5-10 MEV INDUSTRIAL HIGH POWER ELECTRON ACCELERATORS

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Abstract

This paper presents the description of high power linear accelerators for industrial applications. 5 MeV accelerator having 50 kW beam power has been developed and is serially manufactured now. This accelerator can be used in two modes: electron and X-ray generation (using special target). The accelerator with X-ray target can be widely used for food product treatment. Two of such accelerators have been already supplied to USA.

New more powerful accelerator is in the process of designing now. The accelerator has a modular structure and consists of the chain of accelerating cavities, connected by the on-axis located coupling cavities with coupling slots in the walls. Main parameters of the accelerator are: operating frequency of 176 MHz, energy of electrons of 5-10 MeV depending on the number of accelerating cavities, average beam power up to 300 kW at duty factor of 15%. The necessary RF pulse power can be obtained, for example, from TH628 diacrode.

1 INTRODUCTION

In recent time the interest to radiation technologies using high energy gamma rays is increasing due to their high penetration ability. It is especially important for pasteurization of wide spectrum of food products, disinfection of mail deliveries and other applications.

The food products processing requires compact and relatively cheap accelerator because this developing market will require great amount of reliable and rather simple machines having electron energy of 5 or 10 MeV and beam power 50 kW or more. We suppose that new ILU machines will meet these requirements.

The ILU electron accelerators [1-4] are pulse linear high frequency machines purposed for wide application in various technological processes and so they are designed for long continuous and round-the-clock operation in usual industrial conditions. The first ILU machines were developed in the Budker Institute of Nuclear Physics in the beginning of 70-s. All ILU machines are simple in their design, have a high reliability and maintenance ability, are easily serviced and simply controlled. Dozens of ILU machines are working in Russia and in many other countries. The parameters of the ILU accelerators are given in Table 1. They are single cavity single gap machines and cover the energy range from 0.5 to 5 MeV, the beam power can be up to 50 kW.

The ILU-10 machines have energy range up to 5 MeV and beam power up to 50 kW and presently are used for X-ray generation.

Because of low efficiency of gamma-ray conversion in the electron energy range below 5 MeV the intensity of X-rays required for some industrial applications can be achieved only when the beam power will be up to 300 kW. So there is the demand for 5 MeV 300 kW machine.

2 ILU-10 ACCELERATOR

The food products processing requires compact and relatively cheap accelerator because this developing market will require great amount of reliable and rather simple machines having electron energy of 5 MeV and beam power 50 kW or more. New ILU-10 machines having energy of up to 5 MeV and beam power up to 50 kW meet these requirements.

Use of a principle of high-frequency acceleration has allowed to create rather simple design of the machine having modest dimensions and weight. As a result the machine can be placed inside the hall of the smaller dimensions compared to the halls for rectifier type accelerators having the same parameters.

The ILU-10 machines can be used for electron beam treatment of various products or as a source of electron beam for X-rays generation on the special target. The ILU-10 machine has bigger resonator than the preceding model ILU-6 and 2 HF generators and so beam power of 50 kW at energy of 5 MeV is reached. The optimization of resonator and usage of two HF generators placed symmetrically on the upper side of the resonator permitted to avoid the usage of constant bias voltage supplied on the insulated lower half of the resonator of ILU-6 machine to suppress the excitation of discharge in the resonator.

Table I. Parameters of the ILU accelerators.

