ELECTROPHYSICAL SYSTEMS BASED ON CHARGED PARTICLE ACCELERATORS

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INTRODUCTION

The advancement of the charged particle accelerator engineering affects appreciably the modern tendencies of the scientific and technological progress in the world. In a number of advanced countries, this trend is one of the most dynamically progressing in the field of applied science and high-technology production. Such internationally known firms as VARIAN, SIEMENS, PHILIPS, ELECTA, IBA, HITACHI, etc., with an annual budget of milliards of dollars and growth rate of tens of percent may serve as an example. Although nowadays the projects of new large-scale accelerators for physical research are not implemented so quickly and frequently as desired, accelerating facilities are finding ever-widening application in various fields of human activities.

The contribution made by Russian scientists into high-energy beams physics is generally known. High scientific and technical potential in this field, qualified personnel with a high creative potential, modern production and test facilities and state-of-the-art technologies give grounds for us to aim to be among the world leaders in the designing and construction of applied accelerators.

ELECTROPHYSICAL SYSTEMS DEVELOPED IN NIIEFA

The complete process of the accelerating equipment manufacturing is implemented in the D.V. Efremov Institute, NIIEFA starting from the development of new acceleration principles and designing of new models of accelerating equipment and up to its small-scale production, on-site installation, personnel training, offering warranty/after-warranty service and supervision services practically through the whole operating lifetime of the equipment. Recently special attention is paid to the designing of electrophysical systems based on charged particle accelerators with complete production cycle. Further we shall consider the current status of the main systems.

Diagnostic Radiotherapy System

The main purpose of radiotherapy is suppression of tumor growing with a minimal effect on adjacent healthy tissues. With this aim in view, the radiotherapy treatment approach should provide radical effect on pathologic process with minimized dangerous consequences for patient.

The efficiency of radiotherapy treatment depends on clinical and biological factors, such as tumor radiosensibility, radiation tolerance of adjacent tissues involved in the treatment process, stage of disease, etc. These factors are mostly revealed in the process of patient's diagnostics. If radiotherapy is prescribed, a treatment approach is planned: areas to be treated are chosen, critical organs are found out, levels of radiation doses on the target and allowable doses in critical points are specified. The treatment approach is presented in the form of clinical prescriptions for radiotherapy treatment.

The experience of world-advanced radio-therapeutic centers shows that the required quality level of treatment can be achieved only by implementation of integrated computer-based technology, which covers all the stages of radiotherapy treatment.

Rradiotherapy system and clinical diagnostic means should have the following functions. Examination of patients and choice of treatment strategy should be done in clinics using their available diagnostic facilities. In the process of examination the data about patient will be input in the information system. As diagnostic means available in clinics differ greatly, implementation of inexpensive specialized soft-hardware systems seems highly expedient at the initial stage to load diagnostic data in the database.

When a clinic is equipped with modern anatomic and topometric means ensuring direct data exchange with the computer of such a system, there appears a possibility to involve these means in the computerized radiotherapy process.

With this aim in view, works on the development of a prototype of a double-detector gamma-tomograph has been performed in NIIEFA since 2003 in the framework of the "Nuclear Medicine "program [1].

Figure1: The gantry with the detector units

In the digital detector unit, analog signals are transformed at the output of each photomultiplier and are further processed with a digital processor. The detector unit is equipped with a system of IR probes detecting objects within 5-10 m from the detector surface, thus allowing the implementation of the maximum resolution of the system in tomographic studies.

The detector units (up to two in number) are fixed to the gantry (see Fig. 1), which ensures their radial and angular movements by means of electric drives. The gantry is equipped with an electron microprocessor-based system providing both manual and computer control of detector positioning.

The current year we plan the engineering test of the gamma-tomograph prototype.

Construction of a positron-emission tomograph is a natural result of further works on diagnostics [2]. At present we have a team of highly skilled personnel involved in these works (NIIEFA, ITEP, CNIRRI). Provided support from ROSATOM, we consider it possible to have finished the designing of the main components of the tomograph by the end of 2005 and then start the engineering tests of the first domestic PET-center.

The radiotherapy system EFARAD [3] consists of: linear medical accelerators LUER–20M and SL75-5-MT, a radiotherapy topometric system TSR-100, a treatment planning system ScanPlan, an information system Inforad and a treatment verification system VeriRad.

