NIEFA ACCELERATORS FOR INDUSTRY AND MEDICINE

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Abstract

The D.V. Efremov Institute (NIIEFA) is a leading enterprise in Russia involved in designing and manufacturing of applied and medical charged particle accelerators, as well as electrophysical systems based on these accelerators. Since the foundation of the Institute, we have designed, manufactured and delivered to Russian customers and abroad more than three hundred accelerators of different types, in particular, cyclotrons, high-frequency linear electron accelerators, high-voltage accelerators and neutron generators. The activities of the Institute in the field of accelerating engineering encompasses all the stages of an accelerator manufacturing, starting from R & D works to manufacturing, installation, adjustment and maintenance of the equipment delivered.

NUCLEAR MEDICINE

Among the present-day methods of medical examination, the radionuclide diagnostics presents the most complete information on available pathologies. The method is characterized with a high sensitivity, the shortest possible time needed for analysis and reliability of the data obtained. A single-photon emission computer tomograph (SPECT) is an apparatus the most widely used for examination of great masses of population. This apparatus uses radiopharmaceuticals labeled with short-lived isotopes with the half-life period from several hours up to 2-3 days. The clinical experience gained over a number of years demonstrates that in about 20% of cases more accurate positron-emission diagnostics is needed, which applies ultra-short-lived isotopes with the half-life from two up to one hundred and ten minutes. Radio-isotopic examinations allow cardio-vascular and oncologic diseases, the death rate from which is the main factor determining the age of a human life, to be detected at very early stages. Cyclotron is the most proper accelerator allowing necessary ultra and short-lived isotopes to be produced in the most cost-effective way.

NIIEFA has been involved in designing and production of cyclotrons since the day of its foundation. More than forty different models of cyclotrons have been delivered to Russian customers and abroad, and the majority of these machines have been operated until now. Recently, a series of compact cyclotrons has been designed specially for production of medical isotopes [1]. The main parameters of these cyclotrons are given in Table 1.

Specific features of these cyclotrons are: the external injection of hydrogen negative ions, beam extraction by stripping negative ions on carbon foils, the main electromagnet of shielding-type with the vertical median plane, the same principle of construction of the RF-power supply system, vacuum system and automatic control system.

Table 1: Main Parameters of Cyclotrons for Medicine

Parameters	CC-12	CC-18/9	MCC-30/15
Accelerated ions	H^-	H^- / D^-	H^- / D^-
Ion energy, MeV	12	18/9	18…30 / 9…15
Extracted beam current, µA	50	100/50	200/70
Electromagnet:			
- pole diameter, cm	90	115	140
- supply power, kW	5	7	12
- mass,t	10	20	41
Frequency of RF oscillations, MHz	76.4	38.2	40.68
RF generator power, kW	15	20	25
Energy consumption, kW	30	70	100

To give an access to in-chamber components, the iron core is made as a fixed part and a movable part. The movable part is fixed on a support and can be moved apart for a distance up to 800 mm.

The CC-12 compact cyclotron is intended for production of ultra short-lived isotopes directly in medical diagnostic centers. The CC-18/9 cyclotron (Fig. 1) allows both ultra short-lived isotopes and short-lived isotopes to be produced. The CC-18/9 machines are successfully operated in PET centers in Turku (Finland), Saint-Petersburg and Snezhinsk (Tchelyabinsk district), Russia.

Figure 1: The CC-18/9 cyclotron installed in Turku (Finland).

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The MCC-30/15 cyclotron with the variable ion energy provides production of ultra short-lived, short-lived and long-lived isotopes for nuclear medicine. Two charge-exchange devices are installed on the cyclotron for the beam extraction into beamlines. A standard set of the beamline equipment is: matching, switching and correcting electromagnets, quadrupole lens doublet, beam scanners, Faraday cup and necessary vacuum equipment.

