ISBN: 978-3-95450-240-0 ISSN: 2673-5539 doi:10.18429/JACoW-RuPAC2021-FRB03

UPGRATED THE EXTRACTION DEVICE OF FOCUSED ELECTRON BEAM INTO THE ATMOSPHERE

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Abstract

This article deals the factors affecting the diameter and angle of divergence of the electron beam at the exit from the accelerator tube of an industrial ELV series accelerator. Measurements of the parameters of a high-power electron beam were carried out up to a power of 100 kW. On the basis of the data obtained, a new type of gas-dynamic extraction device was designed and pre-tested, which can efficiently output a focused electron beam to the atmosphere.

INTRODUCTION

For more than 30 years at the Institute of Nuclear Physics (INP SB RAS), on ELV-6 accelerator has been successfully operating a multi-stage gas-dynamic extraction device through which a focused electron beam is released into the atmosphere. It uses an accelerating tube with permanent magnets. The design and manufacture of such accelerating tubes are rather complicated. At present, ELV accelerators use simpler and more reliable accelerating tubes without magnetic accompaniment. They have a large aperture of 100 mm and are mass-produced [1]. Since the reliability of serial accelerating tubes is high, and the technology for manufacturing tubes with permanent magnets has been lost. The task was posed of a possible replacement of the accelerating tube with permanent magnets with an accelerating tube with a large aperture without permanent magnets for the ELV-6 accelerators.

BEAM MOTION ANALYSIS

The beam size and its angular divergence at the exit of the accelerating tube are influenced by the following main factors:

1. Longitudinal electric field: carries out the main focusing of the beam;
2. Influence of the magnetic field of heating coil (the beam acquires an azimuthal momentum Pφ0);
3. The space charge of the beam;
4. The ripples of the accelerating voltage;
5. Aberrations of electromagnetic lenses. They also affect the optimal hole size in the outlet diaphragms;
6. Transverse component of the magnetic field of the primary and secondary windings, which leads to oscillations of the beam, and leads to increase the holes in the diaphragms

The calculations were carried out using the SAM program developed at the BINP SB RAS [2]: the effect of the intrinsic magnetic field of the incandescence was taken into account, the influence of the potential of electrodes with an aperture of 20 mm on the parameters of the beam, embedding of the LaB6 pellet and the shape of the cathode electrode was checked.

The potential distribution along the accelerating tube is shown in Fig. 1. A so-called "electric-gate" is formed near the high-voltage edge of the tube; a minimum of potential is created, which prevents the acceleration of secondary particles appearing as a result of ion bombardment of electrode with an aperture of 20 mm.

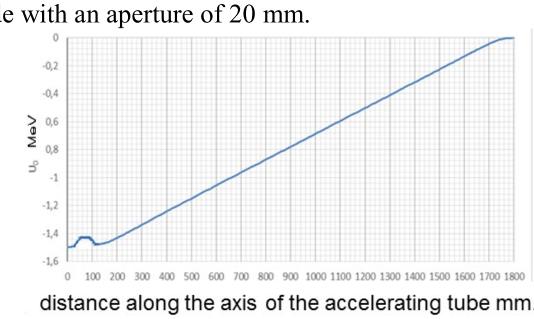

Figure 1: Distribution of potential along the axis of the accelerating tube.

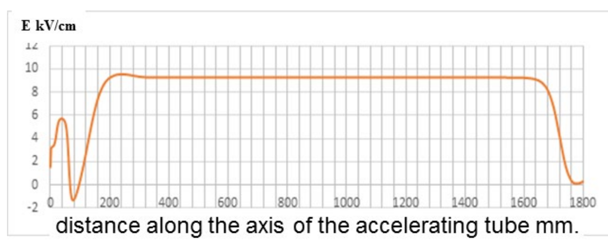

Figure 2: Distribution electric field along the axis of the accelerating tube.

