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INSTRUMENTS AND METHODS OF INVESTIGATION

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High-energy electron accelerators for industrial applications

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Contents

Abstract. The principle of operation and the design of main parts of high-energy industrial electron accelerators are described. Accelerators based on high-voltage dc rectifiers are very efficient, compact and characterized by a high degree of unification of their main units. In total, more than 70 accelerators have been manufactured at the G I Budker Institute of Nuclear Physics, with over 20 of them for export.

1. Introduction

Radiation chemistry is a new field of industry that has been actively developed over recent decades [1 – 3]. The use of ionizing radiation opens the possibility of creating new technologies that are either alternative to existing ones but more effective and ecologically clean or unique and have no analogs in the chemical industry. The electron beam does not contaminate the technological process and the radiation energy is absorbed by the entire bulk of the material along the electron penetration depth, so that radiation-chemical processes belong to highly cost-effective chemical production characterized by exceptionally high purity.

Today the main sources of ionizing radiation are industrial electron accelerators [4], whose main parameters are the energy of accelerated electrons and beam current. The higher the energy, the greater the number of interactions between electrons and atoms in the absorbing material. The beam current gives the number of accelerated electrons interacting with the absorbing material. Finally, the product of the beam current and electron energy in the beam yields the electron beam power.

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Among the main characteristics of the interaction between the accelerated electrons and matter is the absorbed dose of radiation and the electron range in matter. The radiation dose (or simply dose) is the radiation energy absorbed in matter and calculated per unit mass of irradiated material. It is measured in grays and rads: 1 Gy = 1 J kg^{-1} = 100 rad. The larger the dose, the greater the amount of energy absorbed by the material. The electron range defines the depth to which an accelerated electron penetrates the material before it stops; it depends on the electron energy, the density of the material, and the charge to atomic number ratio of the elements that constitute the irradiated material. The characteristic values of the dose in radiative technologies lie in the range of roughly 10 – 250 kGy, and those of the electron range, in the range of roughly 0.1 – 10.0 mm.

Radiation processing can also be performed with gamma-ray devices, in which the decay of radioactive isotopes (mostly ^{60}Co and ^{137}Cs) is used. The main advantage of electron accelerators over gamma-ray sources is the incomparably higher power of the radiation generated by the accelerators, the high directivity of this radiation, the high uniformity of irradiation of an object, and the complete safety of the accelerator in the 'off' state.

Since 1971, the G I Budker Institute of Nuclear Physics, the Siberian Branch of the Russian Academy of Sciences has been developing and building ELV type electron accelerators for applications in industrial and research radiation-engineering devices [5 – 11]. These accelerators are manufactured from unified systems and units, which makes it possible to adapt them at minimum cost to the specific requirements of the technological process, such as the energy range, the power of the electron beam, the length of the exit window, etc. The design and assembly presuppose prolonged and continuous (around-the-clock) operation of the accelerators in an industrial environment.

ELV type accelerators consist of the accelerator proper placed in a vessel under pressure, a vacuum unit, an output device, a control system, a power unit, and a gas unit. Figure 1 is a schematic of such an accelerator. The vessel filled with an electrically insulating gas contains the primary winding, a high-voltage rectifier with a built-in accelerating tube, a high-voltage electrode, and an injector control unit. The fact that

