LOW ENERGY ELECTRON LINACS AND THEIR APPLICATIONS IN CHINA*

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Abstract

In recent years,low energy electron linacs have been developed for radiotherapy and radiography applications as well as irradiation processing. There are now about 200 domestic made low energy linacs in China. Among them,about 155 sets are standing-wave (SW) medical linacs with electron beam energies from 4 to 6 MeV. A 14 MeV SW electron linac with a 270° deflecting system for radiotherapy has been produced. Eight sets of SW electron linacs including two 9 MeV linacs for radiography have been constructed. The major accelerator for irradition processing use is the Dynamitron, but also several domestic made electron linacs with beam energy more than 4 MeV are under operation for this application. Tsinghua University has developed a backward travelling wave (BTW) accelerator structure and a portable X-band SW electron accelerator structure for low energy application.

1 INTRODUCTION

The history of linear accelerator development in China can be traced back to 1956 when Prof. Xie Jialin led a group to start development of electron linear accelerators. The linac was completed in 1964 with beam energy of 30MeV.

The first increase in the pace of development of electron linacs in China was from 1972 to 1977 when the need for radiation therapy pushed the development of electron linacs for medical applications. During that period, four groups from Shanghai, Beijing, Nanjing and Sichuan started to develop medical electron linacs. Tsinghua University and the Beijing Medical Equipment Institute (BMEI) first completed an 8∼10 MeV traveling-wave medical linac in July, 1977. Before long, the Institute of High Energy Physics (IHEP) and the Shanghai Medical Nuclear Instruments Factory (SMNIF) constructed another 8-10 MeV traveling-wave medical linac.

The second increase in development was from the middle of the 1980s to the early 1990s. A series of standing-wave (SW) low energy electron linacs were developed along with a 1.3 GeV high energy traveling-wave electron linac built for BEPC and a 200MeV middle energy traveling wave electron linac as an injector for a synchrotron radiation source .

During that period, a large number of SW medical machines were mass produced. Various electron linacs were developed for different applications[1], but only linacs for radiotherapy, radiography and irradiation processing are discussed in this paper. The paper also introduces some new research results from Tsinghua University for low energy electron linacs during recent years.

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2 LOW ENERGY ELECTRON LINEAR ACCELERATORS FOR RADIOTHERAPY, RADIOGRAPHY AND IRRADIATION PROCESSING

2.1 Electron Linacs for Radiotherapy

Cancers seriously threaten human health and life. Radiotherapy used alone or in combination with surgery or chemotherapy is still an effective therapy. In this field, medical electron linear accelerators have played a major role. According to the estimate of the International Hygiene Organization, two sets of medical accelarators are needed for every one million citizens. Therefore, up to 2400 sets are needed in China. This huge requirement stimulates the development of medical accelerators. After more than 20 years of development, there are about 175 sets domestic made medical linacs in China including traveling-wave and standing-wave types. Among them, about 155 sets are standing-wave medical linacs with electron beam energy from 4 to 6 MeV . During 1979∼1981 Tsinghua University in cooperation with BMEI developed standing-wave accelerator structures including side-coupled and on-axis coupled structures. In 1985, BMEI completed the first SW medical electron linac with 4 MeV beam energy in China. In 1990,Tsinghua University and Beijing Vacuum & Electronics Research Institute (BVERI) developed the first 6 MeV electron SW accelerator guide. That guide was installed in 6 MeV medical electron machine made by WEIDA company in 1991.

A brief summary of domestic made medical linacs is shown in table 1.

Tsinghua University and BVERI successfully developed two 14 MeV SW accelerating wave-guides with 270° deflecting chamber in 1994 and 1995. These waveguides can provide two X-ray modes, 6MV and 15MV, and five E-ray modes, 6, 8, 10, 12, 14MeV. They were attached to two 14MeV medical machines (BJ-14, WDZ-14C). The linac in BJ-14, which was installed in a hospital, was constructed by BMEI.

The domestic made medical linacs are high quantity accelerators and have played an important role in the history of Chinese accelerators.

2.2 Electron Linacs for Radiography

The more than 10 years of development of medical electron linacs provided a good condition for developing elec-

Type	Linac	Energy (Mev)	Radiation	Number of sets	Manufactuer
BJ-10	TW	10	X,E	1	BMFI,Tsinghua University
BJ-10	TW	10	X,E	1	BMEI
BJ-4	SW	4	X	58	BMEI
BJ-6M	SW	6	X	16	BMEI
BJ-6B	SW	6	X	18	BMEI(computerized)
BJ-14	SW	14	X,E	1	BMEI(computerized)
WDVE-6	SW	6	X	62	WEIDA[1]
WDZ-14C	SW	14	X,E	1 (under test)	WEIDA(computerized)
ZJ-10	TW	10	X,E	20	SMNIF
NYZ-18	TW	18	X,E	1 (under test)	SKY[2]

Table 1: Chinese domestic made medical electron linacs

tron linacs for radiography application. In addition, the requirements of heavy industries have accelerated the development of low energy linac for radiography.

