Sterilization complexes based on ILU-type electron accelerators

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Abstract This paper describes the industrial electron accelerators of the ILU type and their usage for sterilization. The ILU machines produced by Budker Institute of Nuclear Physics have energy range of 0.8–10 MeV and beam power up to 100 kW, and they are working in industries all over the world. The ILU-10 and ILU-14 machines are described as well as the industrial sterilization facility based on ILU-6, ILU-10 and ILU-14 machines.

Key words Radio frequency electron accelerator, Electron beam, E-beam treatment, Radiation sterilization, Bremsstrahlung

1 Introduction

The industrial radiation sterilization was introduced in the USA in the 1950s by Ethicon Inc., the division of the Johnson & Johnson. They started trial sterilization of suture products on an electron accelerator. In the 1960s, ^{60}Co sources were widely used for sterilization of healthcare products because these sources could provide higher productive rate than the electron accelerators produced at that time.

In the 1970s, powerful electron accelerators were developed. This caused the change of the trend — the number and total activity of ^{60}Co sources in the USA and Europe are gradually decreasing and the total power of the E-beam facilities is constantly rising. There are eight to nine times more commercial EB units in world-wide operation than commercial gamma-ray irradiators[1,2].

In 1999 the shares of different industrial sterilization processes in the USA were as follows: radiation sterilization (accelerators and isotope sources), 46%; gas (ethylene oxide) sterilization, 52.2%; and thermal sterilization, 1.8%. During the last decade, while many countries started to restrict the gas sterilization practice, the radiation sterilization share has been in continuous increase.

The crucial parameter for radiation sterilization process is the penetration depth of ionizing radiations. Most DC type electron accelerators have electron energy less than 3 MeV, which restricts their usage for sterilization.

Usually radio frequency (RF) type accelerators of 5 MeV or higher energies are used for sterilizing medical products, and the maximum energy of the E-beams should be no more than 10 MeV to avoid the problems of induced radioactivity.

In the energy range of 2.5−10 MeV (used for EB sterilization), the dependence of equal-entrance equal-exit dose on electron energy is nearly linear. The penetration depth restricts the surface thickness of the treated products. The two-sided irradiation permits to increase the admissible thickness of the treated products by a factor of 2.4.

The other way to increase the penetration depth is to generate bremsstrahlung radiations (X-rays) using a target made of heavy metals. The X-rays generated by 5−7.5 MeV E-beams have the same penetration ability as ^{60}Co γ-rays in the range of 30 to 40 g·cm^{-2}.

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In Europe and the USA, many service centers own both ^{60}Co sources and EB irradiators of low or middle energy. A majority of the products are treated by electron beams, and the products that cannot be treated by E-beams are irradiated by ^{60}Co γ-rays.

2 ILU accelerators

2.1 General description

ILU accelerators produced by BINP are of powerful industrial pulse RF machines[3-6]. The RF power systems for all these machines are based on the self-exiting generators using the reliable and inexpensive Russian triode tubes with pulse power no less than 2 MW. The RF systems do not need precise frequency adjustment of the structure and generator. These lead to relatively simple design of the accelerator control system and generator. To a considerable extent, the self-exciting RF generator allows simplified accelerator design with reduced cost, improved reliability and decreased maintenance costs.

The ILU-8 machines with energy range of 0.8–1 MeV are mainly used for crosslinking of wires, tubes and films. The ILU-6 machines with energy up to 2.5 MeV have been used for sterilization of medical products since 1983. The ILU-10 machine generates E-beams of up to 5 MeV. It can be supplied with an X-ray converter.

The new type machine, ILU-14, was developed to meet the growing demands of the industry of high energy radiation processing. Its energy range is 7.5–10 MeV. This machine can treat the products in the EB mode with energy up to 10 MeV and also can work in the X-ray generation mode with energy of 7.5 MeV (maximum electron energy for X-rays generation).

Main parameters of the ILU-type machines and maximum admissible product thicknesses for two-sided treatment mode are given in Table 1.

Table 1 Main parameters of the ILU accelerators.