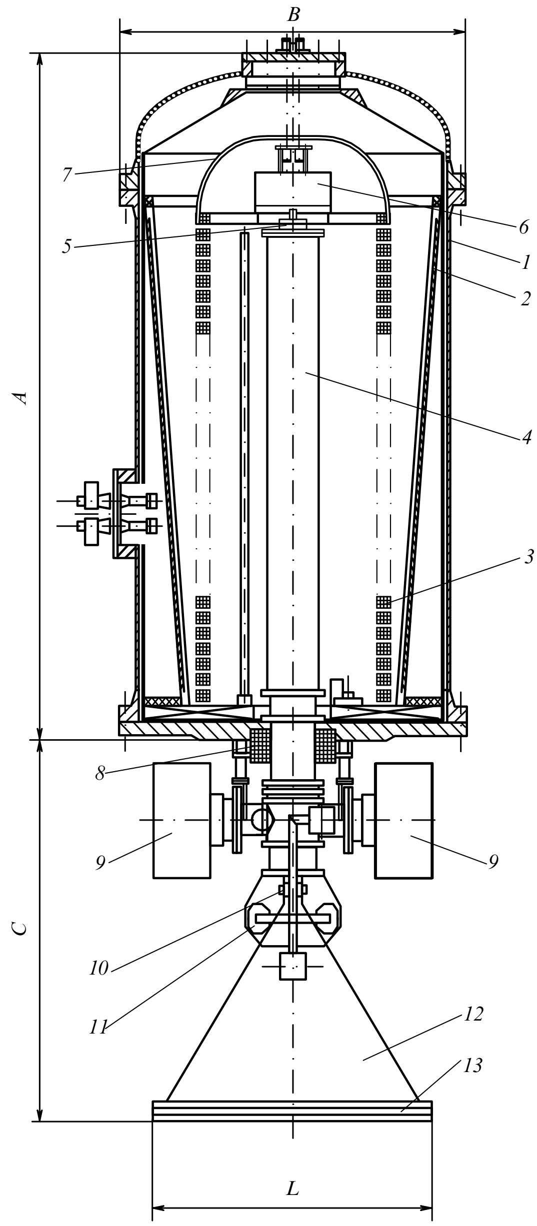

Figure 1. Schematic of an ELV type accelerator: *1*, vessel; *2*, primary winding; *3*, rectifying section; *4*, accelerating tube; *5*, electron injector; *6*, injector control unit; *7*, high-voltage electrode; *8*, magnetic lens; *9*, vacuum pumps; *10* and *11*, scanning electromagnets; *12*, output device, and *13*, titanium foil of the output device.

the accelerating tube is placed inside the high-voltage rectifier column makes ELV type accelerators the most compact machines in their class. The elements of the vacuum unit with the output device are attached to the bottom of the vessel. The total energy that the electrons emitted by the cathode attached to the upper end of the accelerating tube acquire at the exit is $-eU_0$. They fly through the elements of the vacuum unit and land in the output device, where they are evenly distributed over the foil by sweep electromagnets and extracted into the atmosphere. The irradiated material is transported under the frame of the exit window.

2. High-voltage rectifier

The source of high voltage is a cascade generator with parallel inductive coupling or, which is the same, an iron-free transformer with a sectioned secondary winding. The primary winding generates a variable magnetic flux of frequency 400 – 1000 Hz, which induces a voltage in each of the coils of the secondary winding sections as high as 30 kV. This voltage is rectified by the rectifier of each section. The rectifying sections are connected between themselves in series in constant voltage. The column of the rectifying sections ends above with the high-voltage electrode, which homes the injector control unit.

Note that in contrast to 'ordinary' transformers, our construction has no central magnetic circuit. This fact, while essentially simplifying the construction of the high-voltage source, has practically no effect on the operating characteristics of the rectifier due to the high quality of the stabilization system.

The use of low-induction capacitors and intersection connections as well as the presence of damping resistors ensure reliable protection of the elements of the high-voltage rectifier from overvoltage in the event of breakdown in the vacuum and gas insulations. Generally speaking, breakdowns in ELV accelerators are extremely rare, but in designing the accelerators we assumed that even a large number of breakdowns (from hundreds to thousands) should not damage the high-voltage rectifier (this principle is still strictly adhered to).

ELV type accelerators with different energy and power ranges differ in the number of rectifying sections and in the rectification circuitry.

The electron energy is regulated by changing the voltage across the primary winding.

3. Accelerating tube

As noted earlier, the accelerating tube is located inside the high-voltage column, which requires, firstly, screening the electron beam from the variable magnetic fields generated by the current in the primary winding and, secondly, protecting the high-voltage rectifier proper from overvoltage which may appear in vacuum breakdowns in the accelerating tube. Screening from the longitudinal component of the magnetic field is achieved by mounting short-circuited magnetic rings on the accelerating tube, while screening from the transverse component is achieved by mounting rings manufactured from transformer steel. What makes our accelerating tube special is its large aperture, 100 mm. This improves the vacuum conditions in the tube, especially near the cathode. Due to this circumstance the requirements on the accuracy of assembly and adjustment of the accelerating tube and the electron injector can be made less stringent. At the same time, the large aperture of the tube facilitates the emergence of secondary particles in the space between the sections of the accelerating tube that are at the high-voltage and ground potentials. This effect is minimized by optimizing the distribution of potential over the electrodes of the accelerating tube near the tube's high-voltage end.

The maximum operating gradient in the tube amounts to 10 kV cm^{-1}. However, for prolonged and continuous (around-the-clock) operation the gradient should not exceed 8 kV cm^{-1}. This explains why almost no vacuum breakdowns have occurred in accelerating tubes.

