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Extraction into the atmosphere of a focused beam with an energy of 2.5 MeV

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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 developed and preliminary tested, which makes it possible to effectively extract a focused electron beam into the atmosphere in the energy range from 1.4 to 2.5 MeV and a beam current of 30 mA.
Keywords: ELV, extraction device, electron beam, accelerator, particles.

1. Introduction

A device for extracting a focused electron beam into the atmosphere was developed at the Budker Institute of Nuclear Physics (BINP), Siberian Branch, Russian Academy of Sciences (SB RAS) in the mid-1970s. Several ELV-4 electron accelerators equipped with similar extraction devices were installed in the USSR. Such a device, which has the status of a unique scientific facility [1], has been operating at the ELV-6 accelerator of the INP for 30 years. This accelerator, as the previously manufactured ELVs, uses an accelerating tube with magnetic tracking of the beam. Permanent magnets are installed directly on the electrodes inside the accelerating tube. The design and manufacture of such accelerating tubes are fairly complex. Currently, ELV accelerators use easier-to-manufacture and more reliable accelerating tubes without magnetic tracking that have a large (10 cm) aperture. In view of the high reliability of these accelerating tubes and the complexity of the almost lost technology for making tubes with magnetic tracking, it was required to replace the accelerating tube with magnetic tracking in the focused beam extraction device by an accelerating tube with a large aperture without magnetic tracking. In addition, it was planned to significantly reduce the size of the extraction device. It was necessary to study the dynamics of the beam in an accelerating tube with a large aperture, choose the optical design of the extraction device and calculate pressure under differential pumping conditions.

2. Beam dynamic 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 filament coil (the beam acquires an azimuthal momentum $P_{\varphi 0}$);
3. The space charge of the beam;
4. The ripples of the accelerating voltage;
5. Aberrations of electromagnetic lenses. They also affect the optimal size of 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 diaphragms aperture.

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 [2].

3. Measurement of beam parameters

Experimental studies of the beam dynamics in an accelerating tube with a large aperture were carried out on the ELV-4 accelerator.

For a more accurate measurement of the beam parameters, a water-cooled 16 mm diaphragm was fabricated. The size was determined by touching with the electron beam at points located at opposite ends of the diaphragm aperture. 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.1).

