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ELV-15 – new accelerator for industrial applications

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Abstract. Budker Institute of Nuclear Physics produces high power electron beam accelerators for industrial application. A new "ELV-15" accelerator of the ELV type has recently been developed. With the energy range is up to 3.0 MeV and the beam power is up to 100 kW. Increasing the energy up to 3 MeV expands the possibilities of industrial application. It allows to increase the thickness of treated material and cable insulation.
Keywords: ELV, electron beam, accelerator, particles, industrial, irradiation.

1. Introduction

Budker Institute of Nuclear Physics in cooperation with Shanxi Yitaike Electrical Equipment produces high power electron beam accelerators for industrial application. These accelerators have the name "ELV". Flexible (because of the possibility of completing with different under beam systems) and reliable ELV accelerators found wide applications in industries. The family of the ELV accelerators covers the energy range from 0.3 to 3 MeV, and beam current up to 130 mA of beam current, with power up to 100 kW. Special versions of ELV accelerators allows to obtain 400 kW of power with a maximum beam current of 400 mA. Over 200 accelerators were delivered and installed by now. The design and operation principles of ELV type accelerators are well described in [1, 2].

1.1. ELV-15 electron beam accelerator

The development of a new accelerator, with the energy range is up to 3.0 MeV and the beam power is up to 100 kW, has recently been completed. The accelerator was named ELV-15. It has all features of ELV accelerators:

- high electron beam power in wide energy range;
- high efficiency of electron beam (75%), which important for long term operation;
- high stability of electron beam parameters.
- extra-long lifetime and high reliability – 24/7 mode of operation.

In Fig.1 high voltage power source of ELV-15 accelerator and ELV-8 for comparison are shown.

Features of the new high-voltage rectifier are:

- diameter and height of the primary winding were increased;
- the number of turns of the primary winding was increased;
- amount of rectifier sections (i.e. column height) was increased;
- it is possible to use two types of rectifier sections coils: standard and oversized, to work with accelerating tubes of various diameters.

Like an all previous ELV accelerators, a high-pressure vessel filled with SF_6 gas. Inside the vessel are located: a primary winding which comprising two parts, a high-voltage rectifier with an accelerating tube inside, a high-voltage electrode and an injector control unit inside them. Accelerating tube located inside the high-voltage rectifier column makes ELV accelerators the most compact among machines of their class. Elements of the vacuum and electron-optical system of the exhaust device are attached to the bottom of the vessel. Emitted electrons (by the cathode at the upper end of the accelerating tube) have a total energy at the exit from the accelerating tube. The beam current is determined by the cathode temperature. The injector control unit provides supply of the cathode filament.