PARAMETER		ILU-8	ILU-6	ILU-6M	ILU-10	ILU-10M
Energy range, MeV		0.5-1	1-2.5	1-2.5	3-5	2.5-4
Maximum beam power, kW		20	20	50	50	20
Average beam current, mA		25	20	25	15	8
Maximum consumed power, kW		100	100	150	180	100
Weight, tons	Accelerator	0.6	2.2	2.2	2.9	2.5
	Local shielding	76	-	-	-	-

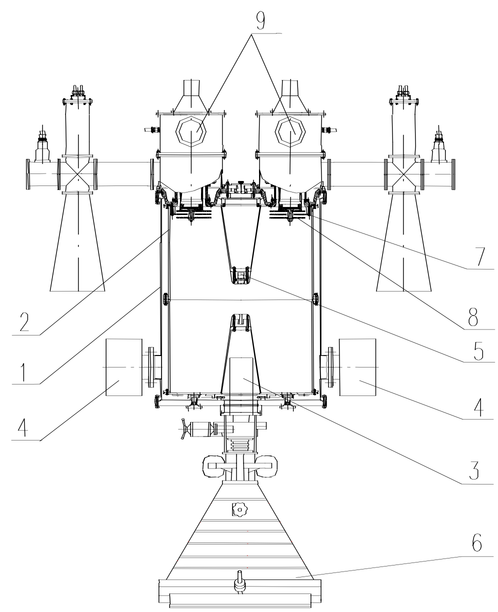

Figure 1: ILU-10 accelerator. 1 - vacuum tank, 2 - resonator, 3 – magnet lens, 4 – high vacuum pumps, 5 - electron gun, 6 – beam scanning system, 7- support, 8 - separating vacuum capacitor, 9 - HF autogenerators.

The design of ILU-10 machine is shown in Figure 1. The HF resonator cavity 2 has toroidal form, its working frequency is 115 MHz. It is placed inside the stainless steel vacuum tank 3. The triode electron gun 5 is formed by the cathode unit and grid placed in one of the protruding electrodes and the accelerating gap of the resonator. The resonator is fed from two HF autogenerators 9 realised on the industrial triodes. The feedback signal is given from the resonator, and the output power passes to the resonator via the separating vacuum capacitors 8. The absence of outer beam injection and usage of self-excited HF generator simplify the design of accelerator and ensure its reliable operation. Such accelerator does not contain details having potentials with respect to the ground that are comparable with accelerating voltage.

The potential on the anode plates of the HF generators gives asymmetry in HF electric field and so the conditions for the excitation of HF discharge are not favorable. The resonator for ILU-10 machine is produced as the single unit, and it decreases the HF losses in the resonator. The total dimensions of ILU-10 machine are not sufficiently greater than that of ILU-6 machine.

To improve the efficiency of beam energy conversion into X-ray power we have to reduce the low energy part of electron energy spectrum. On the ILU-10 machine we have realized it by applying the bias voltage on the electron gun. Two possibilities were checked – the constant bias voltage and bias voltage of first harmonics of resonator's frequency. The voltages were adjusted by their value and phase shift. As it was expected, the bias voltage of first harmonics occurred to be more efficient than constant voltage.

The results of the calculations and measurements of electron beam energy distribution spectra for ILU-10 machine are shown in Figure 2. The measurements were carried out without beam collimating and in presence of magnet lens in the optical tract of the accelerator. This is the reason for the visible difference between the results of the calculations and measurements, especially in case of wide electron beam energy spectrum (without the HF bias voltage).

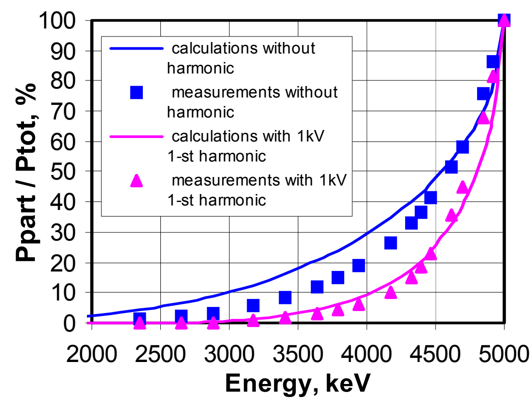

Figure 2: Spectrum of electron beam energy without and with harmonic bias voltage for ILU-10 accelerator.

