Electron Linacs for cargo inspection and other industrial applications

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Abstract. Several kinds of low energy linacs were developed for cargo inspection, non-destructive-test and irradiation in Tsinghua University cooperated with NUCTECH®. This paper gives a brief introduction of the low energy linacs design consideration first, and mainly discusses the new challenges of the electron linacs for cargo inspection and other applications. The interlaced pulse dual energy 9/6MeV linac for material discrimination cargo inspection and the new features of the linacs for fast-scan system are described in detail. Some other linacs are also been introduced in this paper, such as the 9MeV and 15MeV SW linacs developed for industrial non-destructive-test applications and the compact irradiation linac carried by a van.

1. Introduction

Cargo inspection is one of the important components of the homeland security. Most of the cargo inspection systems adopt low energy linacs as their x-ray sources. And cargo inspection has been becoming a more and more important application area of the electron linacs. Together with NUCTECH®, kinds of cargo inspection systems have been developed and more than two hundred sets have been installed and used all over the world. These years, material identification and 100% inspection of the containers at the ports bring new challenges to the cargo inspection techniques and also to the low energy linacs. We successfully developed several kinds of dual energy and fast beam-on linacs for material identification and fast scan cargo inspection systems. Except the above linacs for cargo inspection systems, linacs for high energy x-ray industrial NDT and mail sterilization are also will be introduced here.

Low energy electron linac development at Tsinghua University was begun from more than 30 years ago. The first one developed in Tsinghua U. cooperating with several other universities and institutes was BJ-10[1], which was a 10MeV travelling wave linac for cancer therapy. From that time on, we developed different kinds of linacs for medical and industrial applications [2]. Hundreds of standing wave electron accelerating tubes (with electron gun, target or titanium window and RF window) have been produced in the accelerator lab of Tsinghua University.

2. Technologies of Low Energy Electron Linacs

A low energy electron linac *(see FIG.1.)* is mainly compose of the electron accelerating tube (with electron gun and microwave window), rf power source (magnetron or klystron, pulse transformer, modulator), control system and auxiliary systems (cooling water, dielectric gas and others). Unlike the electron linacs for high energy physics and SR & FEL light sources, most of the low energy linacs use magnetrons as their RF power sources, because of their compact size, cheap price and their high efficiency. And s-band (2998MHz or 2856MHz) RF power sources are mostly used, although x-band structures are more compact and L-band linacs can deliver more electron beam power. For a low energy electron linac used for industrial application, once its performance meets the requirements, reliability and stability are the most important things.

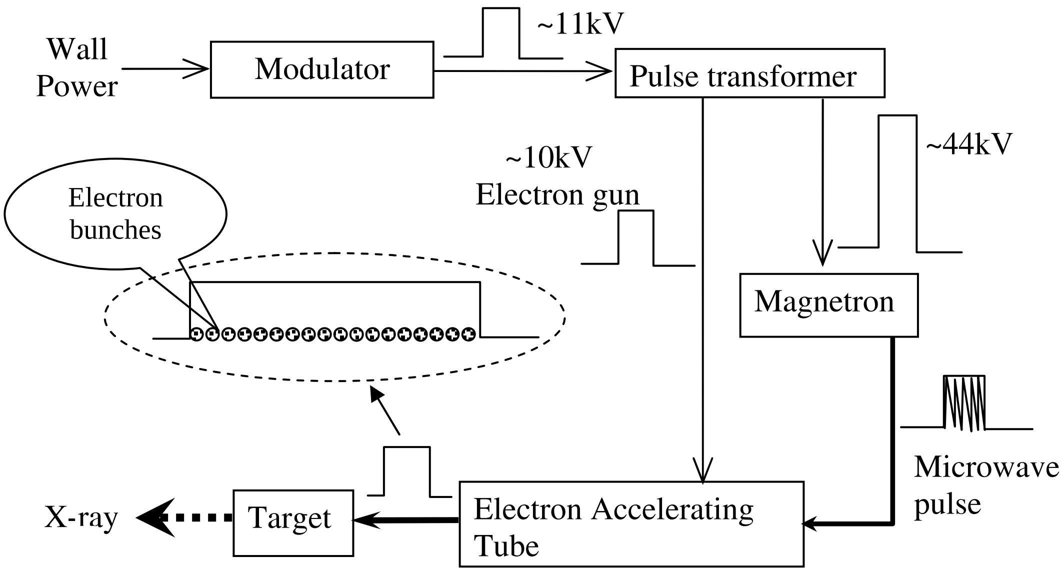

FIG. 1. A principle diagraph of a linac.