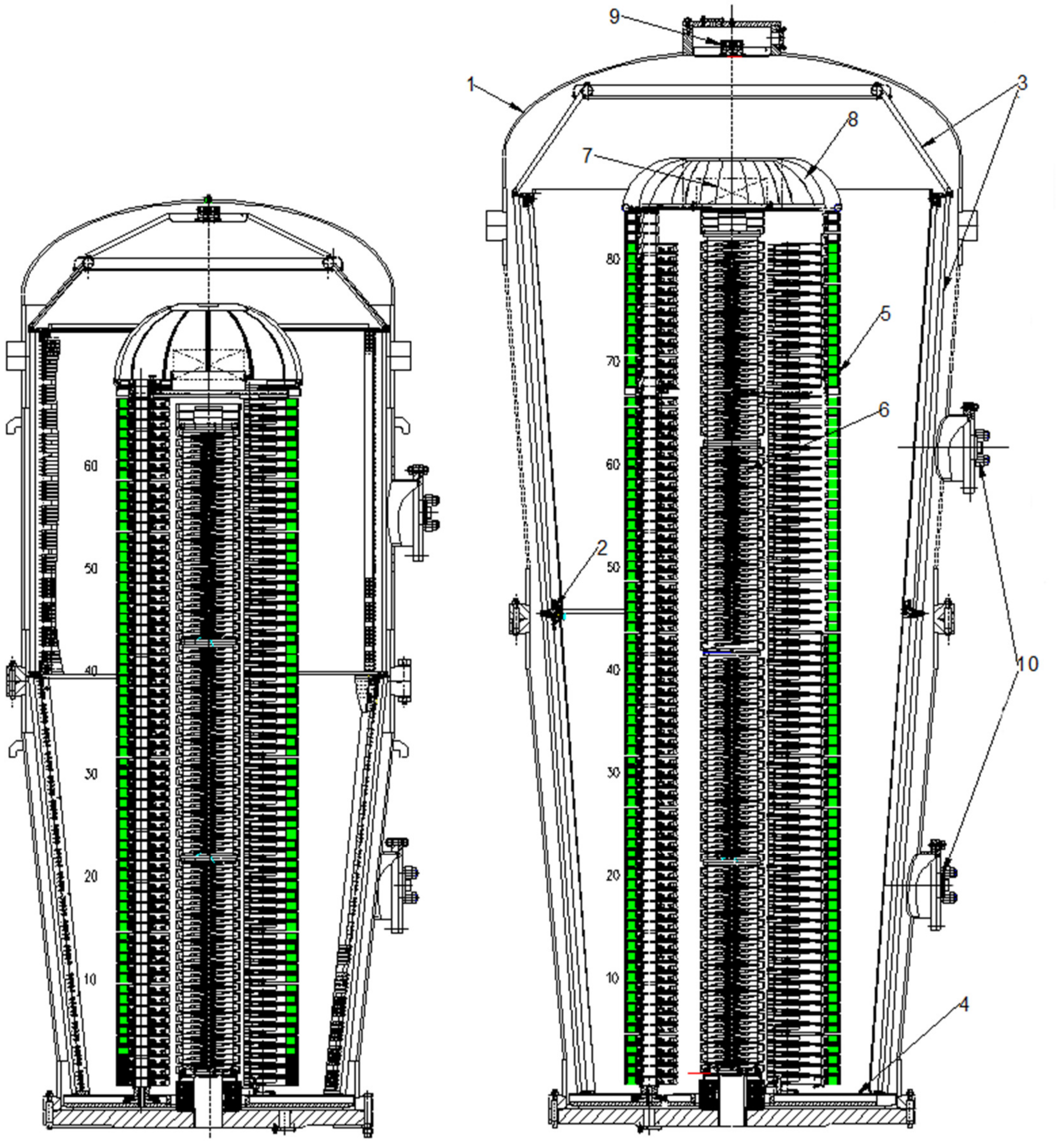

Fig.1. ELV-8 (left) and ELV-15 high voltage rectifiers. 1 – vessel; 2 – primary windings; 3,4 – magnetic circuits; 5 – rectifier sections; 6 – accelerating tube; 7 – injector control unit; 8 – high voltage electrode; 9 – rotary voltmeter with capacitance probe; 10 – primary winding terminals.

1.2. Accelerator parameters

Main parameters of ELV-15 accelerator are listed in Table 1.

Table 1. Main parameters

Maximum energy, MeV	3.0
Minimum energy, MeV	1.5
Maximum beam current, mA	50
Maximum power, kWt	100
Electrical efficiency, %	75
Energy ripples on maximum energy and power, %	<3

The low level of energy ripples are connected with a small beam current and high electron energy (high rectifier voltage).

2. Mechanical design

2.1. Accelerating tube

The accelerating tube consists of 4 pieces, standard for ELV accelerators, about 90 cm long. Each piece is a set of ceramic rings and stainless steel electrodes. Ceramic rings made of Al_2O_3 ceramics are connected to stainless electrodes using high-molecular PVA glue. The potential distribution over the electrodes is set using a divider of high-ohmic resistors. The divider current at maximum energy is 65 μA. At the maximum beam current, the change in the current of the tube divider (due to beam halo, scattering, etc...) does not exceed 1–2 μA. In this case, a 30 mA beam with no focusing passes through a 55 mm diaphragm, at a half meter from the tube outlet. For high currents, an electromagnetic lens is used, installed at the output of the accelerating tube.

