HIGH-POWER INDUSTRIAL ACCELERATOR ILU-14 FOR E-BEAM AND X-RAY PROCESSING

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Abstract

Growing interest to product irradiation by E-beams and X-rays calls for dedicated industrial electron accelerators. Budker INP has developed ILU-14 radio-frequency pulsed linear accelerator capable of providing 100 kW beam at 7.5–10 MeV. The accelerator has fast removable X-ray converter and can operate both in e-beam and X-ray processing modes. The machine utilizes a low frequency (176 MHz) SW accelerating structure. ILU-14 accelerator was developed as turnkey equipment. Technical details and test results are presented.

INTRODUCTION

At Budker INP, a product line of ILU type electron accelerators with beam power up to 50 kW and energy up to 5 MeV has been developing since 1970; tens of the accelerators operate in many countries over the world. The RF power systems for all these machines are based on the self-exiting generators using the low-cost reliable vacuum tubes (GI-50A triodes made in Russia) with pulse power no less than 2 MW. These RF systems do not need precise frequency adjustment of the accelerating structure and generator. It results in relatively simple design of both accelerator control system and generator that allows us to considerably decrease the machines total and maintenance costs and improve their reliability.

The ILU-8 machines with energy range 0.8–1 MeV local shielding are mainly used for treatment of wires, tubes, and films. The ILU-6 machines with energy up to 2.5 MeV have been used for industrial treatment of big wires since 1983. The ILU-10 machines operate at the energy of 5 MeV and can be supplied with X-ray converters [1].

At present, there are the market needs for accelerators with electron energy up to 10 MeV. To produce a new product line covering all the energy and power ranges (up to 10 MeV and 100 kW), a concept of module-type ILU-14 accelerator with new 176 MHz modular accelerating structure has been developed at Budker INP [2]. 5 MeV accelerator prototype (called ILU-12) was successfully tested at Budker INP stand in early 2007. In 2010, 7.5 MeV of the output electron energy was obtained on modified prototype with two power inputs, that corresponds to the designed accelerating rate of the 10 MeV ILU-14 accelerator. ILU-14 machine can meet the growing demands of the industry. The energy range of 7.5–10 MeV allows that machine to treat the products in the EB mode with energies up to 10 MeV and also operate in X-ray generation mode with energy of 7.5 MeV.

The penetration depth of X-rays generated by ILU-10 at the energy of 5 MeV is 35 g/cm^2, that is practically close to the penetration depth of the gamma rays emitted by the cobalt source. The irradiation facility based on the ILU-10 or ILU-14 accelerator with removable X-ray converter can treat the full spectrum of the products that are treated by cobalt sources.

ILU-14 ACCELERATOR

Budker INP can produce high-performance, easy in use and control linear accelerators based on standard RF generator and modulator modules, developed and available in the Institute. The output parameters of such accelerators are defined by the number of generator modules and accelerating structure sections used, and can cover wide range of the output beam energy and average power.

Table 1 presents the main parameters of ILU-14 accelerator, which can operate in two regimes with different output electron energies. The generator is based on standard equipment used in ILU type accelerators (GI-50A triodes, modulator etc.).

Table 1: ILU-14 Accelerator Parameters

Parameter	7.5 MeV regime	10 MeV regime
Generator tube	5xGI-50A	5xGI-50A
Maximal energy	7.5 MeV	10 MeV
Average power	100 kW	100 kW
Energy spread	8 %	7.7 %
Acc. structure efficiency	84 %	71 %
Repetition rate	50 Hz	50 Hz
Total efficiency	29%	25%

Operating Principles

Figure 1 presents ILU-14 accelerator block diagram. The accelerator contains the 176 MHz accelerating structure, self-excited generator based on five GI-50A tubes with the pulsed power of 6 MW (maximal power up to 8 MW), modulators for RF feeding of the tubes, triode RF gun, beam output system, and (optional) an X-ray converter.

