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On the focused beam parameters of an electron gun with a plasma emitter

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Abstract. The report presents the measurement results of the focused beam brightness in the electron gun with plasma emitter. The beam brightness was approximately 1010 A•m-2•sr-1 under the beam power up to 4 kW and an electron energy of 60 keV at the focal distance of 0.5 m. Qualitative assessment of the beam parameters was performed by welding test pieces. The results describing the possibility in principle of using the guns with a plasma emitter in non-vacuum technological devices are presented.

1. Introduction

Electron-beam guns with a plasma emitter based on the emission of electrons from a low-voltage discharge with a hollow cathode [1] have long been used in the beam technologies [2, 3]. In contrast to the widespread triode guns, guns with a plasma emitter are designed by a diode scheme. Current control in such guns is performed without grid electrode. The advantage of such a beam current control [4] is, in contrast to hot cathode triode gun, the electron-optical properties of the focused beam remain practically unchanged at the beam current variation. Within the broad range of the electron-beam experts is widely believed that the guns of this type provide a low beam current density because of the high electrons temperature by the emitting plasma. According to our estimates, based on the known formula of Langmuir [5], for typical parameters of the plasma emitter, the minimum size of a focused electron beam must not exceed a few tens of microns [6].

However, in experiments such a small diameter has not been reached for a long time for beam emitters using discharge processes. The reason was the underestimation of the influence of the magnetic field of the discharge chamber on the properties of the electron beam in the accelerating gap and the drift space of the gun. After the optimization of the magnetic field, electron beams with a power density of up to 10^7 W/cm^2 at 60 keV electron energy can be generated. In addition to the power density in the focal spot, the brightness of the electron beam is equally important to evaluate the electron-optical parameters of the gun. High brightness makes it possible to use guns with a plasma emitter for high-quality welding, applications involving pressure stage systems (non-vacuum, low-vacuum) or processes with high demands on beam quality such as EB drilling or rapid manufacturing or rapid prototyping. The results of our assessment of the beam generated by an electron gun with a plasma emitter are set out below.

2. Test setup and measurement techniques

The measurement of the beam radius r_f at the focal spot and the convergence angle of the focused electron beam on guns with a plasma emitter was carried out at the installation shown in figure 1. The main parts of the installation are the electron-beam gun developed by Elion Ltd. (Russia) for Perndorfer Maschinenbau KG (Austria), the vacuum chamber and probing system (see figure 1*a*).

Electrons emitted from plasma caused by an electric field are required for the operation of a gun with a plasma emitter. The emitting plasma is produced by a low-voltage reflective discharge with a hollow cathode [1].

The basic component of a gun is the discharge chamber, a ceramic-metal unit. Its primary function is to produce charged particles in a Penning-type gas discharge. A schematic diagram of the electrode assembly of an electron gun with a plasma emitter is given in figure 1*b*.

The discharge chamber is formed by a hollow cathode (1), a cylindrical anode (2), and an emitter cathode (4). The voltage (DPS) is necessary for the discharge initiation and operation. It is applied between the cathodes and the anode. A permanent magnet (3) creates a magnetic field of $(0.8 \div 1) \cdot 10^{-1}$ T in the space between the hollow cathode and the emitter cathode.

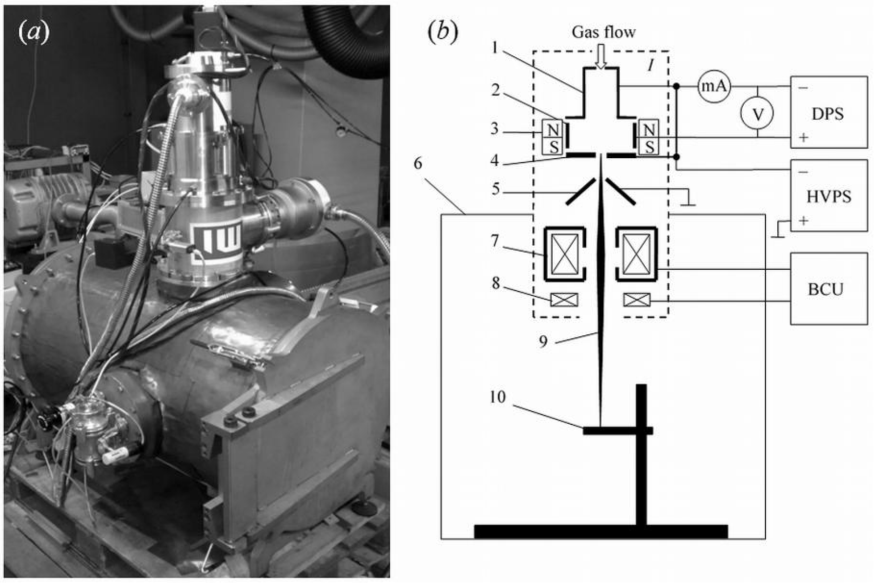

Figure 1. Appearance (a) and configuration (b) of experimental setup: 1 – hollow cathode; 2 – anode; 3 – permanent magnet; 4 – emitter cathode; 5 – accelerating electrode; 6 – vacuum chamber; 7 – focusing lens; 8 – deflection coils; 9 – electron beam; 10 – probing system; DPS – discharge power supply; HVPS – high-voltage power supply; BCU – beam control unit.