2.2. Alignment

Since the height of the accelerating tube was increased to 3.6 m, the requirements on the geometry of the whole system increased accordingly. The height of the accelerator vessel with a high-voltage rectifier inside is 4.5 m, the allowable deviation of the axes is 20 mm. It can be caused by deviations of the vessel, primary winding, or inclination of the rectifier section column and accelerating tube. Aligning can be done by tilting the base of the primary winding, which is centered not only relative to the vessel axis but also relative to the accelerator axis (it need to note what when the base is skewed by 1 mm, the top of the primary is shifted by 5 mm). The position of the accelerating tube is determined by the installation of its neck on a bottom of the vessel. If it has an inclination, the axis of the tube will not align with the vessel axis. In this case, the primary winding is installed so that its axis is close to the accelerator tube axis on one side and the magnetic core (outside the primary winding) does not touch the vessel walls, on the other.

The column of rectifier sections is also installed as coaxially as possible with the accelerating tube and the primary winding. The inclination is created with the spacers installed between the supports of the sections. A total alignment tolerance between column and primary winding of 2 cm is acceptable. The shielding coefficient of the accelerating tube for the longitudinal component of the alternating magnetic field is 50, and for the transverse component it is 10. The field of the primary winding is about 50 G. When the axes are shifted by 2 cm, we have a longitudinal field of 1 G, and a transverse field of 0.03 G. The longitudinal component does not affect the beam dynamics, while the transverse component gives an angle of $8\cdot10^{-4}$ degrees, i.e. beam displacement at the tube exit is about 3 mm.

2.3. The high voltage rectifying column height and the accelerating tube height aligning

Electric potential of accelerating tube is linear grow from the bot tube to the top, same as the potential of high voltage rectifying column. These potentials actually are aligned to prevent discharges. But, in all ELV accelerators, a special potential distribution (by resistive divider) is set on the upper electrodes of the accelerating tube. This distribution determines the focusing of the beam and creates the shutter for secondary particles.

Potential in this area is growing much slower than the potential of the column and creates skew which can cause undesirable (even unacceptable) discharges. In order to eliminate the potential skew, the 3 upper sections of the rectifier are made “empty”, i.e. without coils. Table 2 shows the maximum skew values depending on the number of “empty” sections.

