# ELECTRON LINACS IN NSC KIPT: R&D AND APPLICATION

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A review is given about electron linacs of NSC KIPT and their some applications for research of radiation effects in reactor materials, channeling, plasma-beam interactions, geology (gamma-activation analysis of ore samples), as well as sterilization of single-use medical products, modification of polymers and semiconductors, isotope production for nuclear medicine etc.

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## 1. INTRODUCTION

Characteristic of the Ukraine economy of today's transition period is the absence of stable situation on the radiation technology market. Considering this, it would be good advantage to develop, build and make use of accelerators with a broad range of parameters, capable to meet the market's demands. This ideology is fundamental in the activities of "Accelerator" R&D Production Establishment of the National Science Center "Kharkov Institute of Physics&Technology", the leading organization in Ukraine in creation of electron linacs and applicable technologies. This paper gives a short survey of some electron linear accelerators and the results in the areas of applied physics and radiation technologies.

## 2. ELECTRON LINACS

There are six electron linear accelerators at "Accelerator" R&D Establishment. The biggest one is the oldest linac in Europe LUE-2000 [1]. Three accelerators (EPOS [2], LU-10 [3,4], KYT [5]) are used for performing various radiation processes. The linac LIC [6,7] is used for conducting scientific researches in different fields. The linac KYT-20 is under construction. Main parameters of linacs are represented in Table 1.

### 2.1. ACCELERATOR EPOS

The accelerator EPOS [2] is a two-section linac with an extracted electron beam scanning system. It was built in 1999 on the base of the existing equipment. EPOS has been designed to be used for radiation processing of various items, employing electron beams with energies up to 30 MeV.

### 2.2. ACCELERATOR LU-10

The LU-10 single-section electron linac was commissioned in 1987 [3]. Up to mid-1993 it had operated with one KIU-53 klystron. In 1993 an upgrade was made with the using of the scheme of adding up the RF-power output from two KIU-12 klystrons [4].

***Table 1.*** *Basic Linacs Parameters*

| | EPOS | LU-10 | KYT | LIC | KYT-20 |
|---|---|---|---|---|---|
| Energy range, MeV | 10-30 | 8-18 | 8-14 | 13-18 | 16-28 |
| Operation energy, MeV | 20 | 12 | 9 | 15 | 20 |
| Frequency, MHz | 2797.2 | 2797.2 | 2797.2 | 2797.2 | 2797.2 |
| Number of sections | 2 | 1 | 1 | 1 | 2 |
| DLW length, m | 3.05 | 3.05 | 1.23 | 2.30 | 1.23 |
| Number of klystrons | 2 | 2 | 1 | 1 | 2 |
| RF-pulse width, μs | 5 | 4 | 5 | 2.2 | 5 |
| RF-power input, MW | 10 | 10 | 10 | 18 | 11 |
| Current-pulse width, μs | 4 | 3.5 | 4 | 0.3-1.5 | 4 |
| Repetition rate, pps | 300 | 300 | 300 | 1-6.25 | 300 |
| Average current, μA | 1000 | 1000 | 800 | 0.04-0.24 | 1000 |
| Maximum Bsf, Hz | 3 | 3 | 3 | -- | 3 |
| Size of beam at the exit, cm | 1 x 10 | 1 x 30 | 1 x 30 | -- | 1 x 10 |


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Since 1994 at the LU-10M research has been going on in basic and applied areas of radiation damage physics, radiation technologies and pharmaceuticals sterilization. The facility is equipped with a suspended conveyer belt, a load/unload and storage from for various items for a mass-scale radiation processing, and devices for target irradiation by large doses with necessary cooling.

The accelerator is equipped with metrologically licensed devices for energy spectrum measurements and monitoring of average and pulsed beam current.

### 2.3. ACCELERATOR KYT

The KYT has been operating in NSC KFTI since September 1993 [5]. KYT consists of electron linac with the scanning and electron beam extraction device, cooling and control systems. KYT produces 8-10 MeV electron beam with power up to 10 kW and is meant for performing various radiation technological processes including sterilization of medical articles.

The scanning and electron beam extraction device consists of a scanning magnet and a special system with an air-cooled exit foil.