The working gas (usually air) is fed into the discharge chamber through the hollow cathode channel and is pumped out through the channel in the emitter cathode. The accelerating voltage (HVPS) up to 60 kV is applied to the emitter cathode (4) relative to the grounded accelerating electrode (5). The plasma electrons that leave the chamber through the emitter cathode channel accelerated in the high-voltage electric field and form a beam, which is focused by the magnetic field of the focusing lens (7). The deflection coils (8) are used for beam deflection. It is common to use a low-voltage form of glow discharge, i.e. with a voltage of 350÷450 V. The pressure in the discharge chamber is $(0.5 \div 1) \cdot 10^{-1}$ mbar. The value of the gas flow is small and usually does not exceed $(4.2 \div 5.6) \cdot 10^{-3}$ mbar·l/s. The maximum beam current is 150 mA.

3. Measurement of electron beam diameter

One of the most important parameters of an electron beam is its diameter. The current density of an electron beam is usually distributed in the form of a Gaussian curve. Depending on the application, a diameter is defined as the width of an area covered with a fixed fraction of the maximum value or the integral of the distribution. The half value width (FWHM, Full Width at Half Maximum), well-established in industry and science for the characterization of electron beams, is used in this work. This is the width of the range in which the power density exceeds at least half the maximum value. In this paper, measuring the diameter of the electron beam was carried out by stationary sensor with the deflection system (scanning slit).

For the first method (scanning slit), a system designed by TWI Ltd. was used (see figure 2).

The TWI EB probe system comprises the following:

- The two finger probe with integrated Faraday cup;
- A beam sink, or dump, capable of withstanding the maximum beam power for extended periods;
- A data acquisition system based around an industrial PC.

The probe heads measure a sample of the beam current as it passes through a narrow slit, as the beam is swept across the probe in a direction orthogonal to the alignment of the slit (see figure 2).

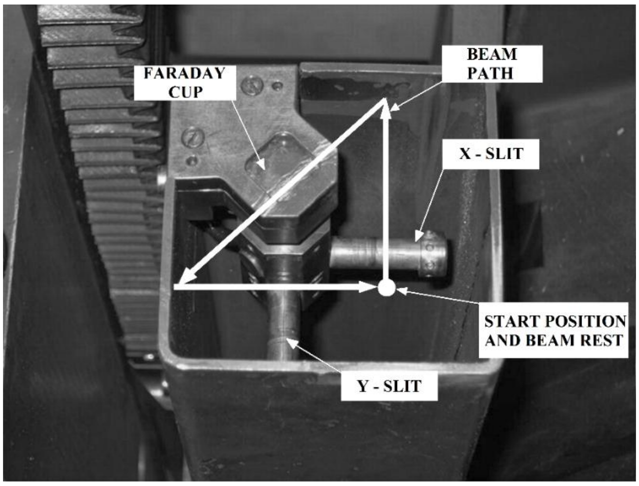

Figure 2. General view of the TWI EB probe device.

The main information gathered by the probe is the width of the beam in the direction of the sweep (see figure 3).

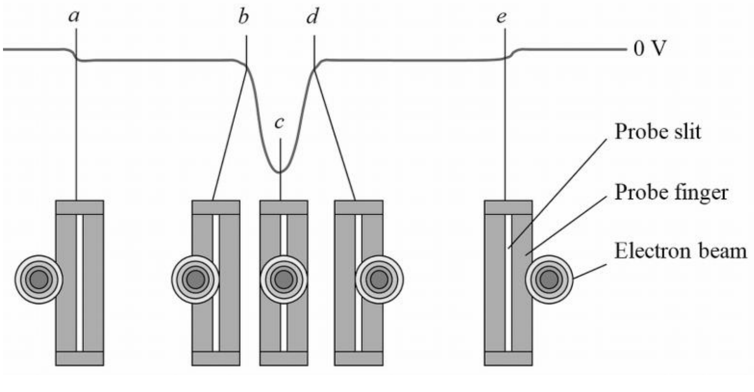

Figure 3. Scheme showing a passage of the beam over probe finger and resulting data trace.

Typically, this width is defined to be the full width of the beam at half of the maximum measured current (FWHM). The second probe is orientated perpendicular to the first and is used to measure the width in the orthogonal direction. In addition to the width of the beam, the beam speed can be measured by collecting current from the probe body. This allows an accurate measure of the velocity of the beam sweep, and enables the width measurements to be converted from a duration to a distance. The two-finger probe relies on the beam moving over the slit at a constant speed to acquire good quality data. The speed should be consistent across both the X and Y finger to ensure that the probe data is comparable. A Faraday cup is designed as an optional feature, to allow the total beam current to be measured. The sensor is a cup with an aperture size sufficient to capture the entire beam as it is swept over – thus enabling the total beam current to be measured.