The linear accelerator LUER-20M is intended for remote radiotherapy with photon beams and electrons with energies ranging from 5 to 20 MeV in static and arc modes. The accelerator allows one to perform complete course of treatment of the majority of oncological patients and may be used for medico-biological research. In July, 2004 the physical startup of the upgraded model of LUER-20M was realized in Yerevan. The machine meets international requirements MEC-601-1 and offers potentialities for stereotactic irradiation.

The linear electron accelerator SL75-5-MT is the basic therapy machine intended for radiotherapy with 6 MeV photon beams in static and arc modes. More than 50 similar machines have been designed and manufactured in NIIEFA and delivered to clinics in Russia.

The X-ray topometric system for radiotherapy TSR-100 is the basic means for preparation of treatment prescriptions. The system is intended for solution of biometrical problems of oncological patients and for verification of treatment plans. The system provides both projection images of a patient body (in the radiotherapy machine geometry with contouring radiation field) and transverse computer tomograms at specified levels. Thus the system combines both an X-ray simulator and a computer tomograph (CT). Conventional fluoro imager is replaced with a digital system for radiation registration equipped with a moving mechanism and collimators for fan-shaped X-ray beam scanning.

The treatment planning system ScanPlan provides planning of treatment with photon beams for any linear medical accelerator, though the main task is treatment planning for the SL75-5–MT accelerator.

The information system InfoRad contains computer-based workstations for doctors and radiology physicists, which are connected with the treatment system units, databases and archives. The system covers all the stages of radiotherapy process.

The EFARAD system is built by the module principle thus allowing flexible distribution of functions between the system hardware and upgrading the system by adding new modules. The system modules are integrated through standard interfaces and form a flexible automated information system intended for implementation of the closed cycle of radiotherapy process [4].

The prospects for further advancement of the radiotherapy system are discussed in detail in our report to be made on the conference.

Systems for Non-destructive Testing

Industrial systems for non-destructive inspection designed and constructed in NIIEFA are based on RF accelerators with electron energy ranging from 3 to 15 MeV. These systems are intended for radiographic inspection of defects in large-scale products with an equivalent steel thickness from 40 up to 600 mm. The systems are successfully used for non-destructive inspection of products of nuclear power plant industry, nuclear shipbuilding and in other fields.

Let's consider in brief one of the latest model of such accelerators with an electron energy up to 16 MeV at an X-ray dose rate up to 120 Gy/min (1 m from target). The general view of the irradiator is given below in Fig.2.

Figure 2: The UEL-15-D accelerator irradiator

The irradiator houses the accelerating structure, RF power supply system and pulse modulator. Nevertheless, the weight of the irradiator is no more than 1100 kg and its overall sizes are: 2040×880×920 mm^2, which is much less than those of foreign analogs. This can be attributed to its the rational layout, application of the KIU-111 low-voltage klystron (power – 6 MW, anode voltage-no more than 55 kV) and a 2 m long optimized biperiodical accelerating structure without focusing solenoids and coils. The primary cone collimator forming the irradiation field is located at the accelerator inlet.

Nowadays, such innovative methods of non-destructive inspection as radioscopy and tomography are implemented.

In radioscopyy an object is scanned layer-by-layer with a fan-shaped X-ray beam. A line of scintillator detectors is used instead of X-ray film. The shadow image of defect is visualized on the monitor of the operator's workstation [5]. Compared to radiographic inspection, the radioscopic one offers lower operating costs and reduced time for data processing. The efficiency is several factors of ten higher, as the inspection is implemented practically in the real time mode. However, the radioscopic inspection is effective when testing objects with a thickness only no more than 350 mm (for steel).

When applied to radioscopy, a standard set of the linear accelerator equipment is supplemented with: a beam collimation system, detection system, system for positioning an object under inspection and operator's workstation with software.

The beam collimation system is intended for beam forming. It consists of three collimators: the primary collimator installed on the radiation source, the secondary collimator installed in front of an inspected object and a collimator placed in front of the detector line.

The positioning system servers to ensure linear travel of an inspected object perpendicular to the axis of the fan-shaped beam. To change the angle, the inspected object is rotated in the beam plane. The measuring element is the detector line of cadmium tungstate ($CdWO_4$) crystals installed behind the last collimator.