For the beam to travel through the vacuum unit and the output device without losses, a magnetic lens is attached to the lower end of the accelerating tube. The lens current as a function of energy is controlled automatically, with no participation from the operator.

4. Output devices for an electron beam extraction from vacuum to the atmosphere

Almost all technological processes that use high-energy electron accelerators presuppose processing of the products in air or other gas media under atmospheric pressure. Hence the beam of electrons accelerated in vacuum must be extracted into the atmosphere. Moreover, an optimum distribution of the beam current density must be produced in the irradiation zone. Output devices are used to ensure that this is the case.

The common approach here is to extract the electrons through a thin air-cooled titanium foil (see Fig. 1). The magnitude of the electron beam current is often limited by the heating of the exit window foil due to ionization losses in the foil. Uniform distribution of the beam current over the area of the exit window is required in the majority of technological processes and is needed to reduce local heating of the foil. This distribution is achieved by shaping the current profile in the coils of the scanning electromagnets.

For processing cylindrical objects (wires, cables, and pipes), the optimum direction of electron motion toward the object is radial or close to radial. To realize such a beam current distribution, we developed (a) magnetic systems that form the radial irradiation zone, and (b) devices that make it possible to irradiate cylindrical objects from four sides. We also built magnetic reflectors of electrons, which enhanced the effectiveness of beam utilization. All these systems found use in radiation-chemical technologies. However, a high-energy electron beam can also be used as a sterile source of bulk heat input to the object processed.

Several devices have been developed for extracting a focused electron beam into the atmosphere. The electron beam current density at the exit of these devices may be as high as 10 A cm^{-2}, and the power density as high as 10 MW cm^{-2}, which are values that no other methods can achieve. The beam extracts through a system of holes in the diaphragms. The holes are burnt by the beam proper, with a diameter in the 1 – 2 mm range. The working vacuum in the accelerating tube is maintained by continuously operating pumps of the differential pumping system. Two variants of accelerators with such output devices have been developed.

In the first variant, the beam is focused by two magnetic lenses. This variant is used in accelerators with a maximum power up to 100 kW. Figure 2 depicts the layout of the output device, whose operation can be described as follows. After the electron beam extraction from the accelerating tube, it is focused by a magnetic lens. In the lens crossover there is a diaphragm. The beam passes through the diaphragm, broadens, and passes through a second lens with an even smaller focal distance. In the crossover of this lens there are two diaphragms. The gas seeping through the holes in the diaphragms is evacuated by vacuum pumps. The maximum beam current at the exit is limited by pulsations in the accelerating voltage, which make the holes in the diaphragms bigger and can be no larger than 2 – 3 %. ELV-2, ELV-3, ELV-4, and ELV-6 type accelerators can be equipped with such devices for extracting a focused electron beam.

When experiments do not require maximum power densities, the output device can be equipped with electromagnets for sweeping in two mutually perpendicular directions, with the beam deflected immediately in the atmosphere. The scanning system makes it also possible to ensure that the configuration of the dose field agrees with the technological requirements.

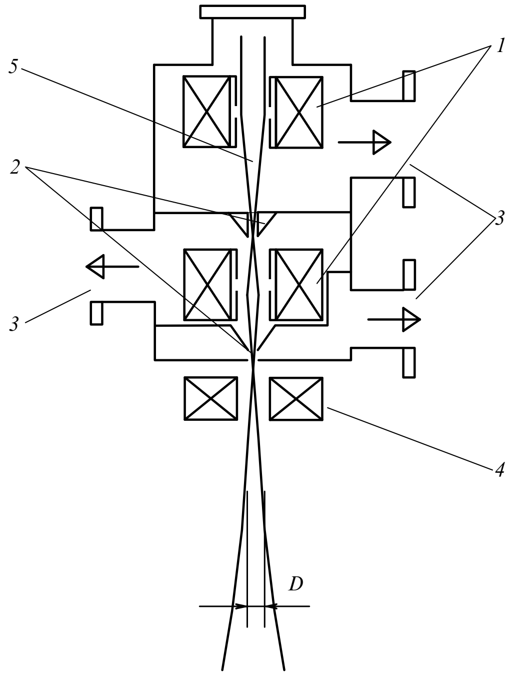

Figure 2. Device allowing a focused electron beam extraction into the atmosphere: *1*, magnetic focusing lenses; *2*, diaphragms; *3*, vacuum lines; *4*, scanning electromagnets, and *5*, electron beam envelope.