The MCC-30/15 cyclotron together with the equipment for two beamlines has been delivered to the University of Jyvaskula, Finland and has been in operation since 2010 (Fig. 2). Preliminary works on organization of serial production of medical cyclotrons are now underway in NIIEFA.

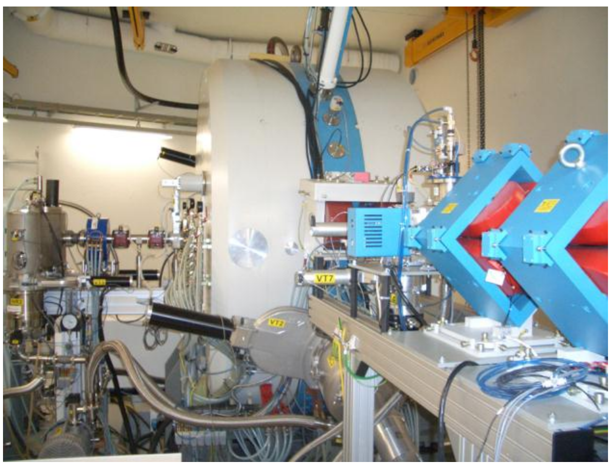

Figure 2: The MCC-30/15 cyclotron installed in the University of Jyvaskula (Finland).

RADIOTHERAPY AND NEUTRON THERAPY

The D.V.Efremov Institute is the only national designer of linear electron accelerators for radiation therapy, and therefore designing and production of electrophysical equipment for medicine is one of priority fields of its activity. Over the years of the Efremov Institute existence, several generations of medical accelerators have been designed and manufactured. About one hundred machines have been delivered to oncologic clinics of Russia and CIS countries.

In the framework of international cooperation with the “Philips Medical Systems. Radiotherapy” firm (Great Britain), a small-scale production of SL-75-5MT accelerators for radiotherapy was organized; up to 15 machines per year were produced. The SL-75-5MT accelerator is a Russia-made version of the “Philips” accelerator (up to 60% of Russian component parts), it is intended for X-ray radiation therapy with an energy of 6 MeV in the static and arc modes. About sixty machines have been manufactured and delivered to clinics of Russia.

In compliance with international standards, after ten years of operation medical accelerators should be either subjected to updating or replaced. To meet these requirements, additional medical equipment is required, the cost of which can be several times more than the cost of the accelerator itself. In this connection, recently a new medical accelerator «ELLUS-6M» with an electron energy of 6 MeV have been designed in the Efremov Institute (Fig. 3) with the following additional equipment:

- multi-leaf collimator to form the X-ray therapeutic beams maximally corresponding to the shape of a tumor;
- translator, an automatic control system used to transfer digital data from the treatment planning system to the control console of the accelerator;
- device for the detection of the X-ray radiation passed through the body of a patient and the table top and for forming the portal images;
- modified patient-support system.

Figure 3: The «ELLUS-6M» accelerator in the N.N. Petrov Institute of Oncology, St.Petersburg.

The «ELLUS-6M» accelerator is equipped with a computer control system compatible with all additional medical equipment. The accuracy of the irradiator rotation velocity setting, the grid modulator of the electron source, which ensures ten-fold variation of the irradiation dose by changing the pulse length, allow the dose rate to be controlled depending on the rotation angle (the IMRT mode).

The accelerator is equipped with the treatment planning system, laser pointers and dose field analyzer with a double-channel measurement system on the basis of diamond detectors. The accelerator with the additional medical equipment has been delivered to the N.N. Petrov Scientific Research Institute of Oncology (St. Petersburg) where starting since 2011 it undergoes medical and operational life tests. After successful completion of the tests, the «ELLUS-6M» accelerator can find wide application including the replacement of obsolete accelerators SL-75MT and cobalt apparatus “Rocus”.

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Nowadays, the accumulated clinical experience has demonstrated that up to 30% patients with severe radioresistant forms of malignant tumors need radiation therapy treatment using neutron ionizing radiation.