The distribution of the electric field on the tube axis is uneven (see Fig. 2). With an increase the electric field, the beam is focused, and with a decrease the field, the beam is defocused. Three characteristic areas can be distinguished. The cathode is located at point 0. The first section is from 0 to 200 mm. In this section, the beam successively undergoes focusing, defocusing, and focusing. Integrally, this section is strongly focusing and has the greatest effect on the beam parameters at the tube exit. In the second section (200-1700 mm), the electric field is uniform and there is no focusing. In the third section - the tube exit - the electric field decreases to 0 and a defocusing lens is formed with a focal length of about 4 Ltr (where Ltr is the tube length), i.e. about 7 meters. Figure 3 shows the calculated beam envelopes for the optimal geometry of the electric field.

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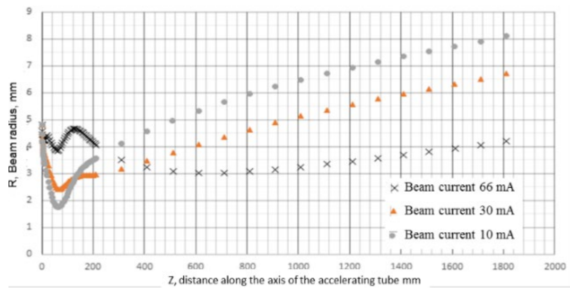

Figure 3: The envelopes for different beam currents at an energy of 1.5 MeV, the length of the accelerating tube is 1800 mm.

The beam current in ELV accelerators is regulated by changing the cathode temperature. The cathode is heated by a tungsten coil, since the spiral is a solenoid, then its magnetic field extends to the emitting tablet and beyond (see Fig. 4).

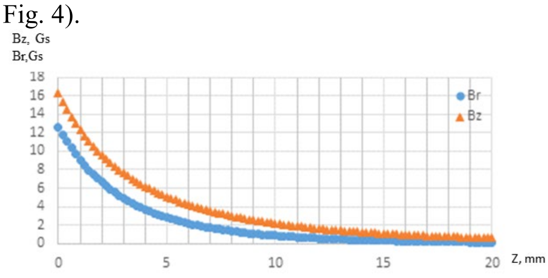

Figure 4: Electron injector heater coil magnetic field. Coordinate z = 0 corresponds to the emitting surface of the tablet.

Because of the magnetic field of the heating coil, the electron acquires an azimuthal momentum Pφ0 of about 4.4 G cm. With a trajectory radius of 5 mm, the angular momentum is obtained 2,2 Gs·cm^2.

$$\Delta r_{\min} = \frac{1}{2}\cdot F \cdot \frac{P_{\phi 0}\cdot r}{P_0} = 0.33mm \tag{1}$$

P_0 – momentum of electrons, F- is the focal length of the lens, $P_{\phi 0}\cdot r$ - is the angular momentum.

The minimum focused beam diameter Δr_{min} is approximately 0.3 mm.

Let us consider the effect of the emittance associated with the cathode temperature on the beam diameter in the plane of the diaphragm. The value of the temperature emittance:

$$\varepsilon_T = \frac{d_k\cdot\Delta P_k}{P_0} = d_k\cdot\alpha_k, (\alpha_k = \frac{\Delta P_k}{P_0}) \tag{2}$$

where d_k is the diameter of the cathode, ΔP_k is the spread of transverse momenta due to the temperature of the cathode, and P_0 is the final momentum of electrons. The divergence of the beam in the crossover at its total energy after the lens is equal to d_L/f_L; where d_L is the diameter of the beam at the entrance to the lens, and f_L is the focal length of the lens, therefore

$$d_{\min} = \frac{\varepsilon_T\cdot f_L}{d_L} = 0,05mm \tag{3}$$

With d_L = 10 mm, $f_л$= 180 mm and ε_T = 3 10^{-3} rad mm, we have $d_{min} \approx 0.05$ mm. This value is negligible.

