Accelerators of ELV-type

Status, development, applications

In the work presented here the parameters of powerful electron accelerators of continuous action are given and the main systems of the accelerator and a wide set of supplementary devices extending the application range of the accelerator is given and some directions of further development are noted.

1.1 Main parameters of ELV accelerators

Beginning from 1971, the Budker Institute of Nuclear Physics Siberian Branch of Russian Academy of Science (SB RAS) started its activity in the development and manufacturing of electron accelerators of the ELV-type for their use in the industrial and research radiation-technological installations. The ELV-type accelerators are designed with use of the unified systems and units enabling thus to adapt them to the specific requirements of the customer by the main parameters such as the energy range, beam power, length of extraction window, etc. The design and schematic solutions provide the long term and round-the -clock operation of accelerators under the conditions of industrial production processes. The specific features of the ELV-accelerators are the simplicity of design, convenience and ease in control and reliability in operation. INP proposes a series of electron accelerators of the ELV-type covering the energy range from 0.2 to 2.5 MeV with a beam of accelerated electrons of up to 200 mA and maximum power of up to 160 kW. By now, over 70 accelerators had been delivered inside our country and abroad and the total operation time exceeds 500 accelerato-years. Basic parameters of the ELV-type accelerators are given below:

	Energy range, MeV	Beam power, kW	Max. beam current, mA
ELV-mini	0.2 - 0.4	20	50
ELV-0.5	0.4 - 0.7	25	40
ELV-1	0.4 - 0.8	25	40
ELV-2	0.8 - 1.5	20	25
ELV-3	0.5 - 0.7	50	100
ELV-4	1.0 - 1.5	50	100
ELV-6	0.8 - 1.2	100	100
ELV-8	1.0 - 2.5	90	50
ELV-6M	0.75 - 0.95	160	200
Torch	0.5 - 0.8	500	800
ELV-12	0.6 - 1.0	400	400

1.2 Design

General view of the ELV-type accelerator with a foil extraction is given in Fig.2. Inside the tank filled with the SF_6 gas are located: primary winding, high voltage rectifier with a built-in accelerating tube, high voltage electrode and the injector control unit. Just the location of the accelerating tube inside the column of high voltage rectifier makes the ELV-accelerators the most compact among the devices of this class. The vacuum system components and extraction device are fixed to the bottom of the tank. Electrons emitted by the cathode, placed on the upper end of the accelerating tube, have the total energy eU_0 on the output of the accelerating tube. Passing through the vacuum system they reach the extraction device where they are homogeneously distributed along the foil by the scanning electromagnets and then extracted into air. The irradiated material is transported under the frame of the extraction window. Fig.1 shows the overall dimensions for the ELV-type accelerators. A simplified electric circuit of the accelerator is given in Fig.3. The horizontal version of the ELV-4 accelerator is given in Fig.4. The transportable version of the ELV-6 accelerator is given in Fig.5.

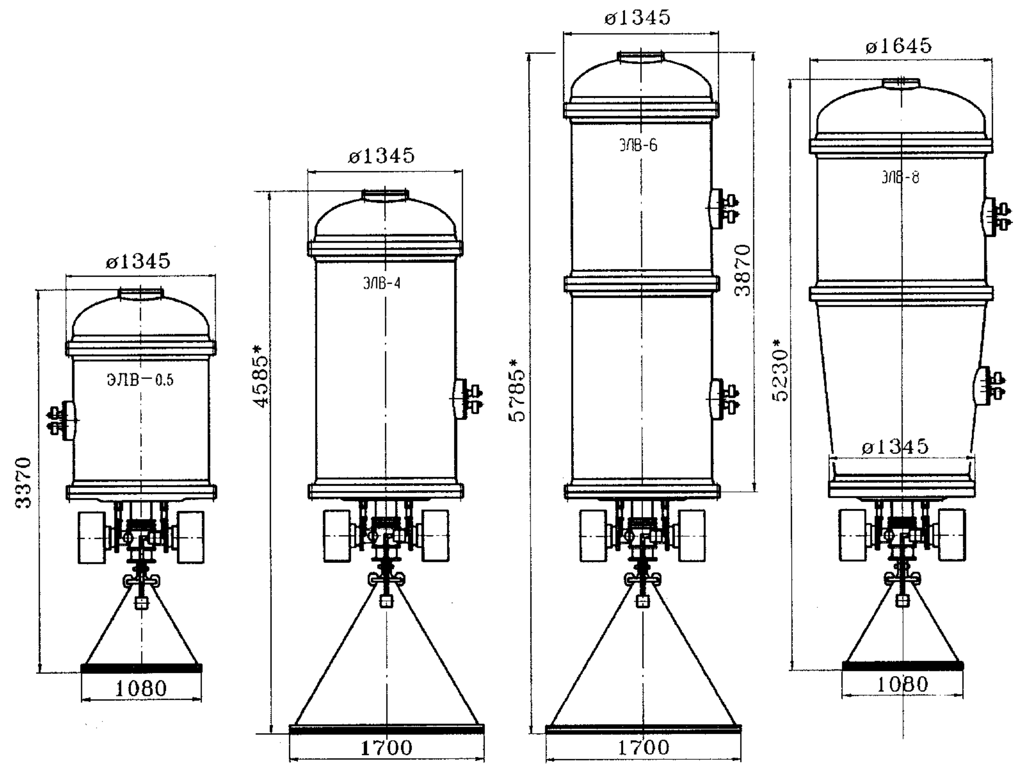


Figure 1: Overall dimensions of ELV-type accelerators

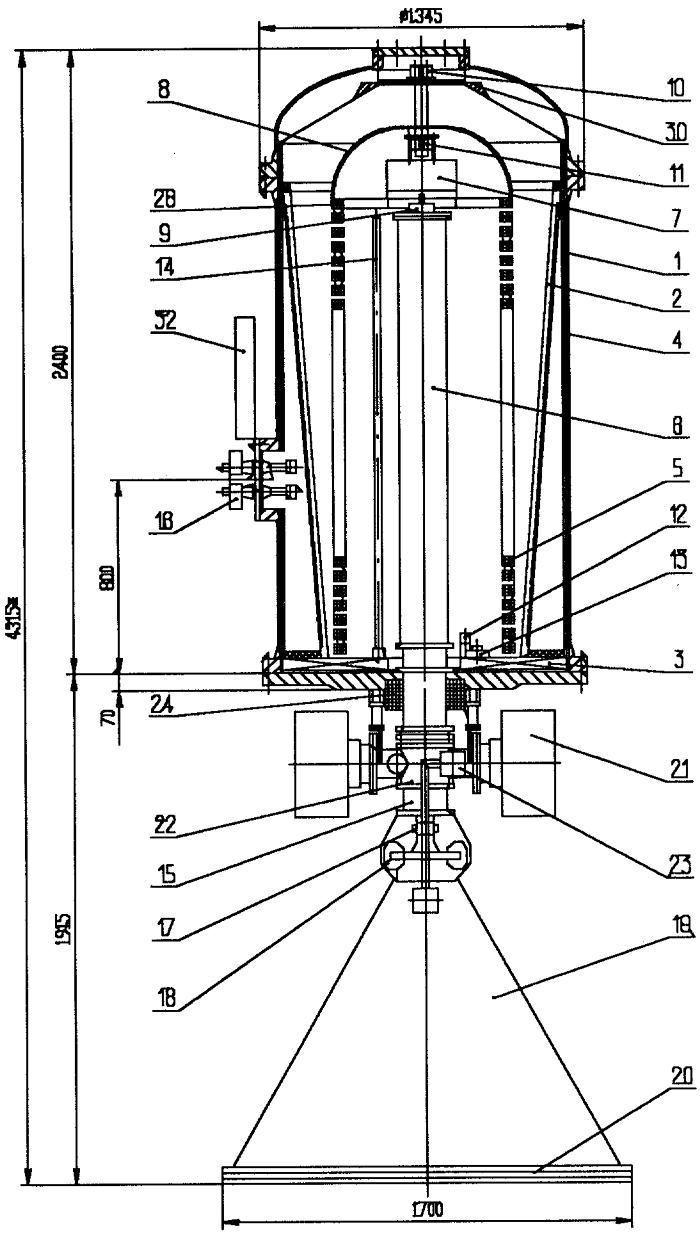


Figure 2: General view of ELV-4 accelerator. *1 - vessel, 2 - primary winding; 3,4 - magnitoguides; 5 - rectifier sections; 6 - accelerating tube; 7 - injector control unit; 8 - high voltage electrode; 9 - injector; 10,11 - optical channels for injector control; 12 - section divider; 13 - capacitor unit; 14 - energy divider; 15 - vacuum gate; 16 - primary winding terminals; 17,18 - scanning coils; 19 - extraction device; 20 - extraction window frame; 21 - vacuum pumps; 22 - cross head; 23 - vacuum gate; 28 - base of high voltage electrode; 29 - magnetic lens; 30 - high voltage shield; 32 - clamp set*