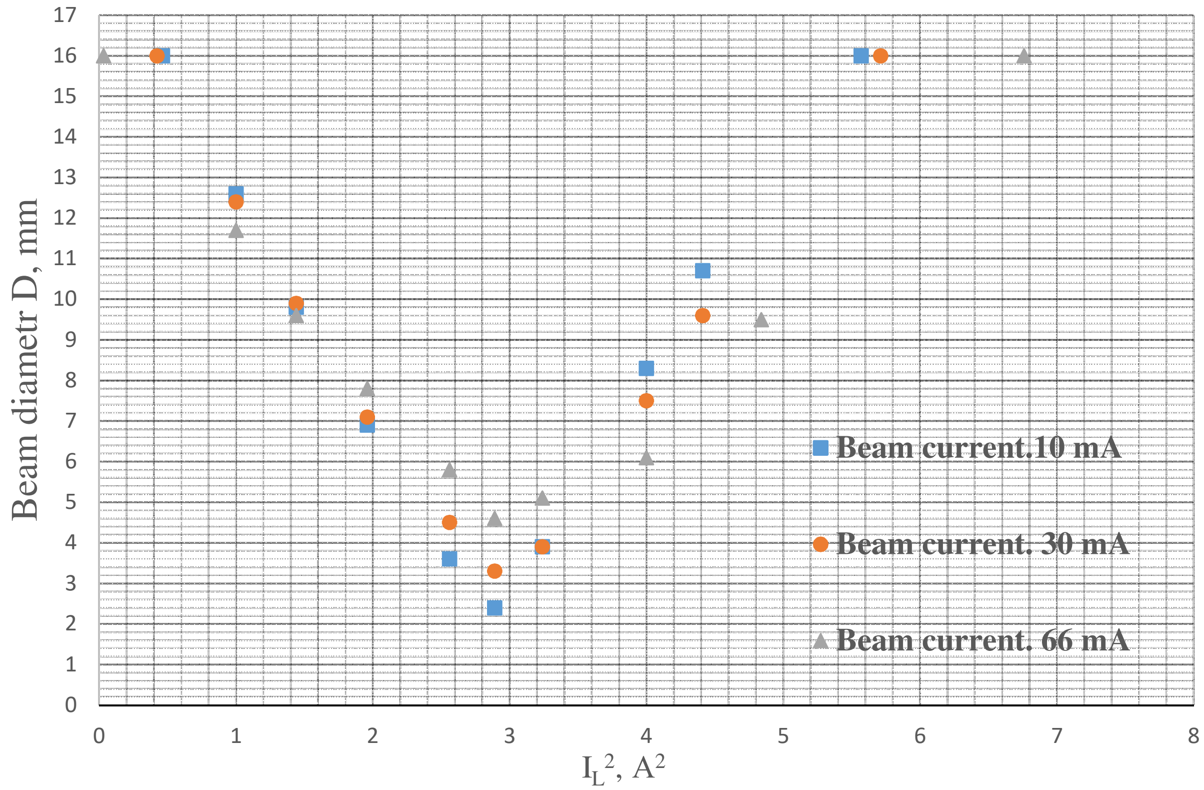

Fig.1. Dependence of the beam size in the diaphragm on the focusing lens current at an energy of 1.5 MeV.

Fig.2 shows a simple design that allows us 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.2.

From the Fig.2 shows that

$$D_{beam} = d_L - (\alpha_L - \alpha_0) \cdot L_D\,, \qquad (1)$$

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

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

where $B\rho$ – 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, normalized to a lens current of 1 A, i.e. at current 1 A.

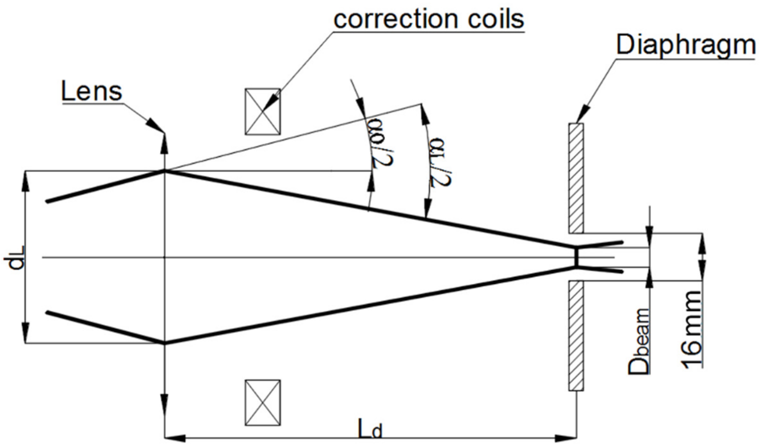

Fig.2. d_L is the diameter of the beam in the lens, D – measuring diaphragm with a hole diameter of 16 mm, D_{beam} is the measured beam diameter in the diaphragm, L_d is the distance from the lens to the diaphragm, which is 940 mm.

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 (1)

$$d_L = \frac{\Delta(D_{beam})}{\Delta(I_L^2)} \frac{4(B\rho)^2}{(\int B_{1A}^2 \cdot dl) \cdot L_D}. \tag{3}$$

From the same curve, as can be seen from (1), 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 (1)

$$\alpha_0 = d_L \frac{f_L - L_{Д}}{L_D \cdot f_L}. \tag{4}$$

After analyzing the experimental data using formulas (3) and (4), we have: $d_L = 9$ mm, $\alpha_0 = 7 \cdot 10^{-3}$ rad. The minimum beam diameter after passed the focusing lens was 2.5 mm.