Parameters	ILU-6	ILU-10	ILU-14
Energy range / MeV	1.7−2.5	4−5	7.5−10
Maximum average beam current / mA	8	10	10 (10 MeV), 13.3 (7.5MeV)
Maximum product thicknesses / g·cm^{-2} (for two-sided irradiation)	2	~4	~8
Productivity for 25 kGy treatment at maximum beam power in the E-beam mode / kg·h^{-1}	1400	~3500	~7000
Maximum penetration depth in the X-ray generation mode / g·cm^{-2}	—	~30	~30
Productivity for 25 kGy treatment at maximum beam power in the X-ray generation mode / kg·h^{-1}	—	~290	~910

The penetration depth of X-rays generated by ILU-10 at 5 MeV is 30 g·cm^{-2}, which is practically close to the penetration depth of ^{60}Co γ-rays. An irradiation facility based on ILU-10 or ILU-14 accelerator with a removable X-ray converter can treat a full spectrum of products treated by a ^{60}Co source.

Some ILU machines are working in China for many years including the ILU-8 at the Shanghai Irradiation Center established by the Shanghai Institute of Applied Physics.

2.2 ILU-10 accelerator

An ILU-10 machine works at 4–5 MeV, which is enough for sterilization processes. The basic unit of the ILU-10 accelerator is a toroidal copper cavity having operating frequency of 116 MHz. It has axial protrusions forming an accelerating gap of 270 mm. The protrusion shape was chosen to form and focus the electron beam so that its injection, acceleration and further passage through the beam scanning and extraction system are performed with minimum losses.

The copper RF cavity 2 is placed into the stainless steel vacuum tank 1 (Fig.1). The triode electron injector 5 is formed by the cathode unit and the grid mounted in the upper protrusion. The lower cavity protrusion and injector form the triode system.

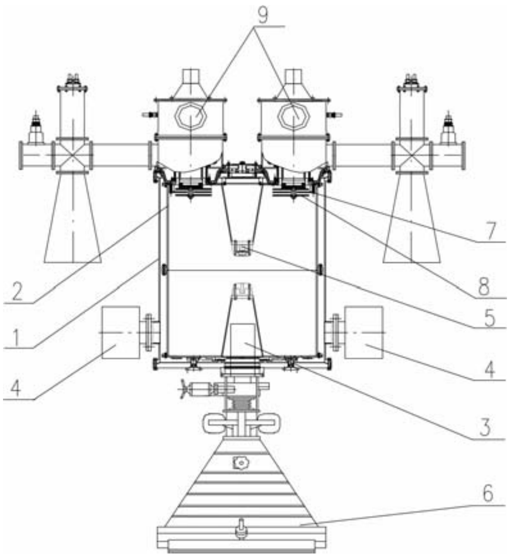

Fig.1 ILU-10 accelerator.
1, vacuum tank; 2, copper toroidal cavity; 3, magnetic lens;
4, ion pumps; 5, triode electron injector; 6, linear beam scanner;
7, coupling loop support; 8, vacuum capacitor;
9, RF generators.

Under the lower electrode of the cavity there is a magnetic lens shaping an electron beam in the accelerator channel and the linear beam scanning and extraction device 6.

Two RF self-exciting generators 9 based on powerful triodes are installed directly on the vacuum tank. Generators 9 are working at frequency of about 116 MHz that is near the specific frequency of the cavity. The anode circuits are coupled to the cavity through inductance loops. The coupling rate is determined by the square of loop and can be tuned by the anode circuits. The feedback in the generator using the common grid circuit is provided by the additional capacitance connecting the tube anode and cathode. The capacitance is about 20 pF. The fine tuning of the feedback value and its phase is made by the cathode short-circuited tail with a movable shortcut contact driven by a servo-motor. The coupling rate of generator with cavity is tuned during the accelerator’s preliminary adjustment by varying the capacity of the vacuum capacitor 8 and the square of the coupling loop by varying the position of its support 7.

The tank is of metal vacuum sealing (copper and indium), with the operation vacuum of 1.33×10^{-8} Pa. Fig.2 shows the ILU-10 machine in the testing facility at BINP.