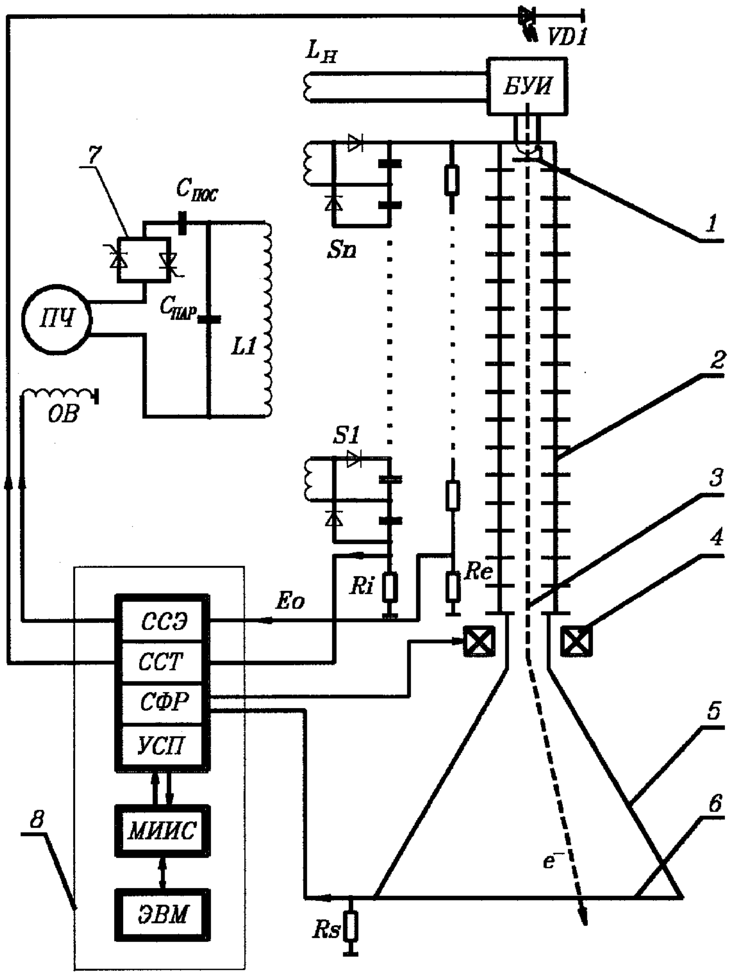


Figure 3: Simplified electric circuit of ELV accelerator. *1 - cathode of electron gun; 2 - accelerating tube; 3 - electron beam; 4 - coils of the raster formation system; 5 - extraction device; 6 - titanium foil; 7 - thyrister switch; 8 - control system (ESS-energy stabilizing system, CSS- current stabilizing system, RFS-raster formation system, MIMS-module information-measuring system, CC-Control Computer, PSCS-power supply control system). FC - frequency converter, ICU-injector control unit*

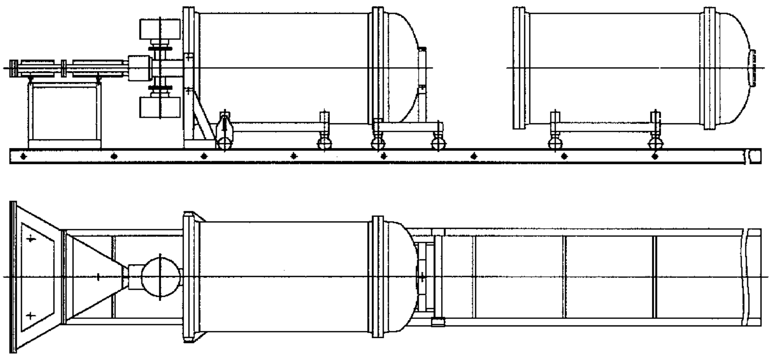


Figure 4: ELV-4 accelerator. Horizontal version. On the basis of this version the ion implanter has been developed at the Institute

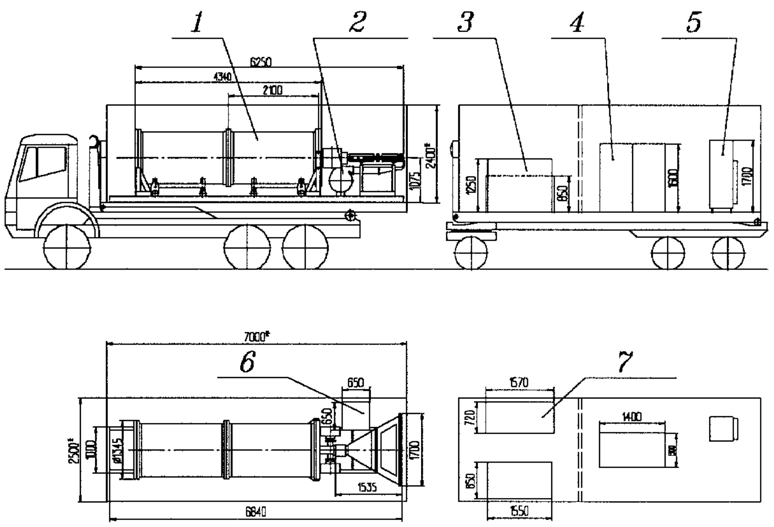


Figure 5: Transportable version of the ELV-6 accelerator. *1 - accelerator; 2 - foil cooling system; 6 - vacuum system; 7 - frequency converter*

Unfortunately, this project had not been yet realized by the number of reasons of no technical origin.

1.3 High voltage rectifier

The source of high voltage is a cascade generator with a parallel inductive coupling. The rectifier section column is installed inside the primary winding. The electric circuit of the section is given in Fig.6. The coil of secondary winding has 3000 turns and maximum voltage induced on its ends is 20 kV. This voltage is rectified by the voltage doubling scheme. Thus, the output voltage of the rectifying section is 40 kV. The rectifying sections are connected either in series (Fig.6a) or in series-parallel (Fig.6b).

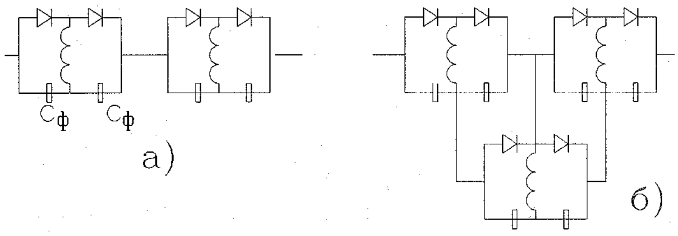


Figure 6: ELV rectifying section circuit and ways of their connection

The rectifiers with the series connection of sections are of higher voltage and those with the series-parallel connection are of higher current. The rectifier section column is terminated with the high voltage electrode inside of which there is the injector control unit and a special coil for its power supply.