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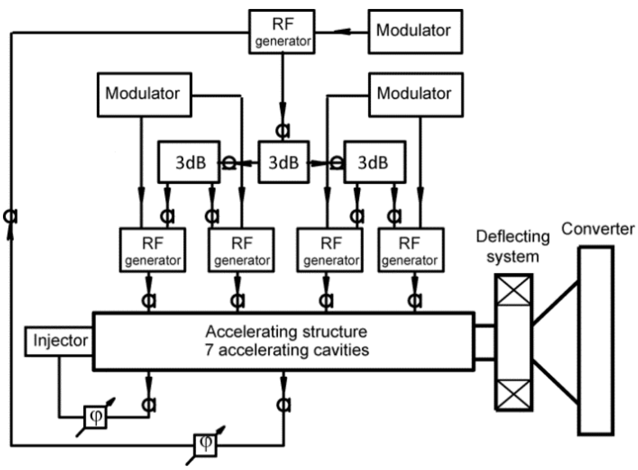

Figure 1: ILU-14 block diagram.

The accelerating structure is a biperiodic coupled cavity chain operating in standing wave regime at π/2 mode.

The two-stage self-excited oscillator with a feedback circuit closed via an accelerating structure cell is used as RF power supply. A signal is delivered to the generator prestage via the phase shifter which provides the proper phase shift in the feedback circuit. In such a system, there is no need for frequency tuning of the structure and generator. It results in relatively simple design of both accelerator control system and generator and soft requirements for temperature stabilization.

Triode RF gun serves as an injector of electron bunches. An additional voltage of the operating frequency harmonic is applied to the cathode-grid gap in order to decrease the beam energy spread. The phase shift is defined by the phase shifting line.

3D view of ILU-14 accelerating structure connected with the RF power generator is shown in Fig.2.

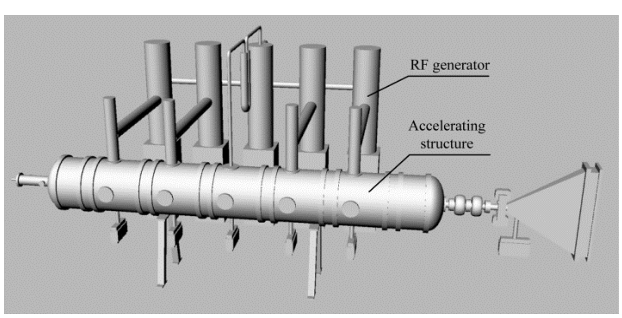

Figure 2: ILU-14 accelerator 3D view.

Accelerating Structure

The accelerating structure determines the main accelerator parameters, specifically RF power to beam power conversion efficiency. So, *n*-times increase of the accelerating cell total number in the structure results in *n*-times decreasing of RF power needed to obtain the required accelerating voltage, but at the same time increases the total structure length. 10 MeV accelerator structure contains 8 accelerating cells. Coupling between the cells provides the structure operation as a single resonant volume. The structure coupling constant is about 8%, shunt impedance is 34 MΩ.

The structure is cooled by a soldered pipe system.

3D view of the accelerating structure period is shown in Fig.3. Seven periods form the half end cell accelerating structure with 8 accelerating cells and the total length of 5.5 m.

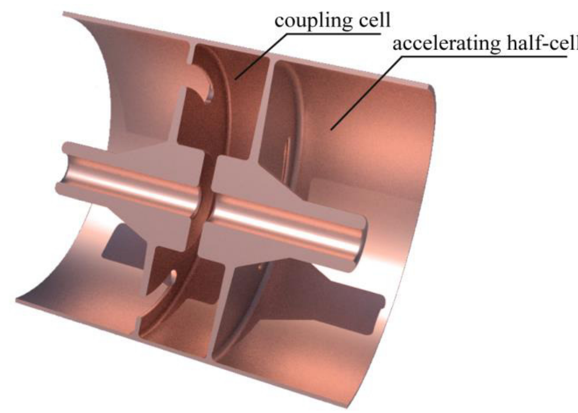

Figure 3: Accelerating structure period (section view).

Electron Gun

One of the accelerator design features is the internal beam injection from the triode RF gun, which is formed by the grid-cathode assembly (Fig.4) placed into the first accelerating cell of the accelerating structure. The required emission current of electron bunches is provided by RF electric field of the accelerating gap which penetrates into the cathode-grid gap through the grid slots. The current micro pulse amplitude and phase duration are adjusted by applying the constant cutoff voltage to the cathode-grid gap ("C" operating regime).