### 2.4. ACCELERATOR LIC

The S-band linear accelerator LIC (Laser Injector Complex) [6,7] was developed and constructed for experimental research of charged particles dynamic, ultra-short wave generation in different systems and wake-field generation in plasma. The main components of the linac are the multipurpose RF gun [8] and a novel accelerating structure with period being two times higher than in similar structure with $2\pi/3$ mode [9]. The gun can be successfully used at both the thermionic and photo emission modes. The important features of accelerating structure are the possibility to accelerate large pulse charge (limit charge in our case is up to 800 nC) and RF focusing of the beam. During 1997-2000 the facility was used for studying the electron focusing in plasma by transverse components of wake-fields [10].

### 2.5. ACCELERATOR KYT-20

Accelerator KYT-20 will be a high-power electron linac for irradiation applications. It is under commissioning at “Accelerator” R&D Production Establishment of NSC KIPT. The linac consists of two accelerating structures with variable geometry and an injector including a diode electron gun, klystron type buncher and accelerating cavity. The linac will be equipped with a beam scanning system to extract the beam trough an air-cooled foil.

## 3. RESEARCH AND DEVELOPMENT

“Accelerator” R&D Production Establishment of NSC KIPT conducts different researches and developments in some fields of accelerator physics. The main of them are: studying the properties of periodic electrodynamic systems and development of different kind accelerator structures, electron guns and injector systems.

### 3.1. SIMULATIONS

The calculation of the electrodynamic characteristics of RF units and the simulation of particle dynamics plays the important role for the electron linac development and research. Analytical and numerical methods of calculations and simulations are mastered and developed in “Accelerator”. They supplement each other permitting to carry out the researches more effectively. The development of analytical model of coupling cavities has allowed developing methods of preliminary calculation and tuning the inhomogeneous disk-loaded waveguides [9, 11, 12, 13, 14, 15, 16, 17, 18, 19]. The analytical calculations of particle dynamics that take into account spatial non-synchronous harmonics of an electromagnetic field in the disk loaded waveguides have allowed to research a RF-focusing effect as well as effects concerning radiation of electrons in such waveguides [9, 20, 21, 22]. More detail research of electron dynamics in the accelerating and shaping systems of the linacs is successfully carrying out with both the world famous software (for example EGUN, SUPERFISH, PARMELA) and home made software. Using this software the diode electron guns of the injectors were designed and researched [23, 24] as well as RF guns [25, 26, 27, 28, 29, 30]. The effect of a back bombardment in thermionic RF guns also was researched [31] as well as the features of electron dynamics in linacs of S and K bands including effect of RF-focusing and places of beam particle loss localization [32, 33, 34].

### 3.2. ELECTRON SOURCES AND INJECTORS

The linac electron source and the injector system as a rule determine the beam characteristics at an accelerator exit. Therefore we put an emphasis on design and study these devices.

The diode electron guns with suitable beam characteristics for the different linacs were designed and fabricated. The hexaboride lanthanum ($LaB_6$), dispenser tungsten impregnated with barium aluminate and BaNi pressed emitter was used as cathodes. Two types guns – high voltage (80-120 kV) and low voltage (25 kV) [23,24] were developed. During ten past years we carried out the investigation of RF electron sources with different types of cathode [35]. These devises can produce a high quality beam and therefore they can be used as injector systems for high brightness electron linacs. The thermionic RF guns with various types of the resonant system are theoretically and experimentally studied [36, 27, 31, 34]. The typical beam characteristics of these RF guns are follows: the particles energy of 0.7-0.9 MeV, the pulse current of 1.5 A, phase bunch length less than 50°, the current pulse length of 0.7 - 1.5 μs, normalized emittance is not more than $12\pi$·mm·mrad. The RF guns for the high current beam generation with nanosecond pulse length based on photocathode and dielectric-metal cathode have been also designed and tested [37, 38]. From 1993 the investigations of physical processes during generation of tubular electron beams in magnetron guns with secondary–emission cold metallic cathodes have been carried out. The dependence of the beam current on the strength of electric and magnetic fields in the anode–cathode gap was studied. It is shown that in the constant magnetic field when changing the electric magnetic field within ±20% the beam formation is held and the beam current follows the law "3/2"[39]. The tubular electron beams of 5 MW pulse power were produced in a single magnetron gun and in a system of magnetron guns with secondary-emission cathodes. The beam current from 1 to 60 A with energy from 5 to 100 keV and pulse duration from 0.5 to 10 μs were produced using a cathode of 1 to 40 mm in diameter. The magnetic field was reached 3000 G, the beam inner diameter was approximately equal to the cathode diameter and the wall beam thickness was from 1 to 2 mm [40, 41]. The guns of this type can be used as electron sources in the accelerator technique and for the development of powerful single-beam and multi-beam microwave devices.