3. Pressure calculation of extraction device with differential pumping

The designed pressure different in the section between the atmosphere and the fourth stage is approximately 10^5 i.e., the pressure in the fourth stage is $P_4 \approx 10^{-2}$ Torr. We will assume that the aperture diameter in the diaphragm D_1 through which air enters the box should be about 2.5 mm, and the flow of the gas $I_n \approx 10^3$ (l·Torr)/s. A diagram for the vacuum calculation of the pumping stages is given in Fig.3. In the first three stages, the gas flow is viscous, in the fourth stage, it is transitional, and in the fifth and sixth stages, it is molecular. The sixth stage is the accelerating tube in which the working pressure is 10^{-6} Torr (10^{-4} Pa). Since, for understanding the gas dynamics in the device, the calculation is simplified, jet effects and the effect of heating of the incoming gas by the electron beam are not considered in this paper. Furthermore, we will assume that the pressure in the evacuating pumps is much lower than the pressure in the pumping stage. The gas flow coming from the previous stage is removed by the evacuating pump, and only a small part of this flow enters the next stage.

We introduce the following notation: D_d^n (cm) is the aperture diameter in the n-th diaphragm, U_d^n (liter/s) is the conductivity of the n-th diaphragm (in the case of the viscous mode, $U_d^n = 16 \cdot (D_d^n)^2$), U_p^n (liter/s) is the conductivity of the pipeline of the n-th stage (in the section from the chamber to the pump) given by the formula $U_p^n = 181 \cdot (P^{n-1} + P^n)(d^n)^4/(2L^n)$ for the viscous mode and by the formula $U_p^n = 12.1(d^n{}_p)^2/L_p^n$ for the molecular mode, d^n (cm) is the diameter of the pipeline, L^n (cm) is the length of the pipeline in the section from the chamber of stage n to the pump, S^n (liter/s) is the pumping speed using the pump of the n-th stage, P^n (Torr) is the pressure in the n-th stage, P^n pump is the pressure at the pump inlet of the n-th stage, and I^n ((l·Torr)/s) is the gas flow rate to the n-th stage. For any stage, the flow rate of the gas coming through the aperture in the diaphragm D_d^n from the previous stage or from the environment at atmospheric pressure (to the first stage) is given by the formula $I^n = S^n(P^{n-1} - P^n) \approx S^nP^{n-1}$. The same gas flow is evacuated by the pump of this stage, in which the pressure is

$$P^n_{pump} = \frac{I^n}{S^n}. \tag{5}$$

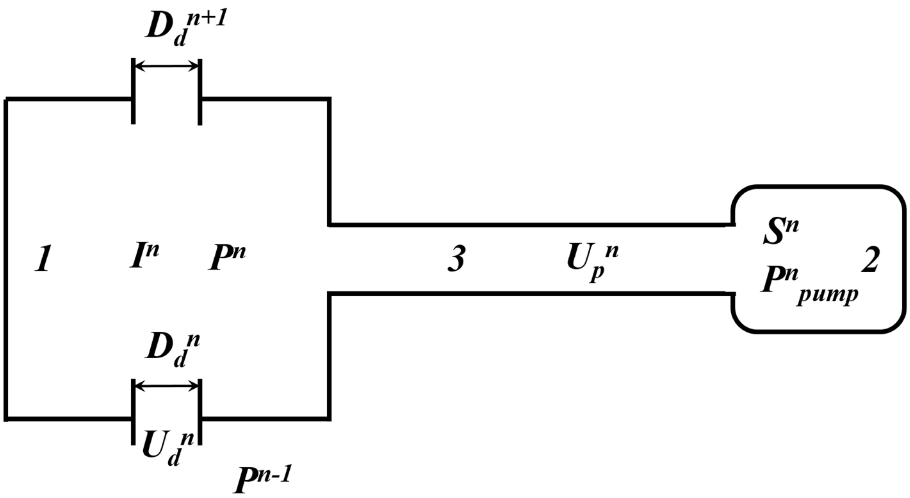

Fig.3. Diagram for the vacuum calculation of the differential pumping stages: *1* – chamber; *2* – pump; *3* – tube.