Note, that compared to the "conventional" transformers in our design there is no central magnetic guide. This circumstance simplifies substantially the high voltage source design does not practically influence on the operational characteristics of the rectifier because of successful design of the primary winding and by the presence of the high quality of the energy stabilizing system and also due to quite low turn voltage (6 V/turn). The transformer specific power in the ELV-type accelerators is about 40 kW/m. The use of the low inductive capacitors K-15-10, original scheme of intrasection connections, and the presence of damping resistances provides the reliable protection of components of high voltage rectifier against of overvoltages during break-downs both of vacuum and gas insulation. Generally specking, the break-down in the ELV-type accelerator is exceptionally rare event, however during the design of accelerator (and this principle is always followed) we assumed that even a great number of break-downs (hundreds and thousands) should not lead to the damage of the high voltage rectifier. The practice proved the high reliability of the high voltage rectifier. The only reason of the high voltage rectifier malfunctions are malfunctions of capacitors K-15-10 caused by the microcharges. Therefore, the preliminary selection of capacitors enables the substantial increase in the rectifier reliability.

1.4 Accelerating tube

The general view of accelerating tube is shown in Fig.7. The channel aperture is 100 mm. This provides good vacuum conditions in the cathode region and consequently, its large lifetime.

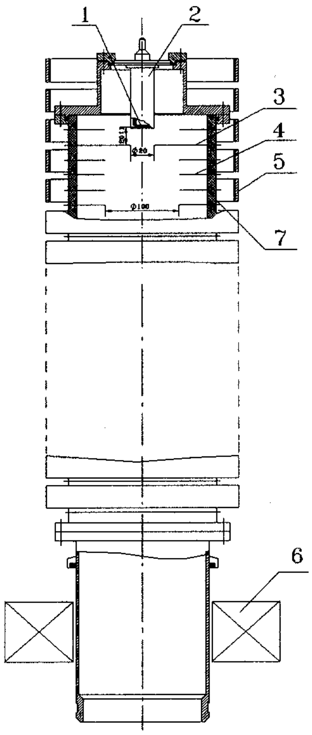


Figure 7: General view of accelerating tube:

1 - cathode,
2 - cathode heater,
3,4 - electrodes,
5 - shielding rings,
6 - magnetic lens,
7 -ceramic

The outer diameter of the insulator is 205 mm, its inner diameter is 180 mm. Step on electrode is 21 mm. The 20 mm ceramic rings UF-46 are connected to electrodes either with the high molecular glue PVA or with the thermodiffusional welding. In order to avoid the influence of alternate magnetic field, the tube is shielded by the short-circuited copper rings. The shielding of the transverse component of the magnetic field a few layers of transformer iron are placed inside the rings. The potential distribution among the electrodes is produced by the highohmic divider. The typical current value of the tube divider is up to 50 mkA.

The voltage distribution is homogeneous except for the upper part where the resistor value is determined by the conditions of the maximum electric strength of a tube (particle focusing on the tube output). The divider resistors are fixed directly on the electrodes. The maximum operation gradient in the tube is 10 kV/cm, however for the regimes of the long-term and round-the-clock operation its value does not exceed 8 kV/cm. Due to this circumstance there is no vacuum break-downs in accelerating tubes. The cathode in the form of the LaB_6 tablet of either 6 or 10 mm in diameter has indirect heating. For the injector heating the power of about 50 W is required. The beam current value is controlled by the cathode temperature, i.e. the gun operated in the regime of the full emission current take-off. To this end, the injector control unit is envisaged which is located under high potential inside the high voltage electrode and the beam current stabilizing unit placed in the control cabinet. The beam current stabilizing system provides its stability on the level no worse than $\pm$ 0.3 mA that does not exceed 1 % of the maximum beam current value. For the lossless passing of the beam through the vacuum system and extraction device, the magnetic lens is installed on the lower end of the accelerating tube. The lens current value is regulated automatically without an operator in case of the energy change.

1.5 Vacuum system

An operational vacuum in the accelerating tube is provided by 2 magneto-discharge pumps of capacity 400 l/s each. The preliminary start is provided by the fore-vacuum aggregate AVZ-20 with a nitrogen trap. As a rule, this aggregate is only used at the first start after opening the vacuum system (assembly, cathode or filter replacement). Further, at normal operation, the intervals in operation of up to 2 days do not require the forevacuum pumping for the start of magnetodischarge pumps. In the design of the vacuum system the quite simple and technological rubber seals are used thereby the operation vacuum value is limited by the level of $10^{-}4$ -$10^{-}5$ Pa. This vacuum level is quite acceptable since the cathode lifetime is not reduced; particle scattering on the residual gas is of the order $10^{-}6$ of the beam current, i.e. the particle flux to the tube electrodes is insignificant, therefore its electric strength does not reduce during the operation with a beam.

The vacuum value is measured by the current of magnetodischarge pumps. The blocking system is a two-step one: at vacuum 5×10^{-4} Pa, the warning signal for the operator is sent to the terminal and at vacuum 10-3 Pa the accelerator is deenergized. The vacuum gate (pos.15 in Fig.2) enables the cathode replacement with no loss of vacuum in the extraction device or on the contrary - the foil replacement without loss of vacuum in the accelerating tube corespondly.

1.6 Extraction device with a foil window

The schematic diagram of the device designed for the beam extraction into air through the foil is given in Fig.8. An electron beam is scanned over the foil in two mutually perpendicular directions with the use of two electromagnets. The scanning frequencies have the ratio 251/15. Due to this, there is no overlapping of beam trajectories and the foil is filled completely. The beam of low frequency is scanned along the foil and the beam of high frequency is scanned across the foil. The scanning frequency along the foil is about of 50 Hz, if there is no special technological requirements. The maximum deflection angle of a beam is 30^o .

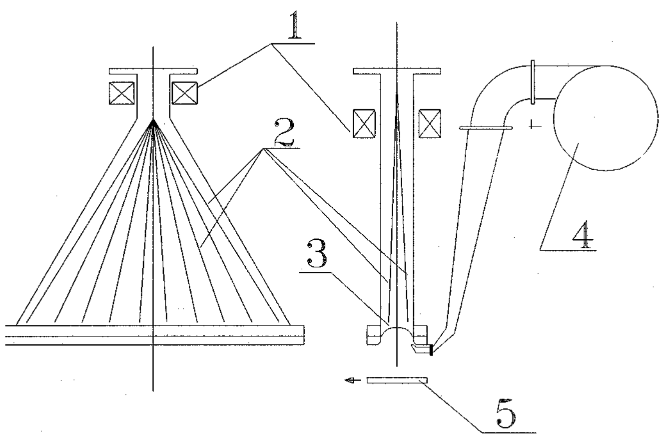


Figure 8: Schematic diagram of extraction device with a foil window. *1 - scanning electromagnets, 2 - beam trajectories; 3 - foil of extraction window; 4 - foil cooling fan; 5 - movable target*

The foil is cooled with an air jet. To this end, the high pressure fan is used with the preliminary rate of the jet of 180-200 km/h. At this rate, an average density of current on the foil does not exceed 100 mkA/cm^2, i. e. maximum extracting current value is 70 mA/m. This is approximately twice as smaller as the maximum admissible value for the current density on the foil for this jet rate. This double reserve of current density throughout the foil makes its lifetime practically limitless. Fig.9 shows the distribution of the linear destiny of a current at a distance of 50 mm from the frame of extraction window. The leaner density of current is a part of the beam measured by the long probe installed across the extraction window. The value of the absorbed dose in the irradiated material is proportional namely to this parameter. Usually, we guarantee an inhomogeneity of the current linear density of no worse than $\pm$ 10 % at a distance no more than 50 mm with the 90 % use of the beam current. The current loss on the distribution tails are caused by the electron scattering on the extraction window foil an in air.