The 14 MeV neutrons necessary for radiation therapy can be produced on comparatively low-cost and small-sized neutron generators on the basis of high-voltage accelerators. The NG-12-I neutron generator designed and manufactured in NIIEFA was used in the system of the Ural Center of Neutron Therapy. After updating the generator specially for neutron therapy of malignant tumors, it provides the neutron yield up to $3 \cdot 10^{12}$ n/s [2].

By now, more than two thousand patients with tumors localized in the head and neck regions have received treatment. In opinion of oncologists, radiation therapy in combination with the neutron beam is highly effective. The majority of patients (79%) demonstrated the complete resorption of tumors and in 76% of cases complete remission was observed. The results obtained provide solid grounds to consider promising the introduction of similar facilities into clinics of Russia.

NON-DESTRUCTIVE TESTING

The most important line of activities of NIIEFA in the field of accelerating engineering is designing and construction of systems for non-destructive testing of large-scale products based on linear accelerators with energy ranging from 3 to 15 MeV. NIIEFA has delivered more than thirty similar machines both to industrial enterprises in Russia and abroad. New accelerators, UEL-10-D and UEL-6-D, have been designed and manufactured especially for non-destructive inspection of products of atomic, chemical and shipbuilding industries.

Radiation characteristics of these machines are as follows: energy of accelerated electrons is 10/6 MeV and maximum average dose rate 1m from target on the central axis is 30/10 Gy/min. The asymmetry of the X-ray field is no more than 5%.

The UEL-10-D accelerator, $2040 \times 950 \times 950 m^3$ in size and 1160 kg in weight, is mounted on a trolley of a bridge crane using a special yoke. This yoke allows the position of the irradiator to be changed relative to an object under inspection: from 180º (rightwards) to 135º (leftwards) in the horizontal plane and from 45º (upwards) up to 95º (downwards) in the vertical plane. The irradiator is made as a support frame of aluminum profile. In contrast to previous models, all the equipment is housed inside the irradiator including the high-voltage power supply system consisting of a high-voltage rectifier and pulse magnetron modulator (Fig. 4).

Different defects, such as voids, cracks and foreign inclusions and their localization can be detected by radiographic, radioscopic and tomographic methods [3].

In the radiography, the X-ray beam passed through an object inspected is recorded on the X-ray film. An advantage of this method is a possibility for inspection of objects with a thickness of up to 600 mm for steel. Quality of the image obtained meets the requirements of the international ASTM E142 standard. Standard film size is 3000×4000 mm. For products of the aforementioned thickness, linear accelerators are the only available tool, which provides a required quality of inspection.

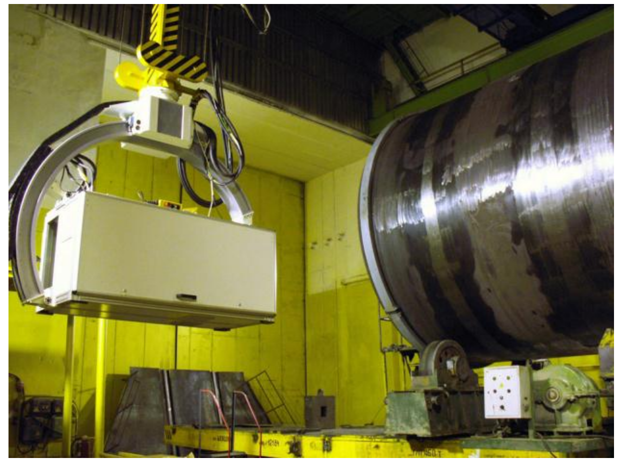

Figure 4: The UEL-10-D accelerator at the Izhorskie Zavody, St. Petersburg.

In radioscopy and tomography, an object under inspection is scanned layer-by-layer by a fan-shaped X-ray beam. A line of scintillation detectors is used instead of the X-ray film. A shadow image of a defect is obtained on the monitor of the operator workstation in the real-time mode.