The pressure in the stage is determined from the formulas

$$P^n = \frac{I^n}{U_P^n} = \frac{U_d^n P^{n-1}}{U_P^n}, \tag{6}$$

$$P^{n+1} = \frac{U_d^{n+1}P^{n-1}}{U_p^{n+1}} = \frac{U_d^{n+1}U_d^n P^{n-1}}{U_p^n U_p^{n+1}}. \tag{7}$$

In particular, for the fourth stage we have

$$P^4 = P^0 \frac{U_d^1 U_d^2 U_d^3 U_d^4}{U_p^1 U_p^2 U_p^3 U_p^4}, \tag{8}$$

where P^0 is the gas pressure at the inlet of the first stage pump, i.e., P_{atm}. As stated above, this is true provided that the pressure in the pumps is significantly lower than the pressure in the evacuated stage and the gas flow between the stages is much less than the flow removed by the pump. The formulas for calculating the conductivity of diaphragms and pipelines vary with a change in both the gas flow mode and the diaphragm design. Therefore, formulas for the viscous gas flow mode are used for the first four stages, and formulas for the molecular gas flow mode for the fifth and sixth stages. The table shows the results of vacuum calculation of parameters for the pumping stages of the extraction device. Analysis of the results shows that the choice of pumps, the outlet size, and the parameters of the vacuum lines can be optimized. Real pressure values in the first, second, and third stages were measured at the pump inlet. In the fourth stage, pressure measurement is currently impossible because of the features of the design. In the sixth stage, the pressure in vacuum is determined from the supply current of the ion pumps (2 mA corresponds to 10^{-6} Torr; the data are taken from the specification of the NMD-0.4 ion pump).

Although the data given in the Table 1 are estimative, they can be used to confirm the correctness of the choice of the pumps and there parameters of the differential pumping system. The measured pump inlet pressures in the first and sixth stages are in good agreement with the calculated pressure at the pump inlet, which also confirms the correctness of the choice.

4. Main results

Based on the measurements carried out, 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.4.

Table 1. Results of vacuum calculation for the pumping stages of the parameters of the extraction device

Parameter name	Stage number *n*					
	1	2	3	4	5	6
Pump type	AVZ-90	AVZ-90	RUTS ZJ-150 +AVZ-20	TMN-450 +2NVR5DM	TMN-450 +2NVR5DM	Two NMD-0.4
Pump capacity S^n, l/s	90	90	150	450	450	400
Aperture diameter in the diaphragm D_d^n, mm	2.5	3.0	3.5	4.5	10.0	12.0
Length of the diaphragm L_d^n, mm	10	10	10	10	200	100
Conductivity of the diaphragm U_d^n, l/s	1.0	1.44	2.0	3.2	0.6	2.1
Gas flow through the diaphragm, I^n, (l·torr)/s	760	12	0.4	0.1	$2{\cdot}10^{-2}$	$6{\cdot}10^{-3}$
Length of the pipeline L_p, m	5.0	5.0	3.0	1.0	0.5	–
Diameter of the pipeline D_p, cm	10	10	6.3	6.3	10	–
Throughput of the pipeline U_p^n, l/s	18000	400	15	30	240	–
Calculated pressure at the stage inlet P^{n-1}, Torr	760	8.5	0.2	$3{\cdot}10^{-2}$	$2{\cdot}10^{-3}$	$8{\cdot}10^{-6}$
Calculated pressure in the stage P^n, Torr	8.5	0.2	$3{\cdot}10^{-2}$	$3{\cdot}10^{-3}$	$8{\cdot}10^{-6}$	$7.5{\cdot}^{10-7}$
Calculated pressure at the pump inlet P^n_{pump}, Torr	8.5	0.13	$3{\cdot}10^{-3}$	$2{\cdot}10^{-4}$	$4{\cdot}10^{-6}$	$7.5{\cdot}10^{-7}$
Measured pressure at the pump inlet $P^n_{pump,meas}$, Torr	10	1	0.4	Not measured	Not measured	10^{-6}