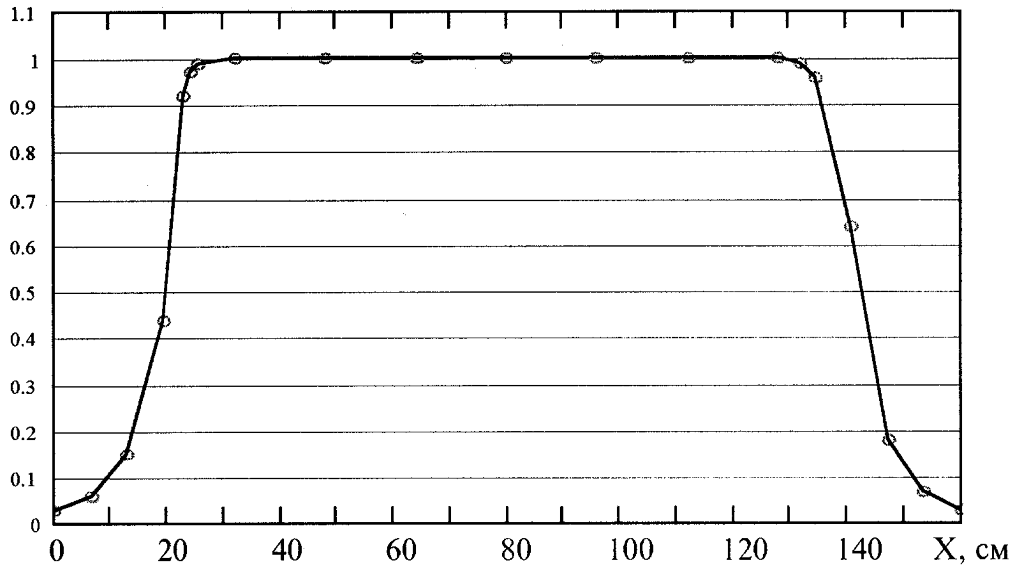


Figure 9: Typical distribution of current linear density under the frame of extraction window at an energy of electrons of 1.5 MeV

1.7 Two-window extraction device

As already mentioned above, the maximum current extracted through the foil window is 70 mA/m. The use of radiation technologies in the large scale industrial production (flue gas treatment of HES, metallurgy; waste water treatment, etc.) require an increase in accelerator power up to a few hundred kilowatts. The electron beam optimum energy for the majority of these application lies within the range of 0.7-1.5 MeV. Therefore, in order to achieve the required power one has to extract into air an electron beam with a current of few hundred mA at quite low current density, i.e. the extraction window area should be enlarged. The use of support grids in the given range of energies is not reasonable since their transparency is 80-90 %. In case of the use of the single window, its width is determined by the mechanical strength of the foil and it does not exceed 7 $\div$ 10 cm. Therefore, it was decided to develop a new extraction device with two extraction foils enabling thus to expand the extraction window area twice with no substantial change in the device overall dimensions. The new extraction device (Fig.10 a, b) has been developed

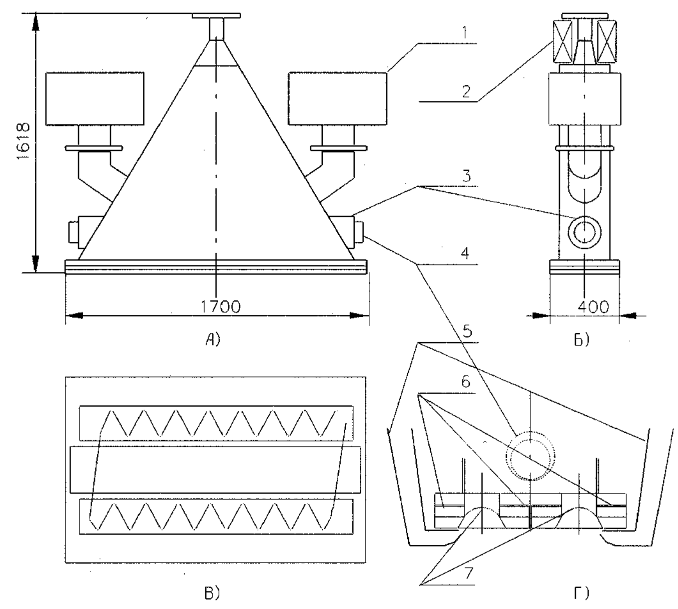


Figure 10: Two-window extraction device: *1 - magnetodischarge pumps, 2 - coils and cores of the beam scanning system, 3 - protection cylinder flange, 4 - protection cylinder, foil blow, 5 - air jet cooling, 6 - frame for fixation of foil, 7 -extraction foils.*

on the basis of the existing design with a length of extraction window of 1600 mm.

Two parallel foils are used in the device. An approximate trajectory of beam movement is shown in Fig.10c. The beam scanning both along and across the window is produced with the help of standard deflecting magnets with the frequency scanning ratio of 15/251. The beam is transported from one to another window with the reswitching magnet. The transport moments are synchronized with the scanning frequency along the foil in such a way that the change of beam current polarity in the reswitching magnet is made at achieving the maximum deflection (on the window ends). For the protection of the foil fixing and its seals against the direct action of a beam during the beam transport the water cooled cylinder is installed (Fig.10 d) which is also the component of the rigidity of construction. Two additional magnetodischarge pumps are installed for better vacuum. They pump directly from the extraction device.

The diaphragm on the extraction device input is an element of vacuum resistance. As a result, the simple system of differential pumping was produced and the accelerating tube vacuum at the operation with a beam is $2 \div 3$ times better than that in the extraction device. At the beam current of 200 mA and an energy of 0.8 MeV the accelerating tube vacuum is 1-2 $\times 10^{-4}$ Pa. Thus, the high beam current does not influence on the vacuum conditions of the accelerating tube. In the process of the development and adjustment of the extraction device two major problems had to be solved:

• to provide a sufficiently short time of the beam transport from one to another window;

• to correct an inhomogeneity of the transverse deflection of a beam along the window caused by the difference in lengths of the beam path from the deflection point to the foil surface and also by the influence of edge focusing of the longitudinal deflection magnet i.e. to compensate for the raster distortion of the "sabre" type.

The minimum time for beam transport is determined by the wall thickness of the extraction device since the reswitching magnet is installed on the outer side of the extraction device and also by the coil inductance of the reswitching magnet. With the wall thickness of stainless mouth of 3 mm the minimum time for changing field polarity of reswitching magnet is about 0.25 ms which provides the beam loss on the level of 3 %.

The correction of raster distortion is produced by giving the required shape of current in the coils of reswitching magnet. The power source of the reswitching magnet is computer controlled with a special circuit on the base of the programmable DAC made in the CAMAC standard. The control of the beam transport system is fully automated and produced by the standard computer in framework of the accelerator general control program.

An electron beam with current of 200 mA at energies of 750-800 keV is extracted with the use of this extraction device. This device was tested in the stand. Long operation of this device is planned on the pilot-industrial plant.

1.8 Control system

The control system for the industrial accelerator determines its operation characteristics such as its reliability, continuous operation, repair fitness, level of personnel qualification. The operator of technological installation is communicated with the accelerator through the computer. The accelerator control system comprises a set of the software and hardware covering all the accelerator units required an operative control and diagnostics. The multifunctional control system enables one:

• to make the automated control of the accelerator. Algorithms introduced into the accelerator control program, solve the problems of the preparation of the accelerator to its operation (speed-up of frequency converter, switch on of the foil blow motor, switch scannings and if necessary, technological equipment), watch the status of blockings and after switching on of the accelerator and install an energy and current of an electron beam in the given regime;

• to stabilize safely the main parameters of an electron beam (electron energy, beam current, size and position of the raster on the foil of the extraction window) which provides the high quality of radiation treatment;

• to provide the continuous diagnostics of the high voltage rectifier and selftesting of the other accelerator systems during the operation of accelerator;

• to synchronize the accelerator operation and technological equipment; in this case, the operation of accelerator integrated into technological line in completely automated regime is possible;

• provides for the personnel a wide choice of commands for the regimes of testing and adjusting the accelerator to be preliminary issued.

Fig.3 shows the functional diagram of the ELV accelerator connections with the control system. The high voltage rectifier column which consists of the connected in series rectifying sections S1 ... Sn through the primary winding L1 takes the power from the frequency converter FC. The high voltage is measured with the help of the energy resistive divider and signal E0 is applied to the input of the energy stabilizing system ESS. The control action proportional to the difference between the requested and real energy is applied to the excitation winding EW of the frequency converter FC. A long time instability of an energy is in the range of 1-2 %.