Compared to the radiographic inspection, the radioscopic method offers higher efficiency and lower operating costs. In the radioscopy, a standard set of the linear accelerator equipment is supplemented with the following (Fig. 5): beam collimation system, detection system, system for positioning an object under inspection, operator workstation with a software.

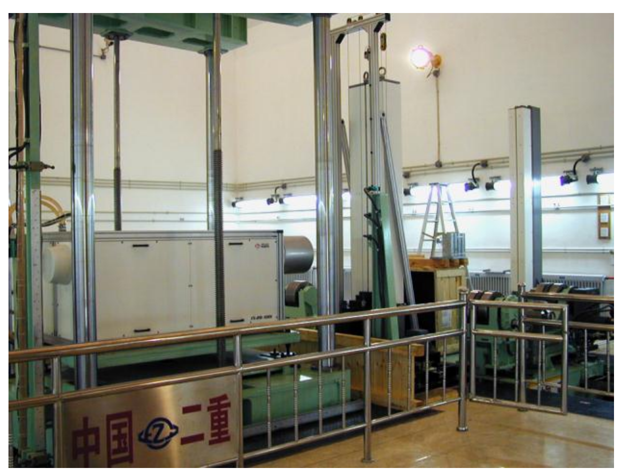

Figure 5: The UEL-15-D accelerator installed in China.

High degree of spatial resolution allows radioscopic systems to be used for inspection of large-scale vehicles and containers without their opening to expose either arms or contraband goods. For this purpose, linear accelerators of the LINAC-2(4) model with an energy in

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the range from 2 up to 4 MeV have been designed and manufactured in NIIEFA. The accelerators are made with local radiation shielding. Figure 6 shows a LINAC-4 accelerator functioning as a part of the SMITH HEIMAN system (Germany) intended for customs inspection [4].

Figure 6: The LINAC-4 accelerator in the SMITH HEIMAN system, Germany.

HIGH-VOLTAGE ACCELERATORS FOR RADIATION PROCESSING

High-voltage charged particle accelerators are ranked high in the ine of the accelerating equipment designed and manufactured in NIIEFA. By now, more than one hundred and thirty high-voltage electron and ion accelerators for various purposes have been delivered to Russian customers and abroad. In NIIEFA first high-voltage accelerators were designed on the basis of electrostatic generators. The maximum proton energy attained 10 MeV. About thirty similar machines intended for research in the field of nuclear physics, particles' injection into cyclic accelerators and ion implantation were manufactured. Many of these accelerators have been updated and have been in successful operation till nowadays, for example in the Federal Nuclear Center in Germany, the University of Helsinki and in the Institute of Nuclear Research, Kazakhstan.

Further, radiation processing of different materials and products with an electron beam to modify their molecular structure and impart new properties becomes one of the most promising fields of practical application of high-voltage accelerators with a charged particle energy of up to 1 MeV.

To introduce radiation processing on industrial enterprises, a series of high-voltage accelerators with an electron beam power of up to 50 kW has been designed in NIIEFA. A typical accelerator of this series is the "ELECTRON-10" (Fig. 7), which consists of a high-voltage generator, electron source, accelerating structure and irradiation field forming system. The high-voltage generator is made on the basis of a single-phase transformer - rectifier, Power is supplied from an ac 3-phase mains 380 V, 50 Hz. Two extraction windows oppositely located and covered with metal foil serve to extract an electron beam into the atmosphere. Such a design ensures the double-sided irradiation of a material for one passage. The automatic control system is made on the basis of an industrial computer.

Figure 7: The «Electron-10» accelerator at the plastic materials production plant, Izhevsk.

The main parameters of the accelerator are: the energy in the 500÷750 kV range, maximum current of accelerated electrons – 70 mA, non-uniformity of the current linear density along the scanning length of 1200 mm is not more than 5%. Accelerators of this series are equipped with a compact local radiation shielding and can be installed together with the equipment of rtechnological lines in conventional rooms. The running hours per year are five thousand hours, which meets the requirements for industrial equipment.