Table 2. Potential skew between accelerating tube and rectifying column

Empty sections, N	0	1	2	3	4
Skew, kV	150	125	100	75	50

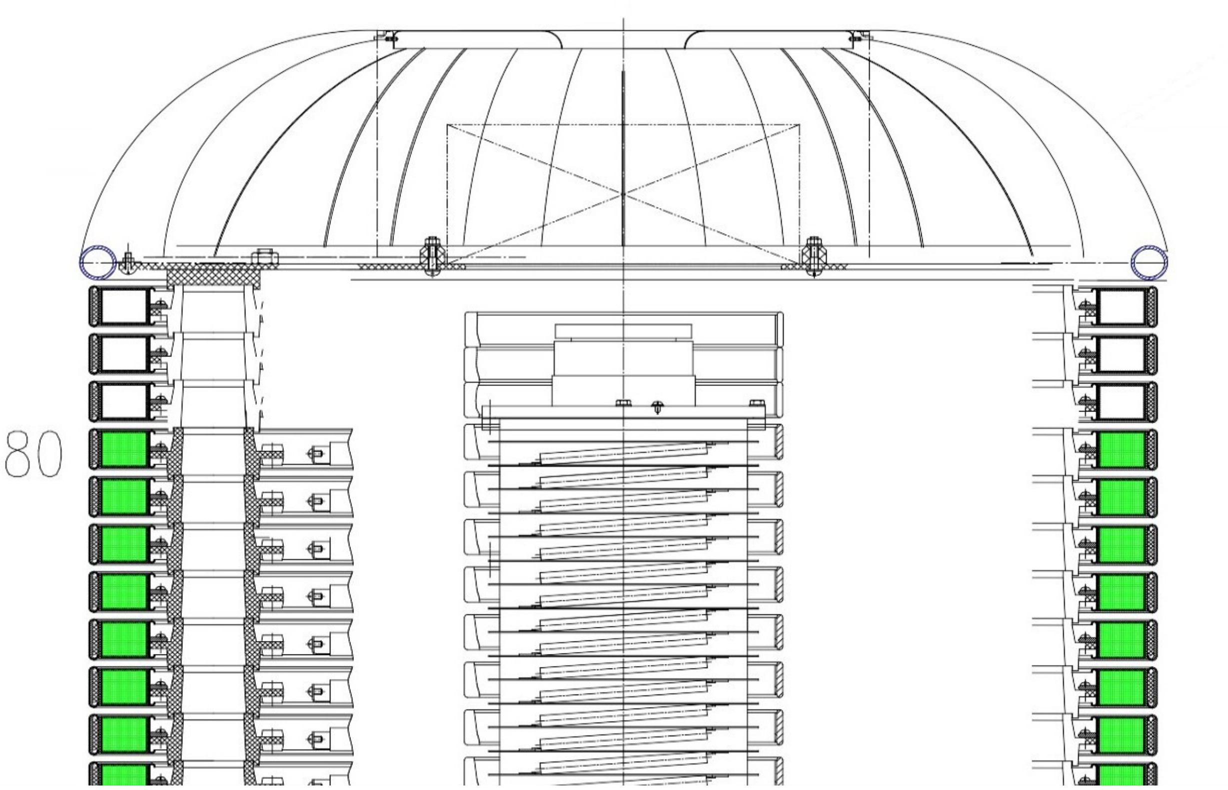

Fig.2. High voltage rectifier column with three "empty" sections on top.

We have chosen the option with three "empty" (Fig.2) sections when the skew is 75 kV. It should be noted that there are no empty sections in ordinary ELVs, and the skew value lies between 100–200 kV, depending on the accelerator model.

2.4. Extraction device

To extract the beam into the atmosphere, a standard ELV extraction device is used. X and Y beam shifters form a raster on a Ti-foil. For uniform filling of the foil, the ratio of scanning frequencies of X and Y shifters is made irrational. The thickness of the foil is 50 μm, and it is cooled by an air jet.

3. Electric field strength of high voltage rectifier

The geometry (symmetry) of the high-voltage rectifier is axial. Therefore, the SAM software was used, which makes it easy and correct to carry out electromagnetic calculations, especially for systems with axial symmetry. The maximum electric field strengths are 180 kV/cm for small diameter sections and 192 kV/cm for large diameter sections. The maximum field strength at the lower edge of the high voltage electrode, by the way this is common for all ELV rectifiers with the following explanation: breakdowns to the ground should occur from the upper end of the column, but not from the underlying sections. Finally, the maximum field strength in ELV-15 is even slightly lower than in ELV-8, which was used as the basis for designing ELV-15.

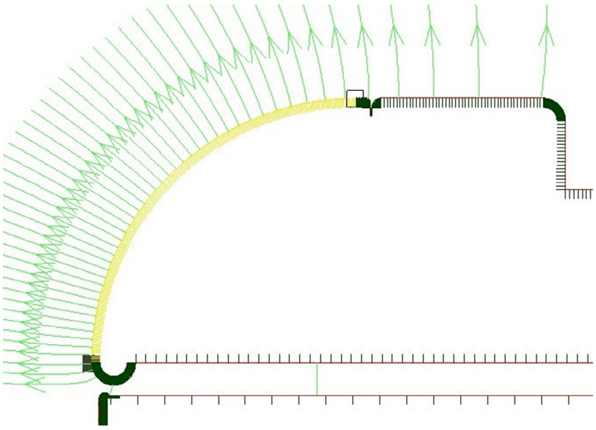

Fig.3. Electric filed strength at the high voltage electrode.

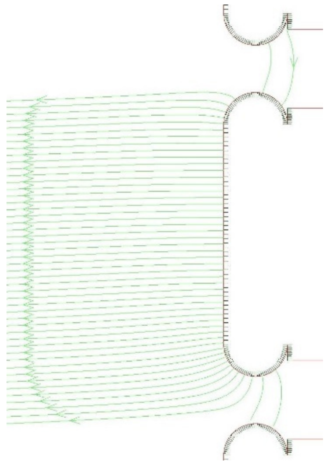

Fig.4. Electric filed strength at the screen of rectifying section.