A positive output of the high voltage rectifier is connected with the "ground" through the current measuring resistor R1. The measuring signal of rectifier current I0 is applied to the input of the current stabilizing system CSS. The error signal from the output of the system through the optical connection line controls the output voltage of the injector control unit ICU applying the current into the heater of the cathode indirect filament.

The beam current control by the filament current regulation increases the cathode lifetime since in this mode, the heater uses the minimum current. The beam current instability lies witching the limits of 1 % of its maximum value. The raster formation system coil 4 (see Fig.3) scans the beam along the foil of extraction window 6. The raster formation system provides the power supply of these coils by the saw tooth current, power supply of the lens, automatic correction of the position (centering) of beam raster on the extraction foil, de-energizing the accelerator if the scanning current or lens current values decrease lower than an admissible value. The raster centering on the foil is made by the beam position stabilizer. The beam position signal is formed by an analog treatment of the beam sediment signal (lower than 1 % of the full current) to the walls of the extraction device measured with the resistor RS . If the raster is not centered on the foil the beam position stabilizer applies the correcting current into the corresponding correction coil. All these three systems (ESS, CSS, RFS) added with the control system of the power supply PSCS make the lower level of the control system - the level of the end control units. All the control commands for giving of modes, etc. are formed on the next level of the control system: the module informatio-measuring system MIMS. The CAMAC section comprising the required set of measuring and control modules either specialized for the ELV accelerators control station made on the base of microprocessor is used as the module information-measuring system. The station comprises the 64-channel input and output registers, 12-bit ADC with 64-channel analog multiplexer on the input, 16 12-bit DAC. On the 3rd upper level of the control system there is the control computer loaded with packet of specialized software. The software of the accelerator control system provides a friendly interface with the user through the system of dynamic menus, text and graphic visualisation of the accelerator operation run.

1.9 Power supply

The power supply of the primary winding of the accelerator is provided by the frequency of 400 HZ from the frequency converter. By now, the rotary frequency converters were used which were attractive by the low price, simplicity, and reliability. The only deficiency of these machines is quite low efficiency (65-80 % depending on power). The attempts are made now to replace them by the static frequency converters (both the thyrister and transistor types). In this case, the total efficiency is expected to increase up to 85 % for the machines of up to 100 kW and up to 92 % for more powerful accelerators.

The thyrister key is designed for the fast (<10 ms) de-energizing the accelerator in case of emergency as: the vacuum or gas insulation break-down, decrease in currents of scanning and lens, foil cooling stop.

All the operative reswitching in the power supply is made by the control program automatically without actions of operator.

1.10 Devices for extraction into air of the concentrated electron beam

When extracting an electron beam into air through the foil the maximum current density does not exceed 100 mkA/cm^2 . However, a number of the beam technologies require higher current densities. To this end, the devices for the extraction of the concentrated electron beam into air are developed. The electron beam current density on the output of these devices may reach 10 A/cm^2 and power density - 10 MW/cm^2. The beam is extracted through the system of holes in diaphragms. The holes are fired by the beam and their diameters are within the limits of 1-2 mm. The operation vacuum in the accelerating tube is provided by the continuously operating by the pumps of differential pumping. Two versions of accelerators with this kind of extraction device were developed.

In the first one the beam is focused by two magnetic lenses. This version is used in the ELV-6 accelerator with maximum power of 100 kW at an energy of 1.5 MeV. The schematic diagram of the extraction device is given in Fig.11. Its operation is briefly described below. An electron beam after the accelerating tube is focused by the magnetic lens. In the lens crossover the diaphragm is placed. Further, an expanded beam reaches the second lens with smaller focus length. In the lens crossover two diaphragms are located. The gas filling through the holes in diaphragms is evacuated with the vacuum pumps. The maximum value of the extracted beam current is limited by the ripplings of accelerating voltage which lead to an increase of holes in diaphragms and admissible on the level of 2-3 %. The ELV-2, ELV-3, ELV-4 and ELV-6 accelerators can be equipped with the described device for the extraction of focused electron beam.

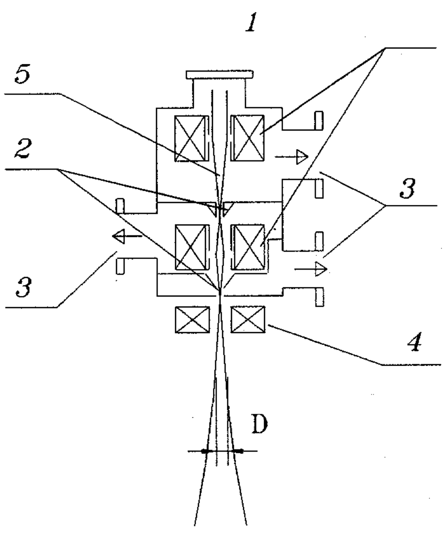


figure11:

Schematic diagram of extraction device:

1 - magnetic lens.
2 - diaphragms,
3 - vacuum lines,
4 - scanning magnets
5 - beam envelope

For the experiments where there is no requirements to the maximum high densities of power, the device is equipped by magnets for scanning in two mutually perpendicular directions. In this case, the beam is deflected in air. The system of scanning enables also to provide the required configuration of a dose field (Fig.12) according to the technology requirements.

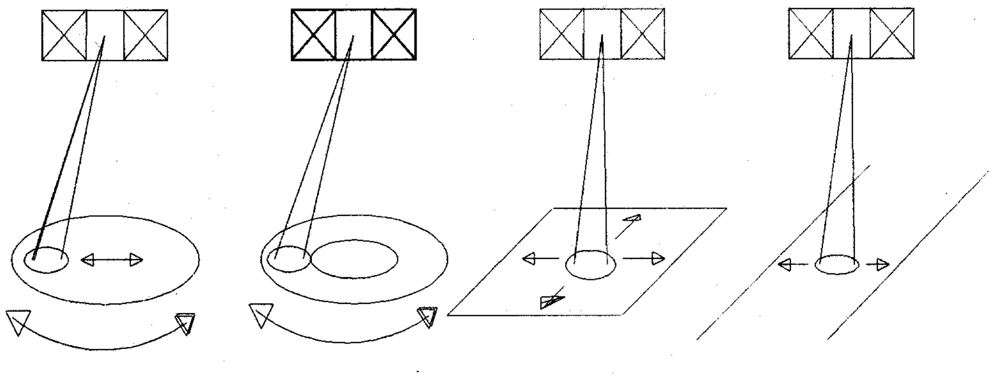


Figure 12: Possible configurations of irradiation fields

Another way to decrease the beam diameter in the output diaphragms is the beam compression by the adiabatically increasing longitudinal magnetic field. This method is used in the 500 kW power TORCH accelerator. The main advantage of an adiabatic compression - low sensitivity of beam size to changes of electron energy which is especially important during the development of accelerators of a power of a few hundred kilowatts where the problem of ripplings and instabilities of an accelerating voltage is quite vital. The accelerating tube and extraction device are placed on the same axis and the magnetic field smoothly increases from 100 G on the cathode to 10000 G in the region of output diaphragms. In this case, the beam size decreases inversely proportionally to the square root of the magnetic field value The longitudinal magnetic field is produced with the system of solenoids and coils. For the increase of the field value just in the region of the output diaphragms the steel concentrator is used. The schematic diagram of the extraction device of this type is given in Fig.13. The power consumed by the magnetic system is 50 kW. The vacuum system consists of the diaphragms and tubes of the high vacuum resistance and it is built-in into the magnetic system. Fig.13 shows the magnetic and vacuum systems of the accelerator.