The compact injector (total length is 20 cm) for technological high power S-band linac has been designed, fabricated and tested [42]. The injector consists of the low voltage (≈ 25 kV) diode electron gun with oxide cathode, klystron type buncher, accelerating cavity, focusing system and beam current monitor. It produces the electron beam with energy more than 600 keV, pulse current above 1.4 A, pulse repetition rate up to 300 pps. This injector has been installed in 10 MeV technological linac [43] in 1993 and worked more than 30,000 hours. The upgraded modifications of the injector are used in 20 MeV technological linac [33] and special 1 MeV test facility. The new injector for high brightness S-band linac has been also designed. The injector consists of low voltage electron gun and a buncher operating on the stand wave mode. The buncher is the chain of coupled cavities with special phase and amplitude distribution along axis. The main feature of the injector is ability to integrate with traveling wave accelerating structure with phase velocity equal velocity of light. During past years we designed electron source and two different injector systems for compact K-band linac [34,44]. First of them is based on the multi-cavity RF gun, and second one is similar to the injector for technological S-band linacs.

### 3.3. RF - STRUCTURES

Recently methods of fabrication and tuning of piecewise-homogeneous accelerating structures (PHAS) have been developed in KIPT. These RF structures consist of series of uniform subsections jointed by transition cells. The uniform subsections differ in a loaded factor and the cell radius. The first developed PHAS named "Kharkov 85" and having π/2 operating mode were installed on the LU-2GeV linac to increase the energy gain and pulse beam current [45, 46, 47, 48]. The PHAS type section having high accelerating gradient up 20 MeV/m was designed and established as injector linac in a compact SR source [49, 50]. The main problem for PHAS tuning is the choice of transition cell parameters. Novel mathematics models of coupled pillboxes and disc-loaded waveguides [12,15,16,17] and tuning techniques [51, 11] were developed to solve this problem. According to these techniques the four inhomogeneous accelerating structures with 2π/3 operating mode have been developed and manufactured [11]. Three of them have quasi-constant law of coupling hole radius variation with a linear decrease of radii in transition cells, while in the fourth one the coupling hole radii decrease linearly from entrance to exit. New modifications of disc-loaded waveguides having (-2π/3) phase shift per cell were designed for the acceleration of short-pulse high current electron beams [52, 53, 54 55, 56]. The operating mode for such structures is the first spatial harmonic. The fundamental harmonic is no synchronous and provides radial RF focusing of a beam [57,58,59,32]. To create the small-sized linear electron accelerator with energy up to 5 MeV the technology of manufacturing and tuning technique of an accelerating X and K band structure are developed [34].

### 3.4. RF SUPPLY SYSTEMS

In accordance with the program of upgrading the 2 GeV linear accelerator as injector for pulse-stretcher ring PSR-2000, and, later, as warranted by the need of design and manufacture of industrial electron linacs with high average beam power, we have carried out research and development of RF-systems, which is aimed at RF supply of an accelerating system and electron bunch forming elements of the injector. As a result, powerful S-band RF-stations for providing a pulse power not less then 10-12 MW with a pulse length of 4-5 μs and repetition rate of 300-400 pps at the entrance of each accelerating section are developed [60,61]. The other type of the RF-stations destined for the high brightness beam study accelerator taste facilities feed have been designed, and fabricated too.

The high-voltage pulse modulator is intended for a feed of a klystron. The high-voltage modulators (anode voltage up to 270kV, pulsed current up to 230 A, pulse width 5 μs, repetition rate 300 - 400 pps) have been designed and blue-printed, constructed, tested and its parameters optimized. The operating units of the HV-modulators have met all design specifications with pulse-forming efficiency > 85 % and total efficiency > 75 %. They have been operated with industrial accelerators and displayed the necessary dependability and stability of the main characteristics

It was shown that klystrons such as AURORA klystrons (pulse output power up to 20 MW, average output power-2.6 kW, efficiency up to 30%), due to optimization of conditions of beam propagation and introduction of additional systems of cooling, ensures of output average power much exceeding a passport value. In particular, in this case the industrial serial klystron AURORA-type can operate at higher repetition rate and larger pulse length as it is regarded by the manufacturer's specifications and its average output power can be increasing from 2.6 up to 24 kW.