4. Accelerating voltage measurement

To measure the accelerating voltage In ELV accelerators, with energies up to 1.5 MeV, a high-voltage resistors divider is used. If the accelerating voltage of the ELV accelerator exceeds 1.5 MV, then a rotary voltmeter [4] is used. The following parameters are monitored during the operation of the accelerator: input voltage and current of the primary winding, current of the frequency converter, voltage of the first section, current of the tube divider. These parameters allow you to control the correctness of the measurements of the rotary voltmeter and the status of the high-voltage rectifier during operation. The initial calibration is done with a precision 200 kV resistive divider and then checked for system linearity. Upon delivery to the customer, the energy is checked either by beam absorption in Al plates or by film dosimeters. Note that the above input data of the accelerator suffices to set the readings of the rotary voltmeter and monitoring the correctness of the rectifier with an accuracy of several percent.

5. Ionization current in the high voltage gas gap

The inert gas SF_6 is used as insulation in the accelerator's high-voltage rectifier. Bremsstrahlung appears during the operation of the accelerator with an electron beam; therefore, a in the high-voltage gap appears current because of the ionization of the SF_6 gas. At an energy of 3 MeV, the bremsstrahlung yield is the highest (among ELV accelerators). On ELV-15, the magnitude of this current was measured. The value of the ionization current was determined by the constant current component of the capacitive sensor, which is a copper plate mounted on the housing of the rotary voltmeter. The ionization current is proportional to the beam current. For a capacitive sensor area of 430 cm^2 and a beam current of 30 mA, the ionization current is 0.17 μA, current density 0.4 nA/cm^2. We can arise two questions: "How does this affect the readings of the rotary voltmeter?" and "Is there any destruction of the SF_6 gas with the formation of aggressive products?"

The plate area of the rotary voltmeter is 15 cm^2, i.e. the average value of the ionization current per plate will be 6 nA. On the measuring capacitance, the voltage of this signal has both components: constant and variable. The constant component is separated by an isolation capacitor, and the variable is shifted by 90° relative to the charging current. Therefore, we get "0" at the output of the synchronous detector of the rotary voltmeter. Thus, the ionization current does not affect the measurements of the rotary voltmeter. Note that there is also no influence of the corona current on the rotary voltmeter. The value of the considered current is an order of magnitude smaller than the value calculated from the dose rate. The bremsstrahlung dose rate in the high-voltage gap is determined by the radiation collimation by the elements of the scanning system, the diaphragm, the vacuum shutter, the tube electrodes, the tube flange, and the distance as $1/R^2$. An approximate estimate for an energy of 3 MeV and a total current of 30 mA gives the dose rate in the gap 3 Gy/h = 30 Rad/h. Thus, the total number of pairs of ions in a cylinder with SF_6 gas with a capacitive sensor cross section (430 cm^2) and a length of 40 cm at a pressure of 10 bar of SF_6 gas will be $2 \cdot 10^{13}$. If we assume that there is no recombination, then the current would be $3 \cdot 10^{-6}$ A = 3 µA. In reality, the current to the capacitive sensor is twenty times less – 0.17 µA. Thus, recombination is about 95%. Assuming that destruction is proportional to the dose rate, we find that is $6 \cdot 10^{-6}$ %/s or 7% per year. And if we proceed from the value of the ionization current, then the losses in the high-voltage gap will be 0.3% per year. Thus, the decomposition of SF_6 gas is negligible. Note that this applies only to the area of the high-voltage electrode, where there is a high dose rate, in other places the dose rate is ten times less and the integral losses are negligible. The operation of the ELV-8 accelerators, which have a maximum energy of 2.5 MeV and a current of 40 mA, does not show deterioration in the quality of the SF6 gas and does not require its replacement for many years.

6. Conclusion

ELV-15 proved to be a good and reliable accelerator. The creation of such a machine increased the model range and expanded the areas of possible application of ELV accelerators. At present, 3 such accelerators have already been delivered to customers, and the first one was delivered in August 2021, assembled and launched in December 2021.

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