In 1989, in cooperation with Tsinghua University, and the Beijing Research Institute of Automation for Machine Building Industry (BRIAMI) , the China Institute of Atomic Energy (CIAE) successfully developed the first standing-wave electron linac for radiography application with a beam energy of 4 MeV and a dose rate of 350$\sim$400 cGy/min.m. Soon after , BMEI and BRIAMI also constructed another electron linac with the same beam energy for radiography.

In 1993, BRIAMI developed another 4 MeV linac with 400$\sim$500 cGy/min.m for radiography. And CIAE constructed a 3 MeV SW linac with 250 cGy/min.m for same use.

In 1993, Tsinghua University, in cooperation with BRIAMI and BVERI developed the first 9 MeV standing-wave accelerating wave guide. BRIAMI then used the waveguide to construct a 9 MeV SW accelerator (DZ-9/3000) for radiography, which was installed in First Heavy Machine Factory. The machine can emit strong X-rays, with dose rates exceeding 3000 cGy/min.m and a small beam spot, Φ1.5mm. This linac uses a S-band 2.6MW tunable magnetron as its RF power source. The accelerated beam current can reach 120mA. The max beam energy can reach to 11MeV with 1000 cGy/min.m.

In 1995 Tsinghua University constructed a 9 MeV traveling wave electron linac as an X-ray radiation source for on-line inspecting large container for customs. The maximum dose rate of this machine reaches 4000 cGy/min.m, the beam spot size is less than Φ1.5mm. The entire inspection system was also developed by Tsinghua University. The system includes the 9 MeV TW linac ,a 6.5m high detector array with front-end electronics, analog-digital convertors & fast data bus, a fornt-computer data calibration & system control and image processing system.

Table 2 gives a brief summary of these types of accelerators.

[1]WEIDA-Guandong Weida Medical Apparatus Group Co..
[2]SKY-Nanjing Sky Medical Instruments Co..

2.3 Electron Linacs for Irradiation Processing

Though the beam power of electron linacs is generally rather low, their beam energies are fairly high. Therefore electron linacs are widely used in irradiatron processing when high energy beams are required, such as the irradiation of large power and high voltage cables, the irradiation of semiconductor devices, etc.

In 1979, the first domestic made electron linac (BF-5) for irradiation processing was developed by BMEI and Tsinghua University.The maximum pulse beam current was 150mA with a beam energy of 4$\sim$5 MeV. A 2.0MW tunable magnetron served as its RF source. This linac was installed in the Beijing Low Energy Physics Center. This machine has been operating reliably for 18 years.

In 1992, BMEI constructed another almost identical machine for the Tianjin Cable Factory.

In 1987, CIAE rebuilted its short-pulse dense-current electron linac as an irradiation linac, with beam energy of 10$\sim$ 14 MeV and a 200mA beam current. Its RF power source was a 10MW klystron.

In 1989, Tsinghua University also rebuilt its electron linac for training and research as an irradiation linac.

In 1996, Nanjing University developed a 4$\sim$12 MeV irradiation linac for Zhuzhou Electro-Train Institute driven by a 3.0 MW klystron. The beam power of the machine is about 3KW, the average beam current is 450 μA.

Table 3 gives a summary of electron linacs for irradiation processing.

As part of the development program for low energy electron linacs, various institutes and universities completed research works on accelerator physics and beam dynamics, with numerous significant results[2].

3 RECENT STUDY RESULTS OF ACCELERATOR STRUCTURES FOR LOW ENERGY ELECTRON LINACS AT TSINGHUA UNIVERSITY

3.1 Backward Travelling Wave Accelerating Structure

In the past 25 years, various TW and SW accelerating structures have been studied in Tsinghua University. These ex-

Type	Linac	Energy (Mev)	Number of sets	Manufactuer
BT-4	SW	4	1	BMEI,BRIAMI
DZ-4/400	SW	4	1	BRIAMI
DZ-9/3000	SW	9	2	BRIAMI
TH-9	TW	9	1	Tsinghua University
Raphytron-3	SW	3	2	CIAE
Raphytron-4	SW	4	2	CIAE

Table 2: Domestic made electron linacs for radiography

TYPE	Linac	Energy (Mev)	Number of sets	Manufactuer
BF-5	TW	4 ∼5	1 1	BMEI,Tsinghua University BMEI
TH-9	TW	8∼10	1	TSHU
	TW	10 ∼ 14	1	CIAE
FEZ-10	TW	4 ∼ 12	1	Nanjing University

Table 3: Domestic made electron linacs for irradiation processing

periences were used to develop a backward travelling wave (BTW) accelerating structure[3], which combines the advantages of the Los Alamos SW cavity pattern and the traveling wave operating mode. The SW cavity possesses high shunt impedence, while the traveling wave structure has good operating stability.