The ripples of the accelerating voltage in this electron accelerator were initially assumed to be 5%. The energy ripple causes the focal length of the lens to change with the pulsation frequency, which leads to an increase in the beam diameter in the crossover.

$$d_{\min} = d_{lens}\frac{\Delta f}{f} \tag{4}$$

Where d_{min} is the minimum diameter of the focused beam cm, d_{lens} is the diameter of the beam at the entrance to the lens, which is 10 mm.

At an energy of 1.5 MeV, $\frac{\Delta f}{f} \approx \frac{\Delta U}{U}$ then, at an energy ripple of $5\cdot10^{-2}$, the effective beam diameter in the first diaphragm at the exit from the outlet will be ≈ 0.5 mm

The tube, which is located inside the high-voltage rectifier and the primary winding, is penetrated by a transverse magnetic field associated with the tilt or misalignment of the accelerating tube and the primary or secondary windings of the transformer. Its value can reach B⊥ = 0.2 G. This leads to the appearance of variable angles Δα at the exit from the accelerating tube

$$\Delta\alpha = \frac{B_\perp\cdot L_{tr}}{B\rho_0} = 5.5\cdot10^{-3} \tag{5}$$

Where is the transverse magnetic field of the primary winding, L_{tr} is the length of the accelerating tube, which is 1800 mm, B·ρ0 is the electron momentum, which is $6.5\cdot10^3$ G·cm for a beam energy of 1.5 MeV

$\Delta d_{min} = f_L\cdot\Delta\alpha$. Where f_L is the focal length of the lens 180 mm. In our case, the oscillations of the beam in the output diaphragm will be Δdmin ≈ $5\cdot10^{-3}\cdot18 = 9\cdot10^{-2}$ cm= 0,9 mm.

This increases the area of the opening in the diaphragm through which the gas passes.

If we sum up all the above effects, then the minimum beam size at the exit from the extraction device will be about 2 mm.

MEASUREMENT OF BEAM PARAMETRS

For a more accurate measurement of the beam parameters, a water-cooled diaphragm with a whole diameter of 16 mm was fabricated. The size was determined by touching the diaphragm with the beam at points located at opposite ends of the diaphragm opening. The magnitude of the current on the diaphragm was 10^{-3} of the total beam current. It was necessary to fix the currents of the deflecting (correcting) coils. They were preliminarily calibrated.

The results of measurements of the beam diameter with an energy of 1.5 MeV, at beam currents of 10, 30, 66 mA, and different currents of the focusing electromagnetic lens are shown in the graphs (see Fig. 5).

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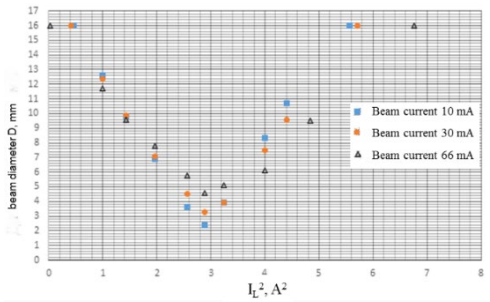

Figure 5: Dependence of the beam size in the diaphragm on the focusing lens current at an energy of 1.5 MeV.

Figure 6 shows a simple scheme that allows you to determine d_L from the dependence D_{beam} $(1/f_L)$, which is equivalent to the dependence D_{beam} (I_L^2) in Fig. 5.

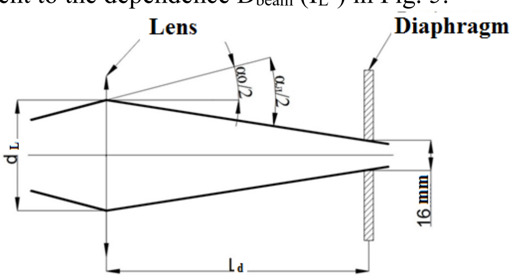

Figure 6: d_L is the diameter of the beam in the lens. D - measuring diaphragm with a hole diameter of 16 mm. D_{beam} is the beam diameter in the diaphragm, L_d is the distance from the lens to the diaphragm, which is 940 mm.

