THE NSC KIPT ELECTRON LINACS - R&D

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The electron linac research and development activity in the "Accelerator" R&D Production Establishment of the National Science Center KIPT are reviewed in the paper. The main results of linac system researches (electron sources, injector systems, accelerating structures, RF supply, control, and beam parameters measurement) obtained for the past ten years are presented.

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1. INTRODUCTION

During many years, the "Accelerator" R&D Production Establishment of the NSC "Kharkov Institute of Physics&Technology" is the leading organization in Ukraine in the development of electron linacs and applied technologies. At present, the main concept of the NSC KIPT linac activities is the development, fabrication and application of accelerators with a wide range of parameters, which capable to meet any market's demands. This ideology is dictated by the absence of stable situation on the Ukrainian market of radiation technologies. The paper gives a short survey of some electron linear accelerators and main results in the field of linacs physics and technique.

2. ELECTRON LINACS

There are six electron linear accelerators designed and fabricated in the "Accelerator" R&D Establishment NSC KIPT besides the oldest linac in Europe LUE-2000 [1]. Four accelerators (EPOS [2], LU-10 [3, 4], KYT [5], KYT-20 [6]) are used for performing various radiation processes. The linac LIC [7, 8] is used for scientific researches in different fields. The linac LU-60 [9] was designed and established as the injector linac in a compact synchrotron radiation source and as accelerating facility for scientific researches. Main parameters of linacs are represented in the table.

Basic Parameters of Linacs

	EPOS	LU-10	KYT	KYT-20	LIC	LU-60
Energy range, MeV	10 -30	8-18	8-14	16-28	13-18	40-60
Operation energy , MeV	20	12	9	20	15	60
Frequency, MHz	2797.2	2797.2	2797.2	2797.2	2797.2	2797.2
Number of sections	2	1	1	2	1	1
DLW length, m	3.05	3.05	1.23	1.23	2.30	3.25
Number of klystrons	2	2	1	2	1	1
RF-pulse width, μs	5	4	5	5	2.2	1.5
RF-power input, MW	10	10	10	11	18	25
Current-pulse width, μs	4	3.5	4	4	1.5(0.007)	0.1
Normalised emittance (rms), π·mm·mrad	-	-	-	-	14	150
Repetition rate, pps	300	300	300	300	1-6.25	1-6.25
Average current, μA	1000	1000	800	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	-	-

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]. It operated with one KIU-53 klystron up to mid-1993. The upgrade was made in 1993 using the scheme of the output RF-power adding up from two KIU-12 klystrons [4].

Since 1994, the LU-10M has been employed for researches in basic and applied areas of radiation damage physics, radiation technologies and pharmaceuticals sterilization. The facility is equipped with a suspended conveyer belt 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 is the first technological linac that completely designed and fabricated in the "Accelerator" R&D Production Establishment. It has been operating since September 1993 [5]. KYT includes the electron linac with the scanning and electron beam extraction device, cooling and control systems. The linac is composed of the accelerating section and an injector including a diode electron gun, klystron type buncher and accelerating cavity. The scanning and electron beam extraction device consists of a scanning magnet and the special system with an air-cooled exit foil. KYT produces 8-10 MeV electron beam with power up to 10 kW to supply various radiation technological processes including sterilization of medical articles.

2.4. Accelerator KYT-20

KYT-20 is the facility for irradiation applications mainly for isotope production for nuclear medicine. The facility based on a high-power electron linac. The linac consists of two accelerating structures with variable geometry and upgraded KYT's injector system. The linac was put into operation in 2002. The wave phase velocity in the structures is equal to the velocity of the light. Length of the accelerating section is 1.23 m, oscillations mode is $\theta=2\pi/3$. The linac is equipped with a beam scanning system to extract the beam through an air-cooled foil. All systems of the accelerator are controlled by the computerized control system [68]. The RF system includes two powerful amplifying klystrons with modulators and wave-guide system. The klystron of the first section operates as a self-excited oscillator. The part of the output RF power from this klystron is divided for the buncher and the accelerating resonator feeding as well as for the excitation of the klystron of the second section by the directional couplers and phase shifters.

2.5. Accelerator LIC

The S-band linear accelerator LIC (Laser Injector Complex) [7, 8] 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 [[10]] and the novel accelerating structure with period being two times higher than in similar structure with $2\pi/3$ mode [[11]]. The gun can be successfully used both in the thermionic and photo-emission modes. The important features of the 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 [[12]]. During 1997-2002 the facility was used for studying the electron focusing in plasma by transverse components of wake-fields [[13]], for experimental study of the millimeter Smith-Purcell radiation [[14]], and for new types of RF gun studying [[15], 42].

2.6. Accelerator LU-60

The base model of the accelerator LU-60 was designed in 1989 – 1990 as electron beam injector into compact synchrotron radiation source. There are two similar accelerators have been constructed. The main features of LU-60 are the use of the RF gun with α-magnet and high gradient (20 MeV/m) accelerating structure. It allows obtaining the high brightness beam with energy 60 MeV and energy spectrum width less than 2 %.

3. RESEARCH AND DEVELOPMENT

"Accelerator" R&D Production Establishment of NSC KIPT conducts different researches and developments in some fields of accelerator physics. The mains of them are: studying the properties of periodic electrodynamic systems and the development of different kinds of 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 [11, [16], [17], [18], [19], [20], [21], [22], [23], [24]]. 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 [11, [25], [26], [27]]. More detail research of electron dynamics in the accelerating and shaping systems of the linacs is successfully carried out with both the world famous software (for example EGUN, SUPERFISH, PARMELA) and home made software. The diode electron guns of the injectors as well as RF guns [[28], [29], [30], [31], [32], [33], [34]] were designed and researched using this software. The effect of a back bombardment in thermionic RF guns also was researched [[35]] 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 [36, 37, 38].