A device for extracting a high-energy electron beam into the atmosphere was designed and tested. In this device, the diaphragms are cooled due to their thermal expansion. The differential pumping system was adapted to the selected optoelectronic scheme of the device. The device was manufactured and installed on the ELV-6 accelerator equipped with a large aperture accelerating tube. During the tests of the accelerator with the new extraction device, stable operation was achieved at a beam power of 70 kW and short-term operation at a power of 100 kW. After long-term operation of the accelerator at a power of 50 kW, the aperture diameters in the diaphragms did not change.

In 2021, this extraction device was installed on the ELV-8 accelerator. During the tests, it was possible to release an electron beam in the energy range from 1.4 to 2.5 MeV, and with a current of up to 50 mA. During long-term operation, an electron beam with a power of 70 kW was produced, and a power of 100 kW was produced for a short time.

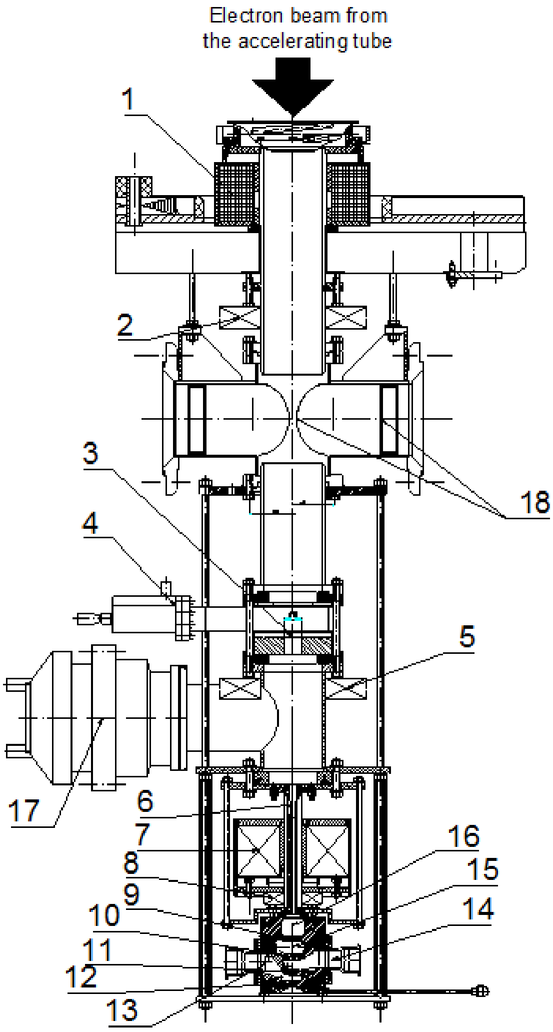

Fig.4. *1* – upper lens *L*1; *2* – upper correctors *C*1; *3* – water-cooled diaphragm with a hole diameter of 7 mm *D*6; *4* – gate valve; *5* – average correctors *C*2; *6* – water-cooled diaphragm with a hole diameter of 10 mm *D*5; *7* – lower lens *L*2; *8* – lower correctors *C*3; *9* – diaphragm with a hole diameter of 4 mm *D*4; *10* – diaphragm with a hole diameter of 3.5 mm *D*3: *11* – diaphragm with a hole diameter of 2.5 mm *D*2; *12* – diaphragm with a hole diameter of 2 mm; *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).

5. References

[1] ELV-6 accelerator, [online], https://ckp-rf.ru/catalog/usu/200984/

[2] Domarov E.V., Vorobev D.S., Golkovsky M.G., et al., *Sib. Fiz. Zh.*, **14**(2), 5, 2019; doi: 10.25205/2541-9447-2019-14-2-5-20