From the Fig. 6 shows that

$$D_{beam} = d_L - (\alpha_L - \alpha_0)\cdot L_Д \tag{6}$$

Where α_0 -is the angle of divergence or convergence of the beam at the entrance to the lens;

$\alpha_L = d_L/f_L$

Focal length of an electromagnetic lens

$$f_L = \frac{4(B\rho)^2}{I^2 \int B_{1A}^2 \cdot dl} \tag{7}$$

Bρ - electron momentum at the exit from the accelerating tube G·cm; I_L is the current of the electromagnetic lens A. $\int B_{1A}^2 dl$- integral of the magnetic field strength for an electromagnetic lens.

Since D_{beam} linearly depends on I_L^2, then from the slope of the curve D_{beam} (I_L^2) one can find d_L: taking the derivative with respect to I_L^2 from the right-hand side of formula (6).

$$d_L = \frac{\Delta(D_{beam})}{\Delta(I_L^2)} \frac{4(B\rho)^2}{(\int B_{1A}^2 \cdot dl)\cdot L_D} \tag{8}$$

From the same curve, as can be seen from (6), it is possible to find the divergence of the beam at the entrance to the lens. To do this, it is necessary to extrapolate the left side of the curve D_{beam} (I_L^2) to $D_{beam} = 0$.Then from (6)

$$\alpha_0 = d_L \frac{f_L - L_Д}{L_D \cdot f_L} \tag{9}$$

The beam diameter at the exit from the accelerating tube is d_L=9 mm. The divergence of the beam at the exit from the accelerating tube $\alpha_0 = 7\cdot 10^{-3}$ rad.

MAIN RESULTS

Based on the measurements carried out in the fall of 2018, a device was designed and manufactured for extraction a focused electron beam into the atmosphere from the ELV accelerator, which has a tube with a large aperture equal to 100 mm.

A general view of extraction device is shown on Fig. 7.

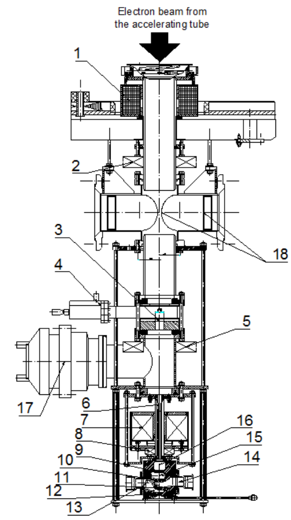

Figure 7: 1 - Upper lens L1; 2 - upper correctors C1; 3 - water-cooled diaphragm with a hole diameter of 7mm D6; 4- Gate valve; 5- average correctors C2; 6 - water-cooled diaphragm with a hole diameter of 10mm D5; 7 - Lower lens L2; 8- lower correctors C3; 9- diaphragm with a hole diameter of 4 mm D4; 10- diaphragm with a hole diameter of 3.5 mm D3: 11- diaphragm with a hole diameter of 2.5 mm D2; 12 - diaphragm with a hole diameter of 2mm; 13 - the first stage of pumping (pump AVZ-90); 14 - the second stage of pumping (pump AVZ-90); 15 - the third stage of pumping(pump RUTS ZJ-150+AVZ-20); 16 - fourth stage (turbomolecular pump NVT-450); 17 - fifth stage (turbomolecular pump NVT-450); 18 - sixth stage (two pumps NMD-0.4).

During the tests, stable operation was achieved at a beam power of 70 kW and a short-term operation at 100 kW. After long-term operation of the accelerator at a power of 50 kW, the diameters of the holes in the diaphragm did not change. Diaphragm hole diameter on the extraction device outlet has 2-2.5 mm.

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