We have done work on the technology development of a klystron re-establishment. Several exemplars of klystron have been re-established in correspondence with developed technology. The output parameters of re-established klystrons are corresponded to the work characteristics after 14 000 hours of exploitation without degradation. As progress of this trend of the work development cathode produce technology was made.

Six versions of the RF power supply system were designed, constructed and installed; their parameters were measured and optimized. In particular the testing results of high power supply stations have shown, that the long, reliable operation is observed for levels of pulse output power not less than 12 MW, average output power not less than 18 kW (400 pps) and 13.5 kW (300 pps), full efficiency of the modulators not less than 70 % and full efficiency of high-frequency stations not less than 22 %.

The elements of the RF power transmission line supply scheme of the injector system were developed for three variants of the injector. There are injectors using HV diode guns, RF guns, and injector based on the low voltage diode guns and pre-accelerating cavities. Also there are two means of exciting the entrance cavity: from the RF-master oscillator with a power of 10 kW and higher long-life stability or at the active oscillator regime of high power klystron operation due to feedback chain.

### 3.5. AUTOMATIC CONTROL SYSTEM

The special system has been developed for linac control [62]. It controls the electron beam current [63,64], the energy [65] and the position [66,67], defends the accelerating and scanning systems from the damage caused by the beam; blocks the modulator and the klystron amplifier in the case of the intolerable operation regimes, regulates the phase and power of the HF signals in the injecting system and also regulates the source power currents in the magnetic system. As well as the radiation dose of the technological samples is controled and the target devices are operated. The program & technical complex consists of PC equipped with CAMAC crate or measuring channels in PC standard, synchronization unit, microprocessor-operated complexes to monitor the klystron amplifier operation, the thermostating system, magnet power supplies, the target equipment.

## 4 APPLICATION

Electron linacs of NSC KIPT are used for research of radiation effects in reactor materials, channeling, plasma-beam interactions, geology (gamma-activation analysis of ore samples), as well as sterilization of single-use medical products, modification of polymers and semiconductors, isotope production for nuclear medicine etc.

### 4.1. RADIATION FACILITIES & METROLOGICAL MAINTENANCE

The linacs mentioned above provide the radiation parameters, which are presented in the Tab. 2.

The analytical methods and technologies using electron (or bremsstrahlung) irradiation [68] demand continuous monitoring of the radiation parameters. To provide a certification of the accelerators and technologies as well as a metrological maintenance of the radiation treatments a number of the standard and technological measurement channels have been developed [69,70]. The technological measurement channels are based on the sensors that do not disturb a radiation field (Rogovski coils of different modification [71], radiation-acoustic string [72], thin-wall ionization chambers [73], etc.). Most of them were previously investigated by means of computer analysis using code GEANT.

***Table 2**. Main parameters of the linacs radiation*

| | Intensity (max) | Flux (max) | Dose rate, $Gy \cdot h^{-1}$ (max) | Dose (range), Gy |
|---|---|---|---|---|
| electrons | $6 \cdot 10^{15}$ $s^{-1}$ (10kW) | $1 \cdot 10^{15}$ $cm^{-2} \cdot s^{-1}$ | $4 \cdot 10^7$ | $10^3 ... 10^{11}$ |
| breaking photons | 2kW | $1 \cdot 10^2$ $W \cdot cm^{-2}$ | $1 \cdot 10^4$ | $10^2 ... 10^8$ |

### 4.2 ISOTOPE PRODUCTION

Nowadays the majority of medical isotopes are produced on the fission reactors and cyclotrons. These technologies entail a problem of great amount of the radioactive waste. Taking into account a continuous growth of the medical isotope utilization, an elaboration of the secure methods for production of them is a problem of extreme importance. The use of electron accelerators is proposed as some opportunity to solve this problem [74,75,76].