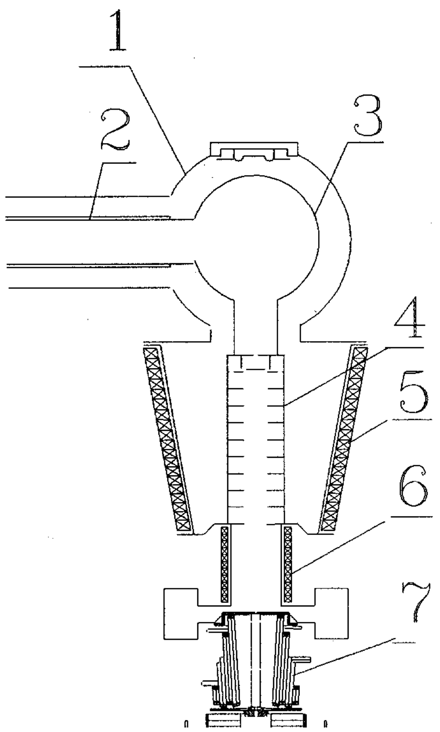
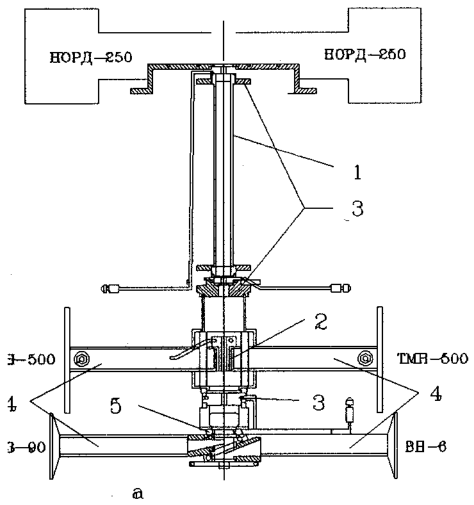


Figure13:

Device for the extraction into air of an adiabatically compressed intense electron beam:
1-tank,
2-high voltage gas feeder connecting the device with the source of an accelerating voltage,
3-high voltage electrode inside of which the components of the injector power supply system are placed, 4-accelerating tube,
5, 6-solenoids producing an increasing longitudinal magnetic field,
7-coils of magnetic system with the built-in system of the differential pumping



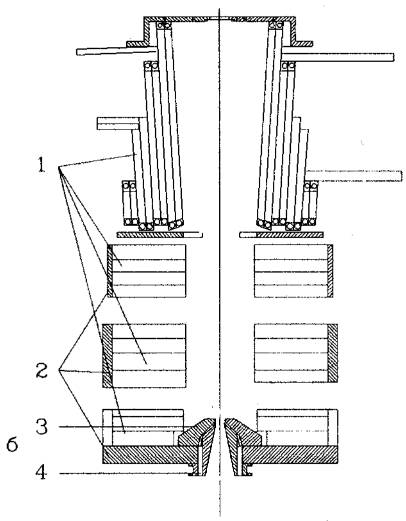


Figure 13: Vacuum system of an extraction device with an adiabatic compression of a beam. (*1,2-tubes of high vacuum resistance, 3, 5-diaphragms, 4 - vacuum lines*)

Figure 13b: - Magnetic system of extraction device.
1-coils, 2-magnetoguides, 3-concentrator, 4-cooling shield

At the first sight, it seems that the efficiency of the described extraction device is lower in comparison with the device where the beam is extracted into air through the foil. However the electron energy loss in 50 mkm Ti foil was 35 kW and in addition, a small fraction of the beam current (1-2 %) reaches the walls of the extraction device. This leads to that, if a 1 A beam would be extracted into air through the foil, the beam powerloss would be of 50 kW, i.e. even at a current of 1 A the efficiency of the device with an adiabatic beam compression is not lower than that of the foil extraction device. With an increase of the beam current the losses during the extraction through the foil increase proportionally to the current value and in the device with an adiabatic compression they remain constant. The maximum extracted current value was 0.8 A.

1.11 System of circulator and two-side irradiation

In order to extend the technological capabilities of accelerators, the systems of two-side and circular irradiation are being developed and manufactured which provide an efficient use of the beam extracted into air through the foil for the irradiation of the cables and tubes of diameter of up to 60 mm as well as for a two-side irradiation of bands of width up to 300 mm. Electrons extracted through the foil, under the action of bending magnets, changes their motion and make the whole irradiation of the subject as is shown in Fig.14.

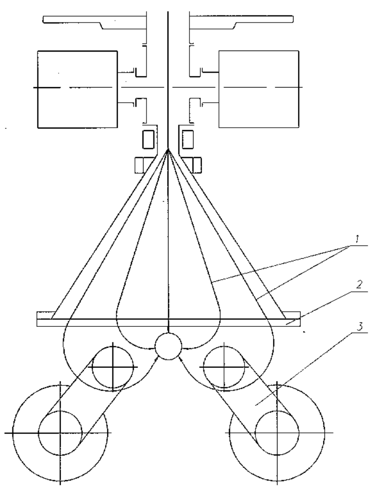


Figure 14: System of Circular Irradiation. *1-electron trajectory, 2-extraction window, 3-bending magnets*

The device for a two-side irradiation is operated similarly. The systems are efficiently operated at an electron energy over 1.2 MeV. At low energies their are also operable, however the beam utilization factor is reduced because of electron scattering in the foil and air. The system is supplied as a supplementary equipment to the typical machine and it is easy installed and removed at the replacement of technology.

1.12 Transport system

The Budker Institute of Nuclear Physics (BINP), Novosibirsk delivers the under-beam equipment for the irradiation of films, cables, and pipes. Fig.15 shows the transport system enabling the oneor two-side irradiation of the cable or pipes. The system can operate either in the autonomous regime or it can be accelerator controlled or it can control the accelerator.

The main parameters of the system are the following:
- drawing rate 0.1 - 400 m/min;
- diameter of cable or pipe 1 - 15 mm;
- power consumption 2.5 kW.

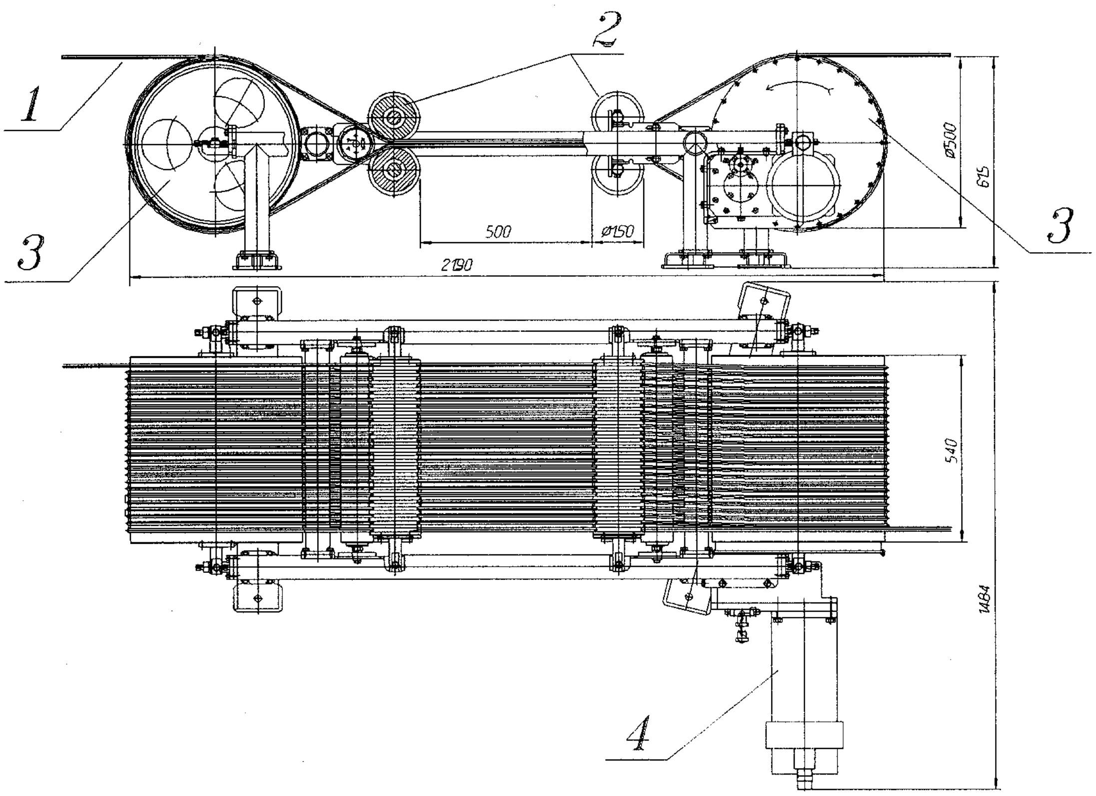


Figure 15: General view of the transport device. *1 - an irradiated object; 2 - guiding rolls; 3 - drums; 4 - drive*

1.13 Accelerators with the local radiation protection

The accelerators whose energies do not exceed 1.0 MeV can have the local radiation protection. Fig.16, 17 show the accelerators ELV-mini and ELV-0.5 with the local protection. Naturally that the presence of the radiation protection reduces the area required for the accelerators and reduces the capital investments in the majority of cases. However, the overall dimensions, weight of the protection and specific features of its design are determined not only by the accelerator dimensions but also by the dimensions of the under-the beam equipment. Therefore, the problem of whether the use of the local protection is reasonable requires the complex approach. Nevertheless, note that the experience enables us to design and construct the local radiation protection practically for any electron-beam technological process.