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 of these devices. We design two type of injector system: injectors based on a RF gun and traditional injectors with a DC diode electron gun.

During ten past years we carried out the investigation of RF electron sources with different types of cathode [39]. 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 [40, 31, 35, 38]. The typical beam characteristics of these RF guns are follows: the particle energy of 0.7-0.9 MeV, the pulse current of 1.5 A, the bunch phase length less than 50°, the current pulse length of 0.7 - 1.5 μs, normalized emittance is not more than 12 π·mm·mrad. The low pulse intensity beam with high frequency pulse repetition rate is required for carrying out experiments on study of the relativistic electron interactions with crystals. Therefore we designed and tested a new RF gun with metallic thermionic cathode [15]. 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 [41, 42].

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 were used as cathodes. Two types guns – high voltage (80...120 kV) and low voltage (25 kV) [33, 34] were developed.

The compact injector (total length is 20 cm) for technological high power S-band linac has been designed, fabricated and tested [43]. 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 [5] in 1993 and worked more than 30 000 hours. The upgraded modifications of the injector are used in 20 MeV technological linac [37] and special 1 MeV test facility. During past years we designed electron source and two different injector systems for compact K-band linac [38, 44]. At present we design the new injector for high brightness S-band linac. The injector consists of low voltage electron gun and a buncher operating on the standing wave mode. The buncher is the chain of identical coupled cavities with special phase and amplitude distribution along the axis [45]. The main feature of the injector is its operating on the non-propagating oscillations. The injector has ability to integrate with travelling wave accelerating structure with phase velocity, which equals to the velocity of light.

3.3. RF - Structures

Methods of fabrication and tuning of piecewise-homogeneous accelerating structures (PHAS) have been recently developed in KIPT. These RF structures consist of series of uniform subsections jointed by transition cells. The uniform subsections are differed in a loaded factor and the cell radius. The first developed PHAS named “Kharkov 85” operating on π/2 mode was installed on the LU-2 GeV linac to increase the energy gain and pulse beam current [46, 47, 48]. The PHAS type section with high accelerating gradient up to 20 MeV/m was designed and established as injector linac in a compact SR source [49, 9]. The main problem for PHAS tuning is the choice of transition cell parameters. Novel mathematics models of coupled pillboxes and disc-loaded waveguides [17, 20, 21, 22] and tuning techniques [50, 16] 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 [16]. 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 are decreased 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 [51, 52, 53 54, 55]. 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 [56, 57, 58, 36]. 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 [38].

3.4. RF Supply Systems

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 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 input of each accelerating section are developed [59, 60]. The other type of the RF-stations destined for the high brightness beam study accelerator test facilities feed have been designed and fabricated, too.

The high-voltage modulators (anode voltage up to 270 kV, pulsed current up to 230 A, pulse width 5 μs, repetition rate 300 – 400 pps) have been designed, fabricated, tested and optimized. The operating units of the HV-modulators have met all design specifications with pulse-forming efficiency > 85 % and total efficiency > 75 %. Designed HV-modulators have operated with industrial accelerators and displayed the necessary dependability and stability of the main characteristics.

It has been shown that such klystrons 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 output average power much exceeding a passport value. In particular, in this case the industrial serial AURORA-type klystron 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 increased from 2.6 up to 24 kW.

We have been developed a technology of a klystron restoration. Several samples of klystron have been restored in correspondence with developed technology. The output parameters of the restored klystrons correspond to the work characteristics after 14 000 hours of operation without degradation. The testing results of the designed 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), total efficiency of the modulators not less than 70 % and total efficiency of high-frequency stations not less than 22 %.

3.5. Beam parameters measurement and control system

Methods and instruments for the measurement and control of beam parameters were designed. Some of them are used for scientific experiments and others ones are used for the metrological maintenance of the technological process.

The bunch length measurements are very important for accelerator physics and accelerator applications in relativistic electronic. Therefore we pay attention to the development of suitable measurement methods. In particular we designed the bunch length monitor that based on generation of coherent diffraction radiation (CDR) from relativistic electron bunches at its motion over a metallic grid [61]. The method based on temporal scanning of the optical radiation of electron bunch was also proposed [62].

The technological measurement channels are based on the sensors that don't disturb a radiation field (Rogovski coils of different modification [63], radiation-acoustic string [64], thin-wall ionization chambers [65], etc.). Most of them were computer simulated a priori using code GEANT. The special system has been developed for linac control [66]. It controls the electron beam current [67, 68], the energy [69] and the position [70, 71], 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 modes. This system adjusts the phase and power of the RF signals in the injecting system and also adjusts the source power currents in the magnetic system. In addition the radiation dose of the technological samples is controlled and the target devices are operated.

4. CONCLUSION

As one can see from the presented results the chosen direction of the development of linac physics and technique in the present economic condition is correct. The accelerators created during past 10 years (KYT, KYT-20, LU-60, LIC) correspond to modern requirements on the design and beam parameters. Despite of the present difficulties the "Accelerator" R&D Production Establishment of the National Science Center "Kharkov Institute of Physics&Technology" stays up as organization that can solve complex tasks on design of new accelerating technique.

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