Fig.2 ILU-10 accelerator in the testing facility at BINP.

2.3 ILU-14 accelerator

The ILU-14 accelerator is a 10 MeV and 10 mA machine. The main features of this machine are the multi-cavity 176 MHz accelerating structure, self-excited generator based on five GI-50A tubes with the output pulse power of 6 MW (maximal power up to 8 MW), triode RF gun, beam extraction system and powerful pulse power supply for the RF tubes.

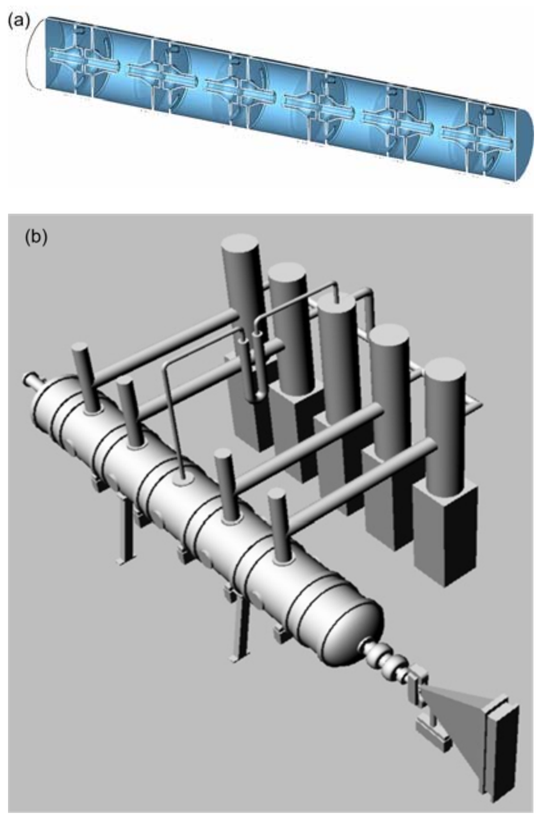

Fig.3 Schematic view of the ILU-14 accelerating structure (a) and the structure connected with RF generator (b).

The accelerating structure is a biperiodic coupled cavity chain operating in standing wave regime at π/2 mode. Fig.3a shows the multi-cavity accelerating structure design. Unlike the ILU-6 and ILU-10, the beam of ILU-14 is in horizontal path. The two-stage self-excited generator with a feedback circuit closed via an accelerating structure cell is used for the RF power supply. The feedback RF power is supplied to the preamplification stage *via* the phase shifter to provide the controllable phase shift in the feedback circuit. The final stage of the 4 triodes works in parallel on the accelerating structure. Such a system does not need precise frequency adjustment of the structure and generator. A schematic view of the ILU-14 structure connected with the RF generator is shown in Fig.3b.

Fig.4 shows the ILU-14 accelerator in the testing facility at BINP, and Fig.5 shows the RF generator for ILU-14. The ILU-14 has the triode RF injector to form the electron bunches. An additional voltage of the operating frequency harmonics is applied to injector's cathode-grid gap to decrease the injection angle and beam energy spread. The phase shift is controlled by the phase shifting line.

Fig.4 ILU-14 accelerator in the testing facility at BINP.

Fig.5 RF generator of the ILU-14 machine in the BINP.

This powerful machine is especially suitable for sterilization of medical goods and decontamination of hospital wastes in hermetically packed recoverable containers. After the radiation treatment these wastes can be processed by well-known technologies.

3 Sterilization complexes

The sterilization complex with a 2.5 MeV ILU-6 machine has been functioning in a pharmaceutical firm in Altay region, Russia. It was established for treating mainly herbal medicinal raw materials, with a working load of up to 52 tons per month. The complex is placed in a 2-storeyd building. Fig.6 is a schematic view of the first floor. The product packages are sent into the irradiation chamber by the conveyor. The moving direction of the conveyor is clockwise and the loading and unloading zones are on the left side. A similar design can be used for a sterilization facility based on the ILU-10 machine.