3 ILU-12 ACCELERATOR

Because of low efficiency of gamma-ray conversion in the electron energy range below 5 MeV there is the demand for 5 MeV machine with power up to 300 kW.

The experience of development and operation of the ILU accelerators [1-4] for the energy up to 5 MeV has shown that the structure with one accelerating gap can be used in industrial accelerators having average beam power up to 50 kW. The increase in average beam power and accelerator's efficiency obviously requires the use of accelerating structure having several accelerating gaps placed in series. The first such machine was ILU-11 [5]. It has 2 accelerating gaps, and we reached the energy of 5 MeV. Now we have developed next machine not copying the structure of ILU-11. The new machine will have the chain of resonators (the same type as in ILU machines) axially placed and coupled via coupling resonators and 5 accelerating gaps. The coupling of resonators is done via the two slots in common walls having length of 80º on azimuth. The advantages of this accelerating structure are the simplicity of single-wall design, convenience of cooling via the channels inside walls and the steadiness to the heat drifts. The obvious disadvantage is the necessity to cover the copper surfaces with titanium nitride to suppress the development of multipactor discharge in the resonators.

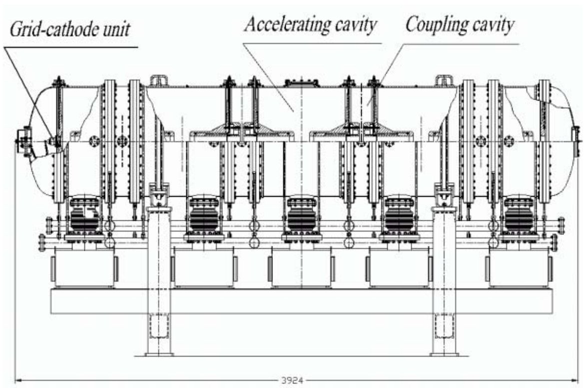

Figure 3: General view of accelerator.

Figure 3 represents the general view of new electron accelerator ILU-12. We expect that it will be efficient machine having energy of 5 MeV and average beam power up to 300 kW. The electrons are accelerated in the low frequency multi-resonator standing wave structure with on-axis situated coupling resonators. This design permits to decrease power losses in each resonator comparing with the single-resonator structure (at the same average beam power level) and to increase the electron efficiency of accelerator. Unlike all the previous ILU machines this accelerator has no outer stainless steel vacuum tank. Its vacuum tank is formed by the accelerating resonators and coupling resonators assembled together through indium sealing by means of studs (bolts). The ends of the structure are covered with the vacuum covers withstanding atmospheric pressure.

The electron beam is injected by triode electron gun formed by cathode-grid unit placed into the first accelerating gap. This concept permits to sufficiently simplify beam injection system.

To realize this new accelerator one has to solve the following problems:

- achievement of required value of pulse beam current at low electric field tension in the cathode-grid gap;
- lossless transportation of powerful electron beam through the accelerating structure without usage of electro- and magnitostatic lenses.
- highly efficient cooling of the accelerating structure's resonators;
- suppression of parasite HF discharges inside the resonators;

The solution these problems will permit to sufficiently simplify the design and hence to decrease the cost of the accelerator and also to improve its reliability and to decrease the maintenance costs.

3.1 Main Requirements to the Accelerator and Schematic Diagram

The accelerator ought to have high electric efficiency and great average beam power up to 300 kW in the energy range near 5 MeV. To decrease the heat power dissipating in the accelerating structure the pulse mode of functioning is chosen. The accelerator's working frequency of 176 MHz permits to use the efficient powerful electronic tubes: diacrode TH628 (efficiency 73%) or tethrode EIMAC 4CM2500KG. Considering the power dissipated in the accelerating structure the average output power of the generator ought to be about 450 kW and peak power - about 2.8-3 MW. The accelerating structure ought to be simple in production.