Since BTW accelerating structure magnetically couples the cavities with off-axis slits ,the beam aperture can be reduced to increase the shunt impedence.

The $3\pi/4$ mode was chosen for our work. A model of 80cm long BTW accelerating structure with input and ontput couplers has been fabricated. The beam aperture is Φ7mm. The experimentally determined shunt impedence is 85.7MΩ/m, 83% of the theoretical value and much larger than the value for disk-loaded wave guides, which are in general 53∼57MΩ/m.

Fig.1 gives the passband property curve.

A 9 MeV TW accelerating structure was designed for a large container inspection system for customs. Its input RF power is about 3.5MW. It has a 1.2m long accelerating structure and a pulse beam current of 170mA.

3.2 X-band On-axis Coupled SW Accelerator Structure

In order to meet the requirement of developing the compact portable X-band SW linac for medical and industrial use, an X-band SW accelerator structure with on-axis coupler has been developed in Tsinghua University[4]. Increase of the operation frequency would bring a lot of advantages, such as not only reducing the size and weight of machine,but also increasing shunt impedance and breakdown threshold level.

Some authors have developed X-band disk-loaded structure[5] and side-coupled structure[5] as well as coaxial structure[6] . However, we prefers the on-axis coupled structure based our experience of S-band research work. Table 4 shows the result of structure optimization compared with other structures. As shown in table 4, the on-axis coupled structure offers a little high shunt impedance than the coaxial structure under the same condition of the beam aperture diameter. Although its theoretical effective shunt impedance is less than the side-coupled one. Our experience shows that the actual shunt impedance of both structures are almost the same for S-band linacs.

As a prototype, a 2 MeV X-band on-axis coupled SW accelerator guide with a buncher was designed ,machined,tuned,brazed and sealed. The accelerator guide is about 150 mm long with 5 buncher cells and 6 main accelerator cells, of which average theoretical effective shunt impedance is 121.4 MΩ/m. The measured Q-value of the guide is 7100 with the coupling factor, β =2.24. The average shunt impedance of the entire guide is 105.0 MΩ/m after being sealed, about 86 % of the theoretical value.

In cooperation with BVERI and CIAE, the commissioning was completed in last year. A 1.0 MW tunable coaxial magnetron (f=9315MHZ) was served as RF power source. A Piece gun emerges a 16KeV converging beam which directly injects into the first cavity of the buncher. When RF input peak power is about 0.68MW, a 2.4 MeV beam with more than 90 mA current has been obtained. The work has prepared a fundamental condition for developing portable X-band SW linacs for medical and industrial application.

4 CONCLUSION

Over the past 25 years, low energy electron linacs have been developed rapidly. About 200 sets of electron linacs have been produced for medical and industrial applications. They play an important role not only in the economical development but also in health care. Low energy electron linacs would be developed rapidly in the next 5 years.

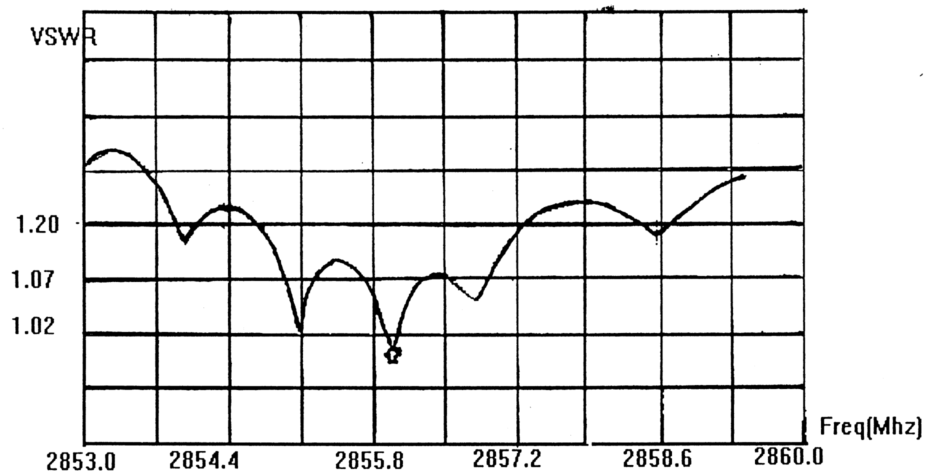

Figure 1: Passband property curve of BTW accelerating structure

Type of structures	Disk-loaded	Side-coupled	Coaxial	On-axis
Type of operation	TW	SW	SW	SW
Mode of operation	$2\pi/3$	$\pi/2$	$\pi/2$	$\pi/2$
Effective diameter (mm)	3.2	5.3	3.2	3.2
Effective shunt impedance(MΩ/m)	80	145	130	133
Beam Aperture diameter(mm)	8.0	4.0	4.0	4.0

Table 4: Parameter for X-band accelerator structure

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