In the second variant, the decrease in the diameter of the accelerator's beam in the output diaphragms is achieved by pinching the beam with an adiabatically increasing longitudinal magnetic field. This method is used in 500-kW accelerators. The main advantage of adiabatic compression is the low sensitivity of the beam size to variations in the electron energy, which is crucial to building accelerators with peak powers of several hundred kilowatts (for which the problem of pulsations and instabilities in the accelerating voltage is rather important). In this case accelerating tube and the output device are on the same axis, and the magnetic field gradually increases from 100 Gs at the cathode to 10000 Gs in the vicinity of the output diaphragms. Here the beam size decreases in inverse proportion to the square root of the magnetic field strength. The longitudinal magnetic field is generated by a system of solenoids and coils. A steel concentrator is used to increase its strength in the vicinity of the output diaphragms. The maximum current in the beam that was extracted into the atmosphere for such a construction of the output device was about 0.8 A.

5. Control system

The control system used in industrial accelerators largely determines their operating characteristics, among which are the convenience of control, reliability, the duration of continuous work, and maintainability.

The operator of a technological installation that uses our accelerator 'communicates' with the latter via a personal computer. The control system of the accelerator consists of a combination of hardware and software that encompasses all units of the accelerator that require real-time control, monitoring, and diagnostics. The multifunctional control system makes it possible to do the following:

Table 1.

Type of accelerator	Energy range, MeV	Maximum beam current, mA	Beam power, kW	Dimensions*, mm			
				A	*B*	C	*L*
Mini-ELV	0.2 – 0.4	50	20	500	450	600	980
ELV-3	0.5 – 0.7	100	50	2360	1345	2000	1500
ELV-4	1.0 – 1.5	40	50	2660	1345	1500	980
ELV-6	0.8 – 1.2	100	100	3870	1345	2000	1500
ELV-6M	0.6 – 0.9	200	150	3870	1345	2000	1500
ELV-8	1.0 – 2.5	50	100	3740	1345	1500	980
ELV-12	0.6 – 1.0	400	400	4300	1645	1800	1600×3

*The dimensions *A*, *B*, *C*, and *L* are specified in Fig. 1

(a) Automate the process of the accelerator control. The algorithms embedded in the control program prepare the accelerator for operation (speeding up the frequency converter and switching on the foil cooling system, the sweeping system and, if necessary, the technological equipment), monitor the state of the blocking system, and bring the energy and current of the electron beam to operational values upon turning-on the accelerator.

(b) Reliably stabilize the main parameters of the electron beam (the electron energy, the beam current, and the size and position of the beam pattern on the exit window foil), which ensures high quality of radiation processing.

(c) Ensure, in the process of operation of the accelerator, continuous diagnostics of the high-voltage rectifier and self-testing of other systems of the accelerator.

(d) Synchronize the operation of the accelerator and other technological devices. This includes the possibility of utilizing the accelerator as a component of a production line operating in a fully automated mode, i.e. without an operator participating in the process.

(e) Provide the service personnel with a broad set of commands for preliminary fixing of the various operation modes, for testing, and for making adjustments.

6. Parameters of ELV accelerators

Using unified elements and units, we built a number of accelerators with a broad range of operating energies, currents, and powers in the electron beam. Table 1 lists the parameters of the accelerators developed at the G I Budker Institute of Nuclear Physics, SB RAS and ready for purchase (the ELV-12 accelerator is in the manufacturing stage).

The main requirement presented to industrial accelerators is their reliability. The high degree of reliability of ELV type accelerators was achieved thanks to many years of experience with accelerators operating in real conditions. Using unified construction elements and units for the entire line of ELV accelerators has made it possible, by changing only the number of such elements and units and their assembly, to retain the reliability of new types of accelerators, thus utilizing the many years of experience accumulated in the course of maintenance of previous models.

In the last two and a half decades, about 50 ELV type accelerators have been built for use in the former Soviet Union and now Russia. They are used in practically all radiation-chemical technological processes developed in our country. More than 22 accelerators have been exported in the last decade to other countries: 10 to China, 5 to the Republic of Korea, 2 to Japan, 2 to Poland, 1 to Czech Republic, 1 to Bulgaria, and 1 to Germany. These accelerators are mainly used to radiationally modify various polymer products. Some accelerators operate at research centers and as pilot plants in the field of ecology (radiation cleaning of sewage and toxic gases). Soon one should expect an expansion of the market of accelerators for ecological applications, namely, a market that will require accelerators with powers of several hundred kilowatts. ELV-12 type accelerators are well-suited for these purposes.

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