More than fifty such accelerators have been delivered. The machines were used for commercial production of roofing, shrink polymer tape for protection of underground gas and oil lines against corrosion, foamed polyethylene and polymer tape with an adhesive layer [5].

A recent advance of NIIEFA in the field of high-voltage accelerators on the basis of three-phase transformer-rectifier is an «ELECTRON 23» with an electron beam power of up to 400 kW and an energy of 1 MeV.

An important field of application of high-voltage accelerators is the activation analysis. The method is used to determine the element composition of a substance by irradiating it with fast or thermal neutron fluxes (14 and 2.5 MeV) with subsequent measurement of the induced gamma activity of irradiated samples.

The most easily available source of neutrons for these purposes is facilities constructed on the basis of high-voltage ion accelerators. 14 MeV neutrons are produced as a result of the D-T reaction under interaction of deuterium ions accelerated up to 150-300 keV with tritium of a metal-tritium target. The D-D reaction produces neutrons with an energy of approximately 2.5 MeV. More than sixty neutron generators producing neutron fluxes with an intensity of up to 10^{13} n/s have been designed and manufactured in NIIEFA.

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RF ACCELERATORS FOR RADIATION PROCESSING

Several models of linear accelerators with the electron energy ranging from 3 up to 15 MeV and average beam power up to 15 kW have been designed and manufactured in NIIEFA for high-energy radiation processing. The accelerators are equipped with horn scanning chambers. Thickness of objects under processing depends on the electron energy; the velocity and throughput depend on the beam power. To generate a directed X-ray beam, an accelerator is equipped with a tungsten-nickel target.

More than fifteen accelerators of the UEL-8-8S model with an energy of 8 MeV and beam power of 5 kW are operated in Russia and abroad, in Poland, Hungary, China and France. In addition to electron beam processing of products of irregular configuration, these machines are also used for the element analysis on the basis of photonuclear reactions. Construction of such systems allowed the use of a highly effective method of the activation analysis to be pioneered at a number of mines. The method is used for detecting ore samples for the content of various chemical elements, up to fifty in number, including Au. The time needed for the analysis of one sample for the content of aurum is less than 22 seconds, and the throughput is one million of analysis per year.

The aforementioned systems operate at a mining – and-processing integrated works in Navoi, Uzbekistan, in the analytic service of geological field parties in Batogai town, Yakutia. For the “in-line” processing of products in standard industrial premises, a 3 MeV UELV-3-3S accelerator with a beam power of up to 3 kW equipped with a local radiation shielding has been designed.

Figure 8: The UELR-10-10S accelerator installed in Beijing, China.

The UELR-10-10S accelerator (Fig. 8) has been designed and manufactured in NIIEFA specially for commercial sterilization centers to be used for processing of disposable medical utensils. Typical penetration depth of electrons is up to 40 mm. Characteristics of the accelerator are as follows: electron energy is 8 MeV, nominal average beam power is 10 kW, radiation field size is 800×20 mm^2 at a distance of 200 mm from the extraction window foil and uniformity along the scanning length of 5%. The accelerator can be operated in the long-term mode: three shifts with a one-hour interval between shifts.

CONCLUSION

Technical characteristics of the accelerating equipment designed and manufactured in NIIEFA are on a par with their foreign analogs and in some cases are even superior to their competitors. Taking into account expenditures for transportation, customs duties, intermediary firms, warranty/after-warranty servicing (especially in case of no foreign service centers), delivery of spare parts, etc ., the total cost of the equipment is much lower.

Nowadays, the demand for applied accelerators round the world increases rapidly. Proper activities towards marketing, promotion and patent right protection as well as the organization of serial production of the accelerating equipment being at present in ever-growing demand can ensure the competitiveness of national projects.

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