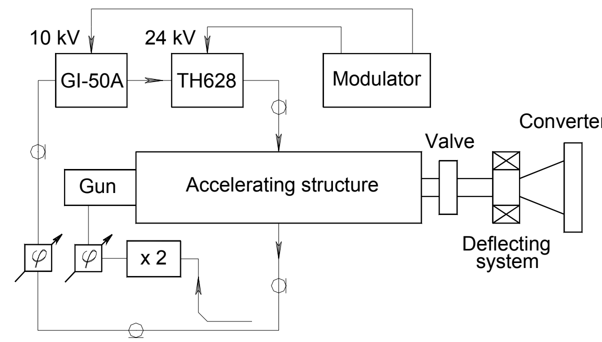

Figure 4: Block diagram of the accelerator

Figure 4 presents the block diagram of the accelerator. The main elements of the accelerator are: triode electron gun, accelerating structure, two-stage HF amplifier, modulator, and X-ray converter.

Triode electron gun is formed by the first accelerating gap. To decrease the energy spread of the electrons in the beam the bias voltage of second harmonics is applied to the cathode-grid circuit of the gun. The phase of this bias voltage is controlled by the phase shifting line.

The accelerating structure of the 5 MeV machine consists of 3 full resonators and 2 half-resonators at the ends.

The two-stage HF amplifier supplies the HF power to the accelerating structure through its central part. To provide the generation the amplifier is fed from the accelerating structure via the phase shifter (necessary to adjust the proper phase shift in the feedback signal). The two-stage circuit was chosen to increase the output power, to optimally tune the final stage and to improve the working conditions of the feedback phase shifter. To get the pulse power of 2.8-3 MW (about 450 kW of average power) the tethrode 4CM2500KG or diacrode TH628 will be used in the last stage. Diacrode TH628 was tested on the testbed of the firm "THOMSON" in the mode of 3 MW of pulse power (and average power of 600 kW). The generator of the ILU-8 accelerator (made on triode GI-50A) can be used as a first stage of the amplifier.

The modulator feeds the HF amplifier. Its pulse power ought to be about 6 MW and average power – about 600 kW, and the output voltages ought to be 10-12 kV for first stage and 24-26 kV for second stage of the amplifier.

The X-ray converter is placed on the output of the accelerator to convert the electron beam power into X-rays.

3.2 Electron Gun

The triode electron gun is formed by the cathode unit and grid placed in one of the protruding electrodes and the first accelerating gap – like in ILU-10 machine. The beam injection system (electron gun) of the described accelerator (see Fig. 1) must provide the pulse electron current up to 5 A while the cathode's square will be 3 cm^2 and amplitude of electric field tension on the plane of grid will be up to 60 kV/cm. The cathode is made from LaB_6 and its diameter is 20 mm.

3.3 Accelerating Structure

The results of performed analysis showed us that concerning the stability of the electrodynamic parameters and simplicity of production the biperiodical accelerating structure with on-axis situated coupling resonators and working oscillation mode $\pi/2$ excited in the structure's plane of symmetry (through the central resonator) has the advantages over other variants. The accelerating structure (see Fig. 3) consists of 4 modules and forms 3 full and 2 half-size side accelerating resonators (and also 4 coupling resonators). Figure 5 represents the module of accelerating structure operating in $\pi/2$ mode, the coupling coefficient is about 10%.

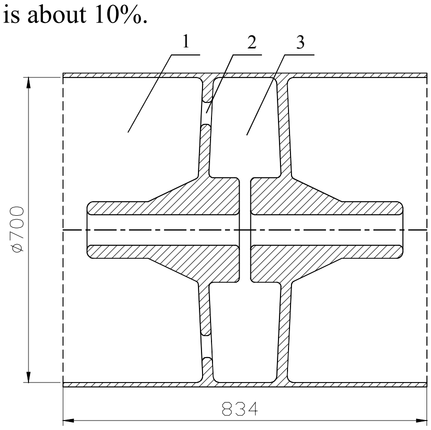

Figure 5: Accelerating structure module with on-axis situated coupling resonator. 1 - accelerating resonator, 2 - coupling slot, 3 - coupling resonator.