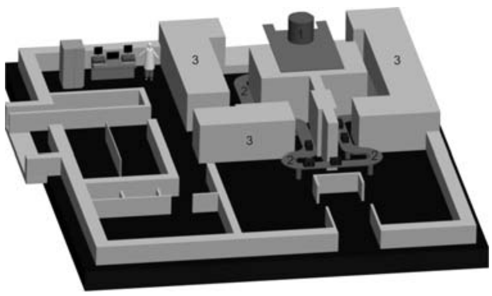

Fig.6 Schematic design of the irradiation complex (1st floor). 1, accelerator tank; 2, conveyor; 3, biological shield.

Fig.7 shows the ILU-10 beam scanning device and the roller conveyor. A standard linear scanning horn for the ILU machine permits to irradiate product cartons in width (across the conveyor) of up to 90 cm. Scanning horns of greater widths can be provided.

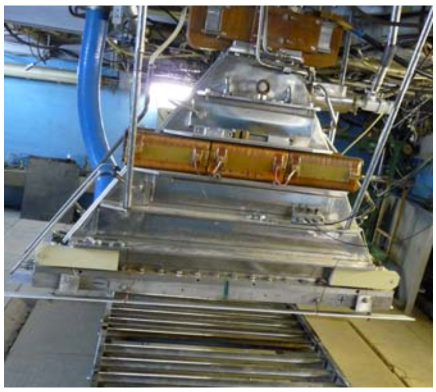

Fig.7 ILU-10 beam scanning horn and roller conveyer.

The conveyor types vary for different irradiation facilities. The ILU-14 irradiation facility is equipped with a pallet conveyor system (Fig.8). The conveyor system permits to group the pallets being irradiated under the beam scan, so as to maximize the beam usage efficiency to a reasonably achievable value.

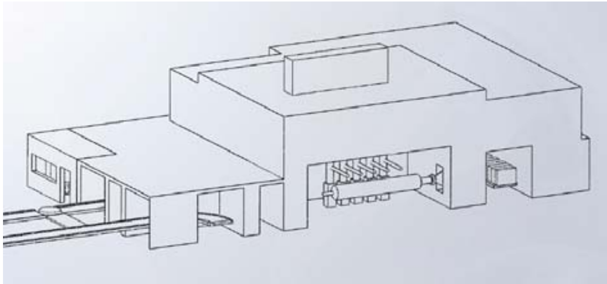

Fig.8 Schematic design of the irradiation complex with ILU-14 machine.

The ILU-10 and ILU-14 machines can work with removable X-ray converters. The X-ray converter function is shown in Fig.9. The conversion efficiency in the forward angle of 60° (to be absorbed by the products) for 5 MeV E-beams (ILU-10) is 8.3% of the beam power, while for 7.5 MeV E-beams (ILU-14) it is 13.2%. The X-ray power absorption in the treated goods depends on the products and on the design of the conveyor system, and is usually about 50%. So the ILU-14 machine can provide useful (to be absorbed by the products) X-ray power of up to 6.6 kW.

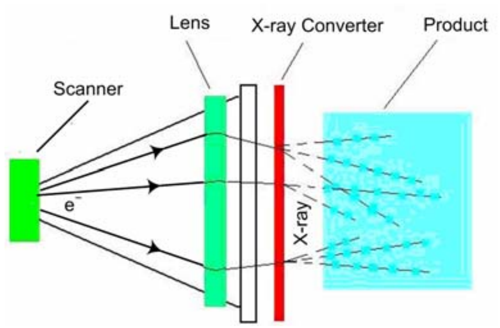

Fig.9 Schematics of the X-ray converter for ILU-10/14 .

4 Conclusion

The new powerful 10 MeV ILU-14 machine can satisfy the growing industrial demands for sterilization of medical products and food treatment. It will be used to develop the new industrial technology for radiation decontamination of hospital wastes. The ILU-14 machine is now passing the testing at BINP. In 2011 it will be installed in an irradiation complex in Moscow.

As an accelerator supplier to industries and research institutions all over the world for decades, the Budker Institute of Nuclear Physics, together with its partners, also suggests the turn-key solutions — the irradiation complexes with accelerator, conveyor system and integrated control systems.

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