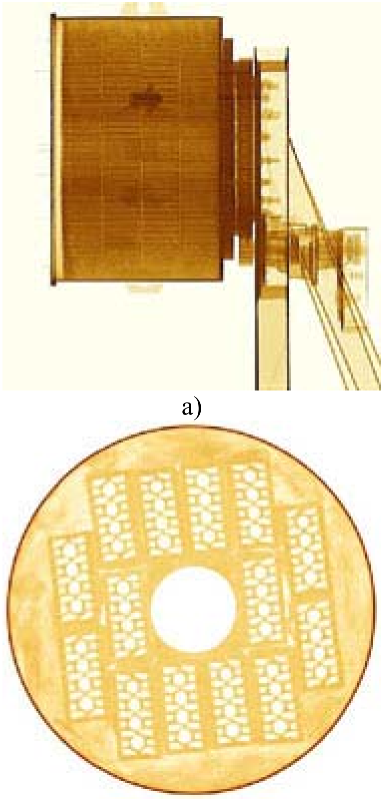
Special software serves for the data processing and visualization; it ensures preliminary processing of data and their digitization, data correction, image filtration and pseudo-colorization. The computer workstation allows the reconstruction of the object shadow image with a subsequent analysis of defects detected. Upon detecting a defect, an operator can localize and zoom up the fragment to have better opportunities for the defect sizing and spotting.

In the radioscopic systems developed in NIIEFA, the latest advances in the linear accelerators engineering, electronics and computer technology were applied, that made it possible to attain high spatial (about 1-2 mm) and density resolution (better than 1%) at an accelerator energy of 16 MeV.

Two-dimensional image obtained under radioscopic scanning can be easily interpreted when an inspected object is of simple internal structure. However, in some cases the structure of inspected object can be unambiguously identified only with computer- aided tomography.

Under tomographic inspection every object section is scanned under continuous or discrete rotation of object in the plane of the fan-shaped beam formed by the irradiator and beam collimation system. The data obtained as a result of angular scanning are written in file in the digital form and processed with methods of mathematical reconstruction. The application of the described procedure to a consequence of cross-sections allows one to obtain a complete image of the three-dimensional density distribution in an inspected object. The set of tomographic system equipment is similar to that of radioscopic system with some modifications made in the design of the positioning system and software.

Fig. 3 demonstrates introscopic and tomographic images of an inspected object.



a)

b)

Figure 3: a) the introscopic image of inspected object, b) the tomographic reconstruction of the object.

EFASCAN System for Radioscopic Inspection of Large-scale Cargoes

As a result of increasing volume of world trade and increasing number and variety of terrorist acts assassinated all over the world there is an insistent need for effective inspection of all transported cargoes in the real time mode to detect weapons, ammunition and contraband goods. With this aim in view, an EFASCAN radioscopic inspection system has been developed in NIIEFA. It is intended for examination of vehicles and large-scale containers without their opening and is distinguished with high throughput [6].

Depending on the way of transportation (auto, sea, air), three versions of the system are suggested.

"EFASCAN" (see Fig. 4) allows the inspection of large-scale containers in a special radiation shielded hall. Radioscopic examination of objects is performed by means of the fan X-ray beam, which is generated by a linear electron accelerator. During the scanning the transportation system moves the examined object across the X-ray beam with a constant speed of 0.4 m/s. Penetrated through the object radiation is registered by a detector line. Signals from the detectors are preliminary processed and transmitted to the workstations of the customs officers. The throughput of the system is 25 containers (2.5×2.5×12 m) per hour.

Figure 4: General view of the EFASCAN complex building

The basic (minimal) set of the equipment consists of: a linear electron accelerator, X-ray beam collimation system, detector line, data transfer system, data processing and visualization system, system for transportation of inspected objects, radiation, electrical and mechanical safety system, automated control system, cargo shipping documents input system and archiving system.

"EFASCAN" can be supplemented with the following options:

- Stereo viewing system of cargo content with an additional equipment such as second detector line, data transfer system, data processing and visualization system, two-slit X-ray collimation system, IR control polarization glasses and a special software. The system allows obtaining volume stereo image of cargo.
- System with two accelerators and double set of equipment, which allows X-ray images of the container in two projections – horizontal and vertical.
- System with dual energy of accelerator, which provides discrimination of groups of materials in the inspected object according to their average atomic number. Colored information on material of inspected cargo is visualized on the display of operator's workstation. The system facilitates the inspection routine of customs officers and detection of smuggled materials such as narcotic and explosive substances, non-ferrous and precious metals, etc.

In one of the modifications of the "EFASCAN-2" inspection system, the attending personnel is protected against ionizing radiation with local shields and due to remote control of the accelerator. Special crane is used for the transportation of the linac, detector line and X-ray beam collimation system.