In order to create required accelerating gradient for electrons to reach the energy of 5 MeV in 4-moduled accelerating structure we need about 0.63 MW of RF pulse power. Assuming this power by level of 0.8 MW (decrease of Q-factor in 10% due to influence of coupling gaps and in 15% due to roughness of surface, etc.). With power supply of 2.8 MW, we can transfer about 2 MW to the beam и can reach electron energy efficiency of more than 70%.

Accepting 300 kW as an average beam power we can set duty factor of 15%. In this case the power losses in each module of accelerating structure (see Fig. 4) will be about 30 kW.

The inner surfaces of the resonators ought to be covered with the titanium nitride to prevent the excitation of the high frequency resonance discharge (multipactor).

The accelerating structure is assembled in vertical position on the assembling support installed near the main support. After the end of assembling the structure is placed on the main support in horizontal position by means of hoisting device. The spallation vacuum pumps and cooling water collector are also fastened to their places on the main support.

4 BEAM DYNAMICS

Numerical simulation of the beam dynamics from the grid to the accelerator output was performed in long-wave approximation using SAM code [6]. The transverse velocity spread of electrons due to scattering on the microlenses formed by grid mesh was taken into account.

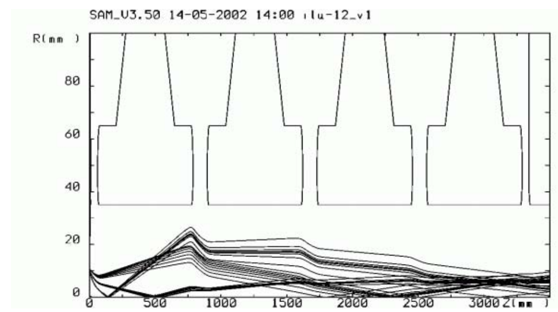

Figure 6: Results of beam dynamic simulation of four-resonator accelerating structure.

Figure 6 shows the results of beam dynamics simulation of four-resonator (forms 3 full and 2 half-size) accelerating structure for energy of 5 MeV. The trajectories of the electrons, started from the cathode edge at different input phases, are shown considering the initial spread of transverse speed of the electrons. The simulations showed that there is no need in any magnetic focusing elements for the successful transportation of the beam.

Figure 7 shows the calculated dependence of the electron energy on the output of the accelerator on the phase of passing the plane of the control grid. To compensate transit effects, it is possible to apply to the cathode-grid gap the additional voltage of either basic, second or third harmonics with appropriate phase (see Fig.7).

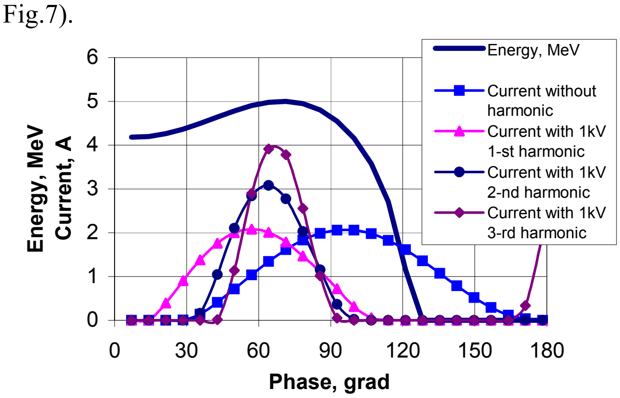

Figure 7: Dependence of electron energy on initial phase without and with grid-cathode bias voltage.

Figure 8 shows the calculated spectrum of electron beam energy on the output of the accelerator without the correction of transit effect (constant bias on the cathode-grid gap) and with applying the additional voltage of either basic, second or third harmonics.