Points *a* and *e* on the figure 3 correspond to the moments of the first and last contact of the beam with the probe finger. At the moment of time corresponding to points *b* and *d*, the beam first and last contacts the slit. At point *c*, most intense part of beam is over slit (Peak beam shape signal is generated).

The beam path was chosen as a triangular pattern moving out over the X finger, tracking across the Faraday cup and falling back to the free fall position across the Y finger as shown by the line in figure 2.

For a beam with Gaussian power distribution brightness can be written as [7]

$$B = \frac{i_{beam}}{(\pi r_f \theta)^2}, \tag{1}$$

where i_{beam} is the beam current, r_f is the beam radius at the focal plane and θ is the convergence angle.

The convergence angle θ of the electron beam can be calculated by

$$tg(\theta) = \frac{r_l - r_f}{b}, \tag{2}$$

where b is the distance of the sharp focus plane to the focusing lens and r_l is the beam radius in the focusing lens.

4. Conclusion

The brightness of the electron beam generated by the gun with a plasma emitter, made at the beam current range of 10÷60 mA was measured. The measurement was carried out at the accelerating voltage 60 kV and the focal plane of the electron beam was set to 520 mm. Table 1 shows the results of our measurement giving the diameter of the focused electron beam, as well as the calculated brightness and the convergence angle, respectively.

Table 1. The results of measuring the electron beam brightness.

Beam current (mA)	Beam diameter at focus (μm)	Convergence angle (rad)	Brightness ($A\cdot m^{-2}\cdot sr^{-1}$)
10	550	$1.6\cdot10^{-3}$	$0.5\cdot10^{10}$
20	560	$1.5\cdot10^{-3}$	$1.2\cdot10^{10}$
40	580	$2.5\cdot10^{-3}$	$0.8\cdot10^{10}$
60	460	$2.7\cdot10^{-3}$	$1.6\cdot10^{10}$
Tungsten hairpin filament cathode [8]			$5\cdot10^{8}$
Tungsten hairpin tip cathode, LaB_6 cathode [8]			$5\cdot10^{10}$
LaB_6 sharp tip cathode [8]			$5\cdot10^{11}$

The test pieces were made for qualitative evaluation of the measured parameters of the electron beam. Macrosection of the sample is shown in figure 4.

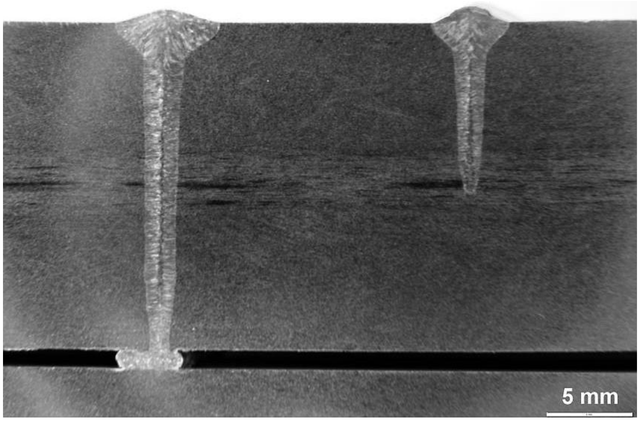

Figure 4. Crossection of the welds.

As evident from Table 1, the brightness of an electron beam from gun with the plasma emitter is not inferior compared to beams from thermionic cathodes of LaB_6 and of superior brightness compared to tungsten filament cathodes. Furthermore, a narrow and deep penetration profile with parallel walls (see figure 4) characterizes the beam with a small convergence angle, which correlates with the results of measurements the beam parameters.

High brightness and small convergence angle of the electron beam generated by the gun with a plasma emitter, have allowed to extract the focused electron beam in the atmosphere with an energy of 60 keV and a current 100 mA (see figure 5).

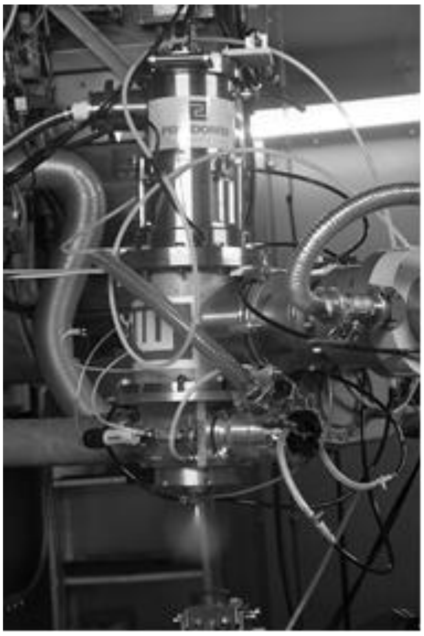

Figure 5. Electron beam from gun with a plasma emitter was extracted in the atmosphere.

The three-stage differential pumping system of Non Vacuum Electron Beam Welding machine (NV EBW 175-25 TU, PTR GmbH, Germany) was used as a prototype of the differential pumping system for gun with a plasma emitter. The pressure drop from the atmosphere to 10^{-4} mbar in the beam-forming region was provided by differential pumping system.

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