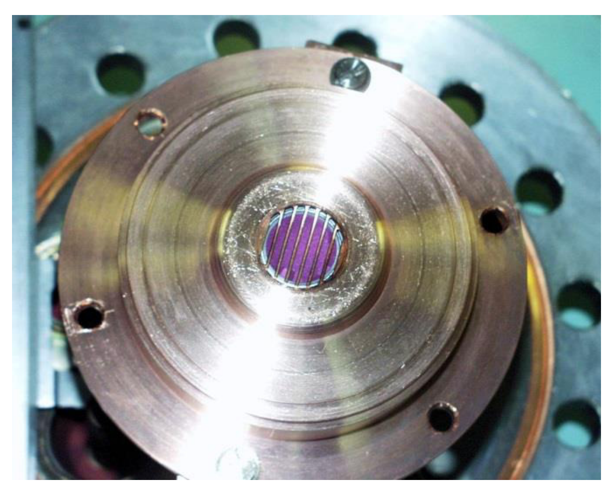

Figure 4: Grid-cathode unit of the RF gun for ILU-14 accelerator.

To improve the beam passing through the accelerating structure (up to almost lossless transportation) and narrow the output beam spectrum, an additional RF voltage extracted from one of the structure accelerating cells (see Fig. 1) is applied to the cathode-grid gap. The optimal electron injection phase relative to the phase of the accelerating RF field in the structure may be set by varying the phase and amplitude of the additional RF voltage [3].

Figure 5 presents the beam passing measurement results obtained on the modified 7.5 MeV prototype.

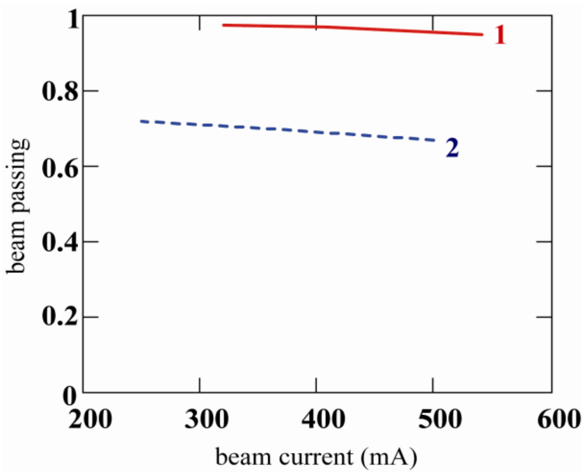

Figure 5: Beam passing vs beam current for two regimes: 1–with applying optimized additional RF voltage to the grid-cathode gap; 2–without additional RF voltage.

Oscillograms of the cathode and collector currents obtained for the regime with the additional RF voltage are shown in Fig.6. The electron energy is 7.5 MeV, beam passing is about 94%.

Beam Dynamics

Beam dynamics in ILU-14 accelerator was simulated with the specially developed computer codes [4] based on modified version of SAM program for design of electron guns and collectors [5]. Results of beam dynamics simulations (beam envelope and electron trajectories) for both 7.5 MeV and 10 MeV operating regimes are shown in Fig.7.

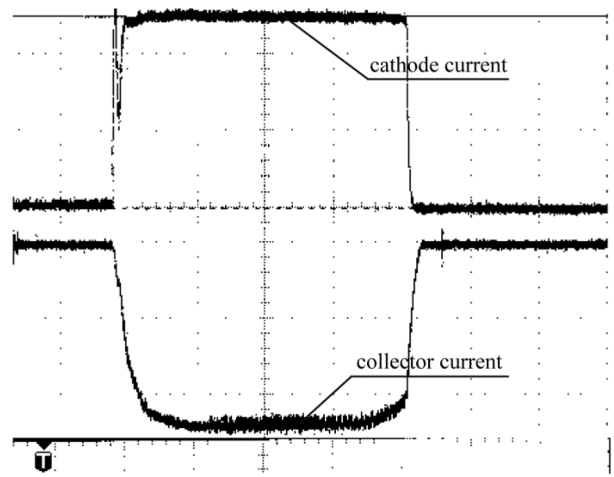

Figure 6: Oscillograms of the cathode and collector currents.

The calculated energy spectrums (output of specially developed computer code) for the 7.5 MeV and 10 MeV regimes are shown in Fig.8.

X-ray Converter

The X-ray converter consists of tantalum plate (1.2 mm) optimized for 7.5 MeV electrons (or other beam energy if allowed), cooling water channel, and aluminium filter for low energy electrons. The X-ray dose in the flat product geometry falls almost exponentially wit absorption length about 20 g/cm^2 for 7.5 MeV X-rays.