The Accelerating tube consists of the accelerating waveguide, the electron gun and the microwave window. The electrons are generated from the electron gun and accelerated by the microwave electric fields in the accelerating waveguide. The RF power is fed into the accelerating tube by a coupler with a microwave window to separate the dielectric gas filled waveguides and the vacuum part of the tube. Normally an x-ray target or an electron window is welded at the end of the tube to generate x-ray or extract the electron beam.

Both travelling wave (TW) and standing wave (SW) structures can be used in the low energy linacs. SW structures are compact, accelerating gradient higher and transverse motion of electron beam can be easily controlled by the RF field, and TW structures are also often used for their high capture factor, wide band width and needn't isolation parts. Normally two kinds of standing wave accelerating structures are adopted in low energy electron linacs *(see FIG.2.)*. The side-coupled structure is more common, for its high efficiency and easy to be tuned. In Tsinghua U., most of the SW accelerating tubes is on-axis magnetic coupled structures, with very thin coupling cavities about 2mm length at S-band. We developed several kinds of SW accelerating tubes *(see FIG.3.)*, with the on-axis coupled structures, for linacs used in cargo inspection or other industrial applications.

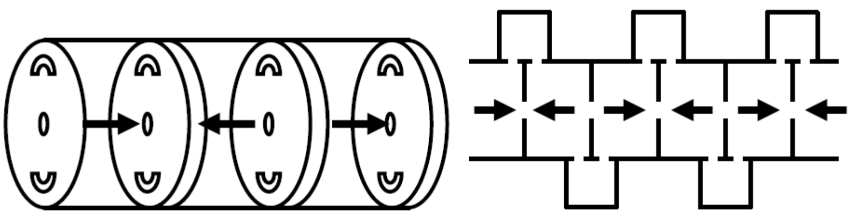

FIG. 2. SW structures, on-axis magnetic coupled (left) and side-coupled (right).

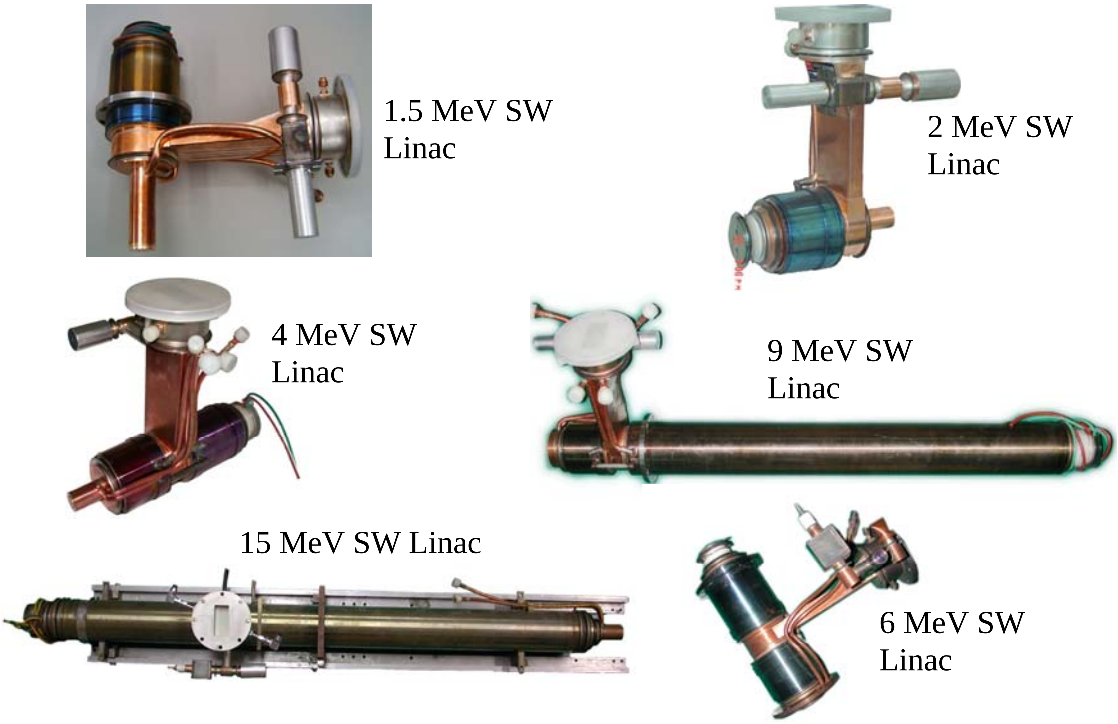

FIG. 3. SW accelerating tubes developed in Tsinghua U for industrial applications.