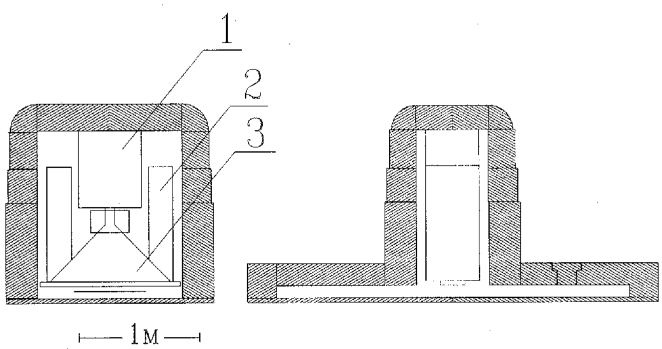


Figure 16: Local protection of the ELV-mini accelerator. 1 - accelerator, 2 - vacuum pumps, 3 - extraction device.

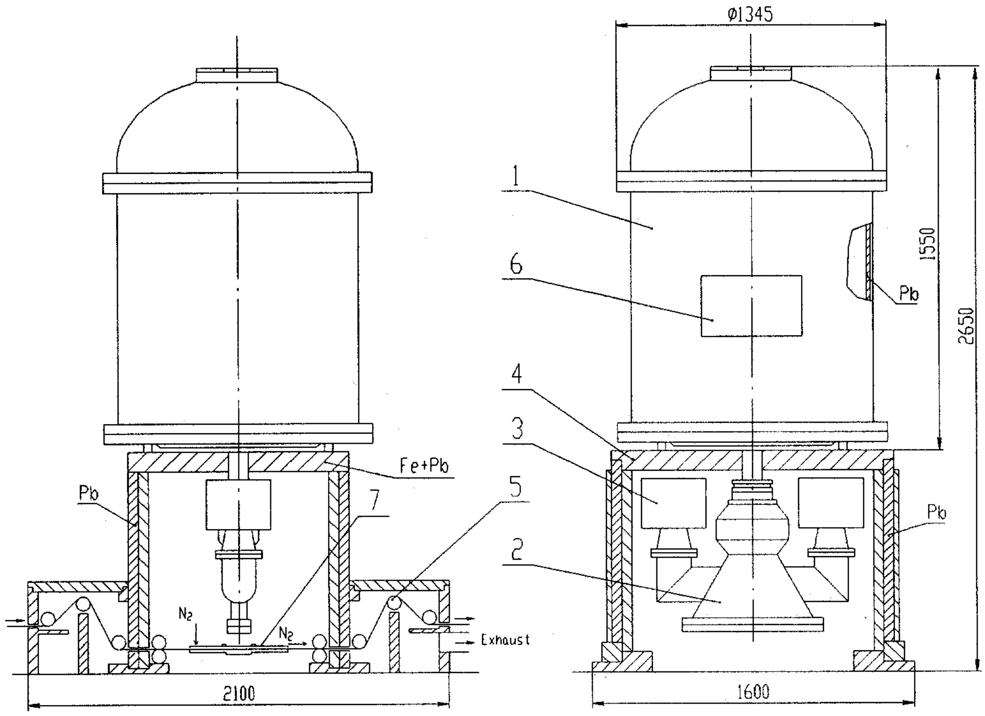


Figure 17: ELV-0.5 accelerator in local radiation protection.*1 - tank, 2 - extraction device, 3 - vacuum pumps, 4 - elements of protection, 5 - conveyer, 6 - admission of control and power supply cables, nitrogen chamber (for the processes required the irradiation in the inert medium)*

1.14 Accelerators with a power of extracted beam of a few hundred kilowatts

The accelerators available have the power mainly of up to 100 kW and cannot satisfy the need of power-intensive radiation technologies (mainly ecological) where the accelerators are required with total electron beam power of units and tens of megawatts. For the manufacturing of such complexes the modules of the unit power of hundreds kilowatts as a minimum are required.

At the Budker INP, a new generation of high voltage accelerators is being developed with the required power of an extracted beam. The representatives of a new family of accelerators are the ELV-6M with an energy of 0.75-1.0 MeV and the power of 160 kW; the "TORCH" accelerator with an energy of 0.5-0.8 MeV at a power of 500 kW , and the ELV-12 accelerator of a power of 400 kW at an energy of 0.6 $\div$ 1.0 MeV.

The ELV-6M accelerator

The schematic diagram of the ELV-6M accelerator is given in Fig.18a. It resembles the ELV-6 accelerator where two rectifying columns operate in parallel to the common load The columns are locate vertically one over another. The accelerating tube is placed in the lower column. Each of the columns consists of 38 rectifying sections connected in series-parallel as is shown in Fig.18b. Note, that the similar connection diagram admits the operation with no filter capacitors in the rectifying section as is shown in Fig.18.

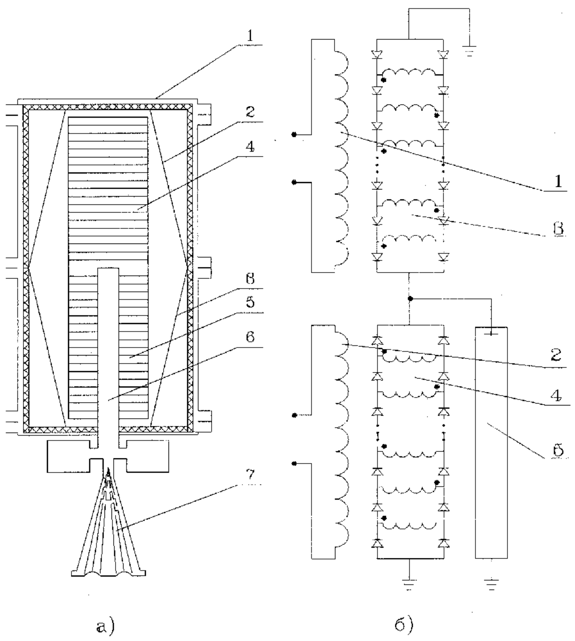


Figure 18: Schematic diagram of the ELV-6M .

Figure 18: Electric circuit of the ELV-6M: *1 - tank; 2,3 - primary windings; 4,5 - columns of rectifying sections; 6 - accelerating tube; 7 - extraction device.*

In this accelerator a new scheme of power supply for the primary windings of the accelerators is used: the windings are connected to different phases of a three-phase frequency converter and the output voltages of each column have the phase shift. This provides an additional smoothing of ripplings of the output voltage. The two-window extraction device for the extraction into air of beam currents of up to 200 mA has been specially developed for this accelerator and it was tested on the same accelerator. The accelerator has been manufactured and tested successfully. Upon the completion of the development of the pilot installation for the electron-beam purification of gases it will be delivered to the Slavyansk HES.

"Torch" accelerator

In the "Torch" accelerator, the high voltage rectifier is placed in a separate tank and it is connected with a accelerating tube through the gas feeder.