For the X-ray mode, the irradiation productivity is about 15 times less than in electron mode because of conversion efficiency, X-ray beam angular distribution, and higher proportion of the scattering. But the product thickness may be much more. For 7.5 MeV X-ray two sided irradiation, the maximal production rate product thickness is about two absorption lengths or 40 g/cm^2 with dose uniformity ratio (DUR) about 1.55.

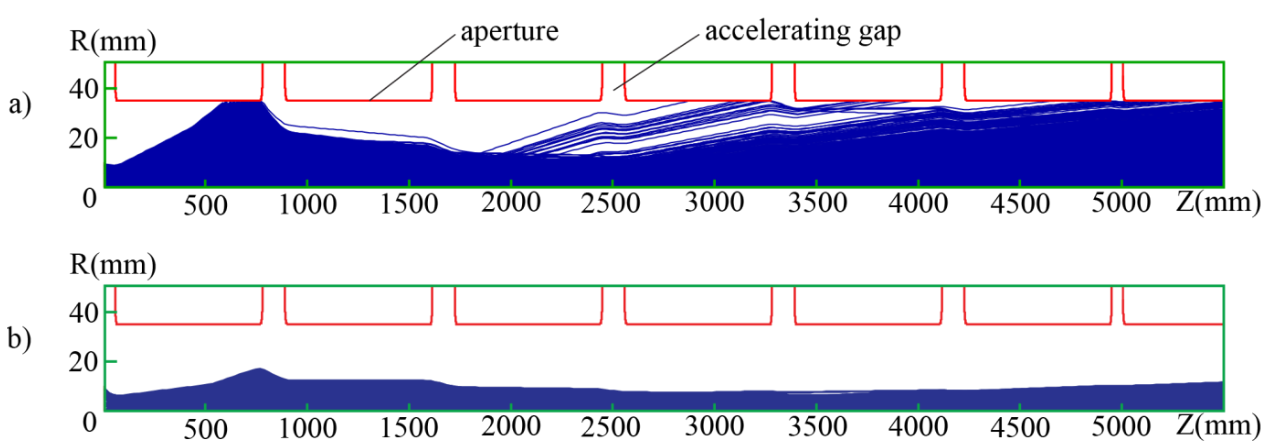

Figure 7: Trajectories of electrons in ILU-14 accelerating structure: a) for 7.5 MeV regime; b) for 10 MeV regime.

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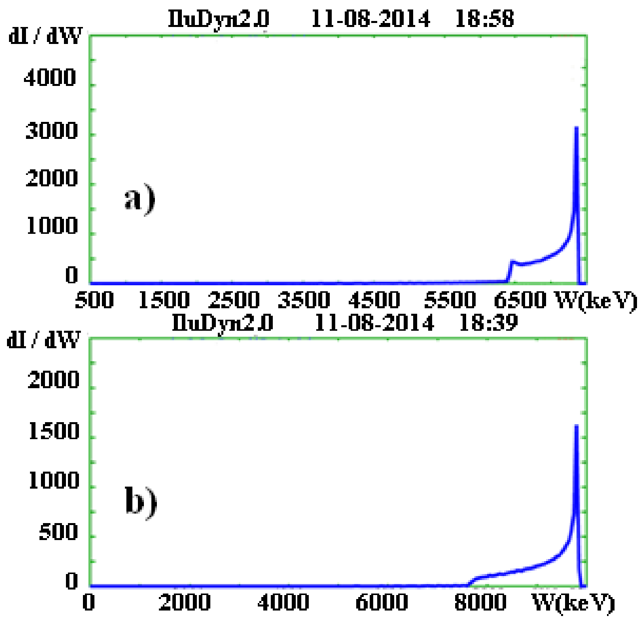

Figure 8: Electron energy spectrums for 7.5 MeV (a) and 10 MeV (b) regimes.

ILU-14 Accelerator for the Complex for Sterilization of Medical Products

The first ILU-14 accelerated was produced for the Complex for sterilization of medical products (Moscow). The machine is under commissioning now (Fig.9).

Figure 9: ILU-14 accelerator in radiation shielded room of the sterilization Complex.

CONCLUSION

New 100 kW linear electron accelerator ILU-14 with energy of 7.5–10 MeV may operate in both EB and X-ray modes that made it good solution for modern irradiation facilities. The machine can be considered as alternative to cobalt sources.

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