3. Cargo Inspection Systems Using Linac as X-ray source

A cargo inspection system mainly consists of the x-ray source, an array of detectors, the software to re-construct the image from the electronic signal of detectors, control systems and the gantry or other mechanic moving systems. Because we need high energy x-rays to penetrate the cargo, normally an electron linac is served as the x-ray source. One or two collimators are used to let only a fan shaped x-ray beam go out of the linac x-ray head into the scanning area.

Three kinds of cargo inspection systems *(see FIG.4.)* were developed at the beginning by Tsinghua U., cooperating with NUCTECH®. The fixed cargo inspection system with a 9MeV TW linac [3] as its x-ray source should be installed in a special building. The 9MeV TW linac can generate more that 30Gy/min@1m x-ray dose rate, with a spot size less than 2mm. The relocatable system uses a 6MeV SW linac as its x-ray source. The linac, detectors and electronics are carried by a gate shape gantry, which can move on rails and scan the cargo. The whole system can be installed in a simply x-ray shielded concrete shed. The mobile container/vehicle system needs a very compact linac, which can be carried by a car. X-band linac is the best choice for it. But considering the stability and expenses, now the s-band 2.5MeV linacs with very low dose rate are used in the most mobile products.

These years, the cargo inspection technology is concentrated on fast scan and material identification. Because of the high moving speed, inspection systems designed specially for railways need the linac to deliver high repetition rate x-ray pulses. And as the wheels of the global shipping industry spin faster and faster, the needs for high throughput inspection systems are increasing continuously. To identify the dangerous materials from others, dual energy inspection systems have been developed, with linacs can deliver interlacing high energy and low energy x-ray pulses.

FIG. 4. Fixed (left), relocatable (middle) and mobile (right) cargo inspection systems.

3.1. Dual Energy Linacs and the Material Identification Cargo Inspection

The x-ray beam is generated by the electron beam hitting a high-Z target in a linac, which is mainly bremsstraghlung radiation. By detecting the attenuation of the x-ray penetrating an object, we can get the shape of it. If a high energy x-ray and a low energy x-ray go through the same object, the equivalent atomic number of the material can be calculated from the signals of the x-rays. The dual-energy method has been widely applied in luggage x-ray inspection systems for the purpose of material discrimination. But for cargo inspection, it's much more difficult to use the dual-energy method for material discrimination, because the difference of attenuation factors is much smaller at several MeV x-ray range for different materials with the same equivalent thickness [4]. To achieve material identification in a cargo inspection system, the linac must deliver not only interlacing high and low energy x-rays, but also very stable dose rate x-ray pulses.

The electron energy of a linac is given by Equation (1), where Z_s is the impedance and L is the length of the accelerating structure, I is the pulse current, P_0 is the rf pulse power from the magnetron of klystron, φ_s is the accelerating phase and β_c is the coupling coefficient of the rf power to the accelerating structure. The dose rate J_x (cGy/min@1m) is in proportion to the duty factor $\tau{\cdot}F$ (τ is the pulse width, F is the repetition rate), pulse current I and nth power of the electron energy V_s (Equation (2)). And n is a factor related to the electron energy, for example, n=2.7 (Vs=6MV) and 3(Vs=3MV).

$$V_S = \frac{2\sqrt{\beta_c}}{1+\beta_c}\sqrt{Z_s \cdot L \cdot P_0}\cos\varphi_S - \frac{1}{1+\beta_c} I \cdot Z_s \cdot L \qquad (1)$$

$$J_x = 0.067\tau \cdot F \cdot I \cdot V_S^n \qquad (2)$$

In a dual energy linac, the Z_s, L and β_c are fixed. We can get higher electron energy with higher rf power and lower electron current, and vice versa.

The dose rate and energy stabilities are very important for the dual energy linac, for they affect the material discrimination seriously. The rf power, beam current and the frequency difference between the rf power source and the accelerating tube are the main factors to affect the dose rate and energy stabilities. If we use a magnetron as the rf power source, the rf power and the rf frequency are depended on the high voltage from the modulator and pulse transformer. The beam current is determined by the high voltage power source of the electron gun and its perveance. For a SW linac the frequency difference between the rf power source and the accelerating tube can be controlled by the AFC (Automatic Frequency Control) system. To stabilize the dose rate and energy of the linac, the high voltage power sources must be stabilized first. The dose rate will be unstable from pulse to pulse *(see FIG.5.)*, without special high voltage stabilization method.