It should be noted that with an available specialized vehicle, a mobile facility for inspection of cargoes on roads can be constructed. With this object in view, a small-size accelerator with local radiation shielding has been designed and manufactured in NIIEFA and is effectively used on customs inspection facilities HCV – MOBILE of the HEIMANN S.A. firm. Rational layout of the accelerator, module design of the radiation shielding made it possible to have such a compact irradiator 1480 kg in weight and 850×200×975 mm in size (see Fig.5). The energy of electrons can be chosen in the range from 1.9 to 4 MeV by changing the number of accelerating cells with the sizes of the irradiator kept unchanged.

Figure 5: Linac for mobile inspection system.

"EFASCAN-3" is intended for the radioscopic examination of freight trains moving with a speed of 15 km/h maximum. A special detection system provides a spatial resolution up to 10mm and density resolution up to 1%. Protection against ionizing radiation is provided with local shields and due to remote control of the accelerator.

Main Advantages of the Above Systems:

- Continuous round-the-clock operation of customs checkpoint resulting in its higher throughput, efficiency and quality of inspection with low expenditures for its implementation.
- Obtaining most exhaustive real-time information on the object under inspection.
- High-speed data processing and high quality of images ensured by applied software.
- Opportunity to compare the actual contents of inspected containers with the cargo declared in the cargo manifest.
- Archiving the obtained data.
- Opportunity of scrupulous analysis of suspicious items with no reduction of the system throughput due to several available workstations.

System for Detection of Explosive, Fissionable and Narcotic Substances of Vegetable Origin

Nuclear methods are highly promising for detection of explosive, fissionable and narcotic substances and these are precisely nuclear methods, which may ensure further progress in this field.

The works on the development of a system intended for detection of explosive (ES) and fissionable (FS) substances are in progress in NIIEFA. The system is based on a compact linear RF accelerator of deuterium ions generating pulse flows of neutrons up to 10^{14} n/pulses by impinging a special target. The detection method is based on ES identification from nitrogen, oxygen and carbon atoms: their high concentrations unambiguously testify presence of explosive substances in an inspected object. Compared to other available means, this method offers an appreciably lower level of false alarms.

Nowadays, production facilities for manufacturing such systems are available, the accelerator and the interaction chamber have gone into production, the multi-detector system and electron apparatus used for generation and processing of signals from an inspected object have been manufactured, the major part of the software is available, and accelerating structures undergo tests. To test the detection system and the detection method itself, measurements were done with a beam of neutrons produced on a cyclotron. Analysis of the results has shown that radiation lines produced by constituent elements of ES can be identified. In practice, gamma-radiation background will be reduced due to the pulse operating mode of the accelerator and applied synchronous detector method. Considerable difficulties were experienced in manufacturing the accelerators with RFQ structures with an operating frequency of 433 MHz. However, after purchasing a modern precision versatile machine tool, a new process for electrodes' machining was developed, which allowed us to adhere to specified tolerances of 10 microns for dimensions defining the field symmetry and electrodes' modulation .We plan to carry out engineering tests of the system as early as next year.

CONCLUSIONS

The experience gained in the development and construction of electrophysical systems in NIIEFA allows us to draw some general conclusions concerning the trends for further progress of applied accelerators.

First, these accelerators, in themselves, are not in great demand both in Russia and abroad. To provide a final result of (diagnosis, treatment, customs document, processing or any ready product), the electrophysical systems call for an additional electrophysical equipment to be designed. In addition, creation of such systems usually involves contractors competent in corresponding fields of science and engineering sometimes, foreign partners. Besides, a designing firm should be granted the international quality certificate for production of corresponding electro-physical equipment, be entitled for training of operating personnel, have a possibility of remote diagnostics, warranty and after-warranty service of the equipment (i.e. should have service center).

I wish to draw your attention that in the present-day contracts and tenders, in addition to competitive performances of the equipment all the above-said requirements are stipulated.

Second, components of the electrophysical systems should be compatible in hardware and software, complete computer control should be provided and controls on the operator's panel should be minimum in number.

Third, the software of such systems is of prime importance, as it embodies the major part of intellectual labor (results of research, technological know-how and possible options).

In conclusion, I would like to express hope that accelerator-based electrophysical systems will become attractive in economic, financial and innovative aspects and will be widely applied not only to industry and medicine but also will come into use in everyday life.

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