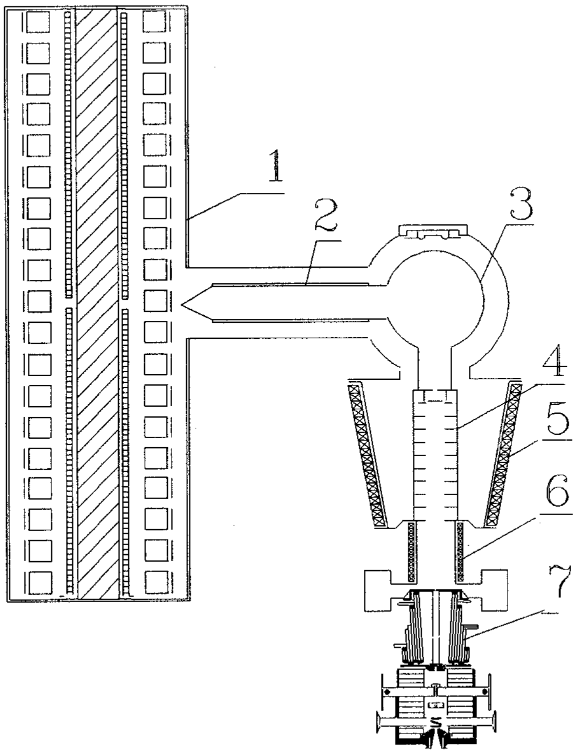


Figure 19: "Torch-accelerator": *1 - the source of accelerating voltage, 2 - gas feeder, 3 -injector control system, 4 - accelerating tube, 5,6,7 - the system of raster formation and vacuum system*

The rectifier consists of two parallel columns with an output of high voltage in between. The sections of each columns are connected in series-parallel and there is no filter capacitors in them. The primary winding with the central magneticguide is located inside the column of the high voltage rectifier. The accelerator operation frequency is 1000 Hz and it is supplied from the converter PPFV-500. The accelerator schematic diagram is shown in Fig.19. It was equipped with the device for the extraction into air of the adiabatically compressed electron beam which was described above. The maximum parameters obtained on this accelerator are the following: beam current = 0.8 A at an energy of 0.5 MeV, an energy = 0.8 MeV at a current of 0.5 A, the beam power = 500 kW (0.7 MeV $\times$ 0.7 A).

ELV-12 accelerator

The ELV-12 accelerator unites the design solves tested in the process of the development of previous accelerators. The schematic diagram of the accelerator is given in Fig.20. The high voltage power supply source, which consists of 2 parallel columns, is placed in a separate tank and it is connected by the gas feeders with 2 accelerating modules.

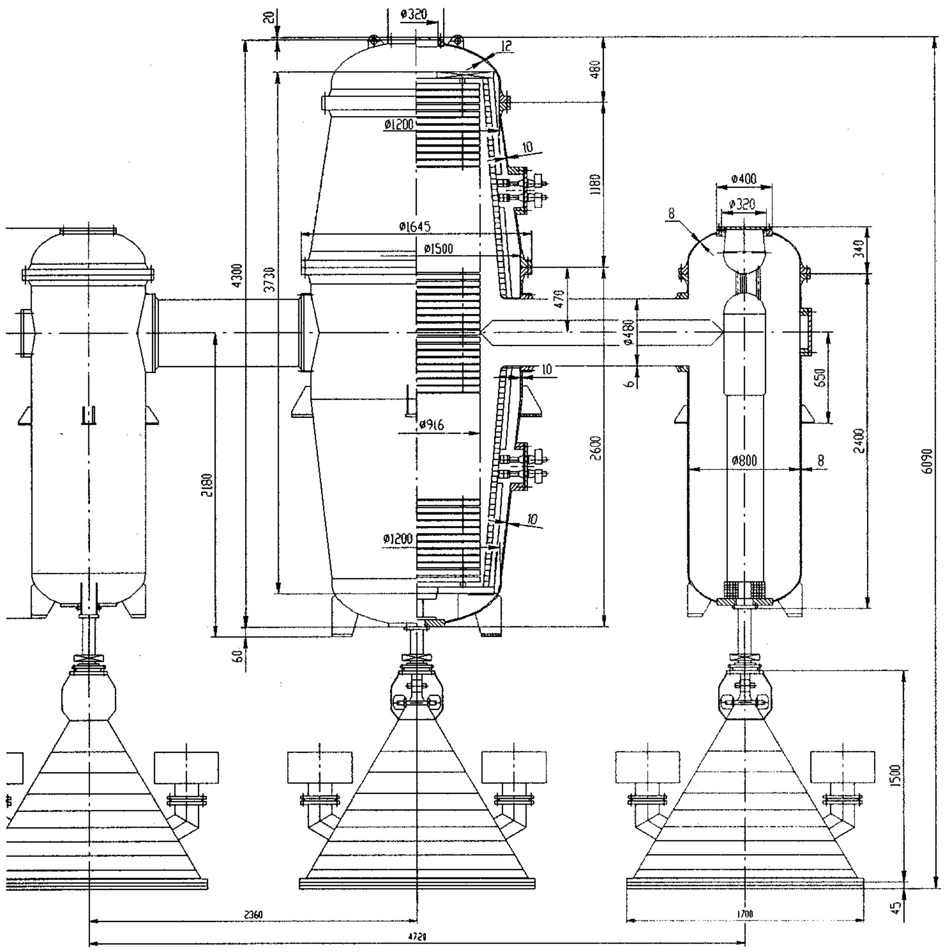


Figure 20: General view of ELV-12 accelerator (the version with three accelerating tubes)

The rectifying sections in the columns are connected in series-parallel and they do not have the filter capacitors since the output capacity is quite large due to the presence of gas feeders and the operation frequency increased up to 1000 Hz. The new coils of the secondary windings are developed for this accelerator. They have larger diameter and the winding voltage increased up to 20 V/turn. The power supply is planned from the thyristor frequency converter. The accelerating module is an accelerating tube placed in a separate tank and connected to the two-window extraction device. In addition, one tube may be located inside the accelerator tank. The beam current in each module is regulated independently that enabling the regulation in wide range of the power distribution of an absorbed dose. The maximum current value of the individual module is 200 mA. In this case, the maximum total accelerator current is 400 mA. In principle, the rectifier under construction (if necessary) would provide the power up 1 MW with an increased number of irradiators. The ELV-12 accelerator is mainly designed for the operation in the electron beam devices for the purification of the gas and sewage water. At present, the accelerator is under construction.

1.15 Main application of the ELV accelerators

	Type of technology	Country	Number
	Modification of polymer products		
1	Modification of the polyethylene insulation for the production of thermoresistant wires and cables 0.5-120 mm^2 with the capacity of up to 200 m/min	Russia	5
		Belorussia	5
		Ukraine	5
		Chekhiya	1
		China	9
2	The production of thermoshrinkable pipes, films and bands with the capacity of up to 1000 kg/h	Russia	3
		Moldavia	2
		China	2
3	The production of prepreg and gel	Russia	2
4	The production of artificial leather and rubber-technical products with the capacity of up to 1000 m /h	Russia	4
5	Curing lacquer-paint coatings on different bases for the building industry of up to 500 m^2/h	Russia	2
		Uzbekistan	1
	Purpose of ecology		
6	Sewage water treatment	Russia	4
7	Purification of flue gases of thermal station from sulphur oxides and nitrogen oxides with the capacity of 20000 m^3/h	Russia	1
		Poland	2
		Japan	2
	Other applications		
8	Surfacing building-up and hardening of metal, the production of catalysts for the synthesis of ammonia and the development of high temperature chemical technologies	Russia	5
9	Disinsectization of grain with a capacity of up to 200 t/h	Russia	1
		Ukraine	2
10	For the research purpose	Russia	5
		Bulgaria	1
		Germany	1
		Korea	1

In total, over 70 accelerators operate in the technological lines and research centers

Conclusion

The accumulated experience in the design, development, and manufacturing of the ELV-series accelerators enables us to propose to the customer the machines which by their parameters do not rank below but in the majority of cases even surpassing the best world samples of such machines.

In work participated:

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