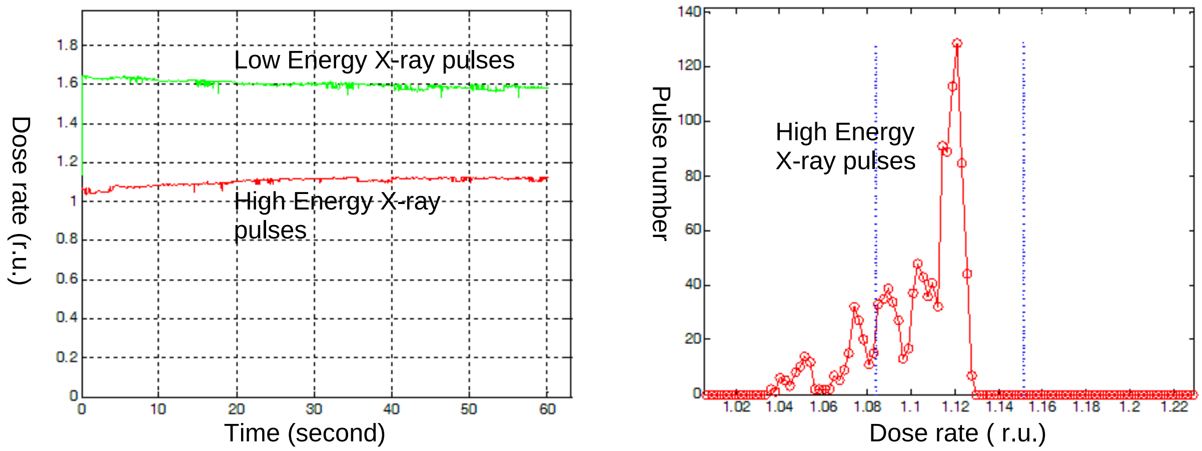

FIG. 5. The pulse to pulse dose rate measurement in a dual energy linac without any high voltage stabilization.

The first dual energy system developed in Tsinghua U., cooperating with NUCTECH®, used a 9/6MeV dual energy SW linac *(see FIG.6.)*. Some of the parameters are shown in TABLE I. A magnetron was used as the power source. This linac can be worked at three modes: 9MeV, 6MeV and interlaced 9/6MeV. Therefore, the dual energy cargo inspection system can output gray images and coloured images with material discrimination *(see FIG.7.)* [5]. Several kinds of dual energy systems have been developed and used at customs all over the world.

FIG. 6. The 9/6 MeV dual energy linac.

TABLE I: PARAMETERS OF THE 9/6MeV DUAL ENERGY LINAC.

Parameters	**High Energy**	**Low Energy**
RF Power Source	Magnetron, MG5193, 2.6MW, 2998MHz	
Pulse Width	4~5µs	
Repetition Rate	150pps	150pps
Electron Energy	9-10MeV	6-7MeV
Dose Rate at 1m X-ray Spot size	1000cGy/min <2mm	500cGy/min <2mm

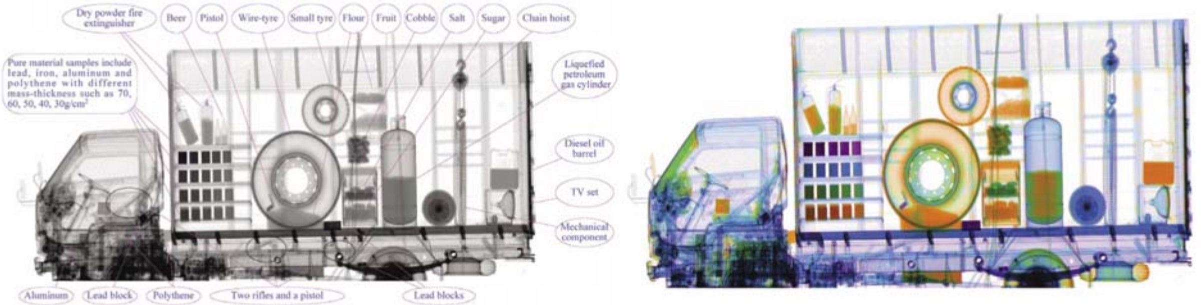

FIG. 7. Images of the 9/6 MeV dual energy cargo inspection system, gray image (left) and the colour image after colourisation (right)

3.2. Fast Beam-on Linacs and the Fast Scan Cargo Inspection

NUCTECH® FS3000 *(see FIG.8.)* is a new system especially designed for high throughput and 100% inspection [6], with a linac of 2.5MeV or 4MeV as its X-ray source. To get high throughput of vehicles, they must pass through the scanning tunnel directly without stopping. The vehicles can be driven though the scanning tunnel with a speed of about 15km/h. It can scan 200-400 units of 40ft containers per hour.

