the imaging X-ray diagnostic tool. It was demonstrated that the large-area electron beams could be effectively formed in the multi-aperture system with the single on-
axis arc-discharge plasma generator even in the presence of the guiding magnetic field. All apertures are emitting in the 499-apertured EOS with the diameter ca. 12 cm. The beam current density is quite uniform up to the radius 2.5 cm and gradually decreases to the periphery.

It should be noted that the beam emission profile is weakly dependent on the magnetic field strength in the arc channel of the washer gun. The effective diameter of the beam imprint practically does not change when the field varies in the range from 100 to 800 mT. On this basis, one can assume that the geometry of the magnetic flux in the hollow anode of the arc is not the key factor determining the cross-sectional size of the discharge plasma near the emission grid.

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References
[1] Kurkuchekov V V et al. 2013 Fusion Sci. Technol. 63 1T 292-4
[2] Vyacheslavov L et al. 2016 Novel electron beam based test facility for observation of dynamics of tungsten erosion under intense ELM-like heat loads AIP Conferences Series to be published
[3] Davydenko V I, Morozov I I, Roslyakov G V and Savkin V Y 1987 Instrum. Exp. Tech. 29 6
[4] Fiksel G, Almagri A F, Craig D, Iida M, Prager S C and Sarff JS 1996 Plasma Sources Sci. Technol. 5 78-83
[5] Ebel H 2006 Advances in X-Ray Analysis 49 267 – 73
[6] Ebel H 1999 X-Ray Tube Spectra X-Ray Spectrometry 28 255-66
[7] Hubbell J H and Seltzer S M 2004 Tables of X-Ray Mass Attenuation Coefficients and Mass Energy-Absorption Coefficients (version 1.4). (National Institute of Standards and Technology http://physics.nist.gov/xaamdi )
[8] Smith S W 1997 The Scientist and Engineer’s Guide to Digital signal Processing (California Technical Publishing http://www.dspguide.com/) chapter 25