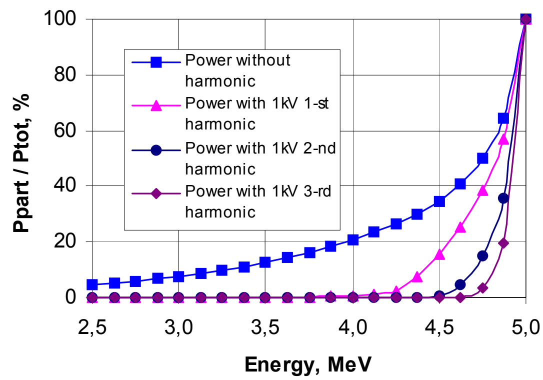

Figure 8: Spectrum of electron beam energy without and with harmonic bias voltage.

The partial power P_{part} shown in Fig. 8 is determined according the formula:

$$P_{part}(W) = \int_0^W \frac{\partial P}{\partial W} dW , \qquad (1)$$

where $\partial P / \partial W$ is the differential density of electron beam power and $P_{tot} = P_{part}(W_{\max})$ is the full beam power.

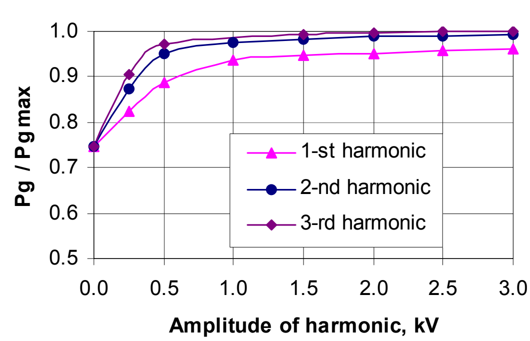

Figure 9: Dependence of γ-quanta relative power on amplitude of harmonic bias voltage at fixed beam power.

Figure 9 shows the calculated dependence of relative electron beam power conversion efficiency into γ-quanta power on amplitude of harmonic bias voltage at fixed beam power of 300 kW and energy of 5 MeV.

5 CONCLUSION

The achievement of full accelerator's parameters (5 MeV, 300 kW of average beam power) will require the creation of powerful HF generator (450 kW of average HF power, 2.8 MW of peak power), feeder system, proper HF power input into accelerating structure, X-ray converter and testing facility with all infrastructure.

The accelerating structure of ILU-12 machine was conceived considering the possibility of following increase in working energy. According our experience and estimations, the accelerating structure of ILU-12 machine can reliably work in the energy range up to 10 MeV or even higher. We have plans to create the next machine for energy up to 10 MeV after the manufacturing and testing of ILU-12 machine for energy of 5 MeV.

6 REFERENCES

[1] V.L. Auslender. ILU-type electron accelerators for industrial technologies. Nuclear Instruments and Methods in Physical Research B 89 (1994) 46-48.

[2] V.L. Auslender. The EB Treatment - Current and Future Applications. In "Isotopes and Radiation Technology in Industry" (Eds. S. M. Rao, K. M. Kulkarni), Perfect Prints, India, 1994. Pp. 123-136.

[3] Auslender, V.A. Polyakov, A.G. Golnik et al. The installation for the single-use medical devices sterilization based on the electron accelerator type ILU. Radiat.Phys.Chem. Vol.42, Nos 1-3, pp.563-566, 1993.

[4] V.L. Auslender, et al. Compact ILU-type electron accelerators as a base for industrial 4-sided irradiation systems for cable and tubes. Radiation Physics and Chemistry 54 (1999) 609-618.

[5] V.L. Auslender, et al. E-beam and gamma applications. Report presented at International Meeting on Radiation Processing IMRP12 in Avignon, France, 2001.

[6] B. Fomel, M. Tiunov, V. Yakovlev. SAM – an interactive code for evaluation of electron guns. Preprint Budker INP 96-11, 1996.