To ensure the safety of the driver is the most important design demand for this system. The linac must have the ability to get steady beam within less than 0.1s and should be shut off as soon as the scanning finishes. The frequency of X-ray pulses are adjusted automatically according to the speed of the scanned vehicles, which ensures the scanning images non-distortion *(see FIG.8.)*.

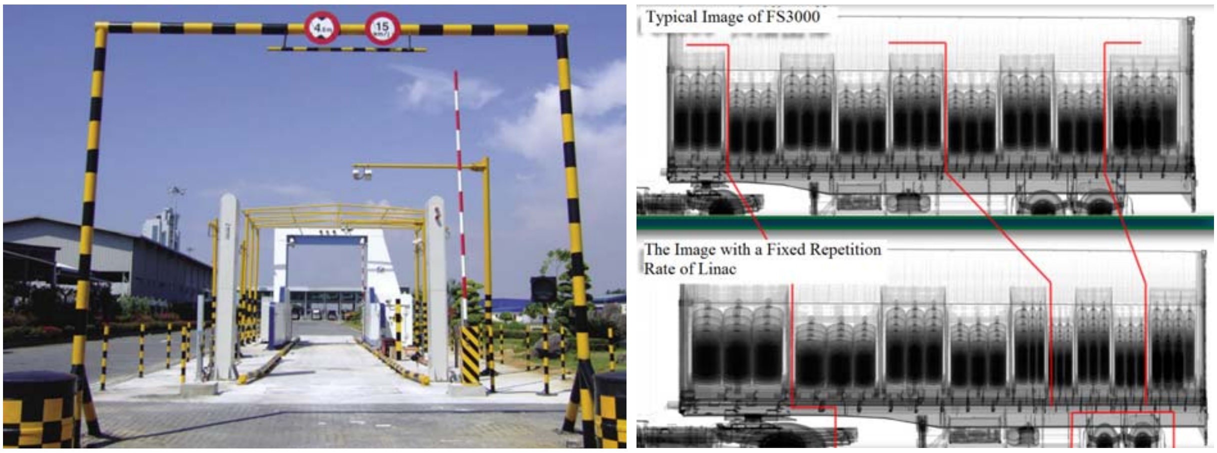

FIG. 8. FS3000 fast scan cargo inspection system (left) and its typical image (right)

4. Linacs Developed for Other Industrial NDT Applications

A series of NDT linacs–HEXTRON®s, with electron energy from 2MeV to 9MeV have been developed for industrial applications. We take HEXTRON-3000 *(see FIG.9.)* as an example. Its electron energy is 9MeV with dose rate 3000cGy/min, and x-ray spot size less than 1.5mm. An industrial CT system have been finished using HEXTRON-3000 with space resolution of 2.5lp/mm and density resolution of 0.5%. A 15MeV SW linac with dose rate about 200Gy/min@1m has also been developed, which uses a 5MW klystron as its rf power source.

FIG. 9. HEXTRON-3000 SW Linac (left) and the CT image with it (right)

5. The Mobile Sterilization System

Electron irradiation has been widely used in sterilization and industrial irradiation processing, such as crosslinking. Different kinds of accelerators can be used for electron irradiation. Electron linac can achieve high electron energy (for example 10MeV) easily, but it is very hard to reach very high average electron power (for example 100kW). We developed a compact SW linac used for sterilization, which can be carried by a motor van *(see FIG. 10.)*. This linac works at 2998MHz, 4.7μs pulse width and 250pps repetition rate. It can deliver more than 1kW electron power, with electron energy 2.5MeV.

FIG. 10. A mobile sterilization system using a SW compact linac

6. Summary

Kinds of low energy electron linacs have been developed by Tsinghua U. and NUCTECH for cargo inspection systems and other industrial applications. Although the radiotherapy is still the most important application of low energy linacs, new application areas have been becoming more and more important. Among them, the cargo inspection system for homeland security has been widely used in lot of countries. New demands to the linacs for new applications have been continuously put forward to the designers. And these also bring much more innovations to the low energy linacs.

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