**Technetium-99m**. This isotope provides now up to 90 % of medical analyses using gamma-scintigraphy method (see, for sample, [77]). At the same time a production of the 1 Ci of $^{99}Mo$ (a parent-isotope of $^{99m}Tc$) on a reactor is accompanied by generation up to 50 Ci of long-lived radioactive waste [78]. The method based on photonuclear reactions under breaking photons of high-current electron accelerator provides a sufficient yield of the $^{99}Mo$ without generation of large amount of the waste [79,80].

**Isotopes for PET**. A rather essential role in a diagnostics of various kinds of diseases is assigned to pharmaceuticals labeled by radionuclids as $^{11}C$, $^{13}N$, $^{15}O$ and $^{18}F$. These positron-active nuclides are widely used as the sources of annihilation gamma-radiation with the energy of 511 keV in positron-emission tomograph (PET). There was shown in our investigation that on electron linac (25 MeV, 20 kW) one can produce the mentioned isotopes with the specific activity $1.9 \cdot 10^7$; $1.67 \cdot 10^6$; $2.5 \cdot 10^6$; and $1.7 \cdot 10^6$ Bq/g·μA (beam current) respectively [81].

**Other isotopes**. The analysis of the different photonuclear reactions and their cross-sections has shown that a lot of medical isotopes (i.e. $^{32}P$, $^{33}P$, $^{43}K$, $^{57}Co$, $^{68}Ga$, $^{73}As$, $^{89}Sr$, $^{103}Pd$, $^{125}I$, $^{181}W$ etc.) can be produced on electron accelerators as well [82].

### 4.3. GAMMA-ACTIVATION METHOD

The characteristic γ-radiation of the samples irradiated by high-energy breaking photons can be used for determination of their element (isotope) content. This effect discovers a lot of applications in the science, technology, ecology etc. So, it is known that γ-activation analysis is used for express-measurement of the Au concentration in the ore samples [83]. We have shown a possibility of its application in the analysis of the rare and noble metals [84,85,86] as well as in biophysics [87].

It seems to be one more promising linac application for characterization of radioactive waste of wrecked Chernobil 4-th unit. So, the waste activation with high-energy breaking photons enables a transformation of the β-active isotope ($^{90}$Sr) into γ–active one ($^{89}$Sr) and makes easier its identification. Also a practically nonactive $^{238}$U can be transformed into γ-active $^{237}$U using $^{238}$U(γ,n)$^{237}$U reaction (i.e. determined by means of γ-activation analysis).

On the other hand a problem of reliable disposal of the long-lived waste is of particular importance as well. The confinement materials (including the geological structures) for such disposal have to keep their protection properties with respect to radionuclide transport under absorbed dose value up to ~$10^8$ Gy during hundreds years or so. The appropriate methods for production of the radionuclide-tracers and operative determination of their diffusion coefficients into geological barriers under different doses of the bremsstrahlung are elaborated [88].

### 4.4. ELECTRON RADIATION PROCESSING

Sterilization is one of the widespread applications of radiation. Its advantages are high effectiveness, ecological security and low cost. So, the plant for sterilization based on LU-10 linac was put into operation [89,90]. The plant is equiped by conveyor for distant transportation of treated products to irradiation zone and back. The productivity of the plant is up to 15 tons per operating day (for absorbed dose value up to 25 kGy).

A radiation modification of semiconductors enables to improve their time resolution. So, more than $10^5$ units of various tyristors and silicon plates was treated on LU-10 [91].

A radiation treatment of polyethylene is accompanied by a growth of its molecular weight, melting temperature and appearance of “memory” effect. The latter is used for production of thermoshrinkable PE wares mainly for electrotechnical industry (cable isolation box etc.).

### 4.5 RADIATION TEST

The radiation facilities of the NSC KIPT descried above enable the tests of different materials, devices and construction elements within a wide range of the radiation parameters and dose values. So, during last period there was tested a number of the fission reactor elements and materials [92,93] ceramics [94], magnetics [95], concrete and granite samples [23] as well as semiconductor detectors of γ-radiation. The methods for express-imitation of radiation defects and prognostication of radiation stability of the construction materials were elaborated.

## 5. CONCLUSION

As one can see from the presented results, “Accelerator” R&D Production Establishment is a dynamic developing department of the National Science Center “Kharkov Institute of Physics&Technology” which plays an important role at the Ukrainian market of radiation technologies.

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