APPLICATIONS OF LOW ENERGY ACCELERATORS IN CHINA

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Abstract

In recent years, low energy accelerators has been rapidly developed for medical and industrial applications. This paper presents the current applications of accelerators for radiotherapy, electron-beam irradiation processing, production of radioactive isotopes, electron-beam coal-fired flue gas treatment, container inspection for customs and radiography. There are about 600 sets of electron linacs used for radiotherapy in China. There are about 70 accelerators used for irradiation processing with a total electron-beam power of about 3300 KW. More than 10 kinds of radioactive isotopes are produced with cyclotrons and a proton linac for use in PET and other radioactive clinical treatment methods as well as diagnosis. Many experiments have been developed for removing SO_2 and NO_x from coal-fired flue gas, including a model plant with a capacity of 300,000 NM^3/h flue gas. 14 sets of domestically manufactured container inspection systems with electron linacs as radiation sources have been installed at seaports and about 20 sets of electron linacs are used for radiography.

1 INTRODUCTION

Since the last conference, APAC98, both low energy accelerators and their applications have rapidly developed. More than 600 electron linacs are used for radiotherapy in China, including about 300 domestically manufactured linacs. In 2001, a 20 MeV standing-wave accelerating tube was developed with an "energy switch" which fits the on-axis coupled accelerating structure. More than 55 sets of accelerator for irradiation have electron beam power of more than 5KW with a total electron beam power of about 3300 KW, of which more than 40 sets are domestically manufactured. The income from irradiation processing with those machines has reached 2000 million Chinese Yuan.

9~10 sets of 10~30 MeV cyclotrons and a 35 MeV proton linac are producing large amounts of radioactive isotopes such as ^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{67}Ga, ^{201}Tl, ^{123}I, ^{89}Sr, ^{188}W, ^{188}Re for the use in PET and other radioactive clinical treatment and diagnosis methods. A model plant with a capacity of 300,000 NM^3/h flue gas and a pilot plant with a capacity of 3000~12000 NM^3/h flue gas were constructed in Sichuan province for removing SO_2 and NO_x from coal-fired flue gas. Recently, a new application has been opened for accelerators with three types of domestic container inspection systems developed with electron linacs as radiation sources. 14 of these systems have been installed at seaports in China. About 20 sets of SW electron linacs are being used for radiography in heavy industry companies, with 11 sets being domestically manufactured.

2 LINEAR ACCELERATORS FOR RADIOTHERAPY

Cancer still seriously threatens human health and life. Every year, about 180 million patients are diagnosed as suffering from cancer in China. About 60~70% of these patients could receive radiotherapy from accelerators. This huge need has been pushing the development of medical accelerators in China since the 1960s. In the 1960s, several 15~20 MeV medical batatrons were developed to treat cancers. In 1977, the first medical electron travelling-wave linear accelerator was completed with a beam energy of 8~10 MeV to provide electron-rays and x-rays for radiotherapy. From the end of the 1980s to the middle of the 1990s, 4 MeV and 6 MeV standing-wave (SW) medical electron linacs were mass-produced with more than 120 domestic SW medical electron linacs in use. These medical electron linacs are still being developed further. There are now four companies which mass produce medical electron linacs with electron beam energies from 4 to 14 MeV, as shown as table 1, with more than 300 domestic machines in use. There are also about 300 imported medical linacs in use.

This year, a 20 MeV standing-wave accelerating tube with an "energy switch" which fits the on-axis coupled accelerating structure was developed by Tsinghua University in cooperation with BVERI. It can provide 6 or 15 MV X-rays and 5, 7, 9, 12, 15 or 20 MeV electron rays. The patent has been issued for the "energy switch" (CN1237079A, 1999). This progress has laid a solid foundation for further development of a 20 MeV SW medical linac with the on-axis coupler's "energy switch" in the near future. The 20 MeV SW acceleration tube is shown in Figure 1 with a 270° deflecting chamber in the tube end.

A 35 MeV proton linac serving as a fast neutron source for neutron therapy was developed by the Institute of High Energy Physics (IHEP). Both the proton beam and the neutron beam are horizontal and fixed in place. A view of the 35 MeV proton linac therapy treatment room is given in Figure 2.

Table 1: Chinese domestically made medical electron linacs

Type	Linac	Energy(MeV)	Radiation	Number of sets	Manufacturer
BJ-10	TW	10	X, E	1	BMEI, Tsinghua University
BJ-10	TW	10	X, E	1	BMEI
BJ-4	SW	4	X	58	BMEI
BJ-6M	SW	6	X	25	BMEI
BJ-6B	SW	6	X	90	BMEI
BJ-14	SW	14	X, E	4	BMEI
WDVE-6	SW	6	X	92	WEIDA
WDZ-14C	SW	14	X, E	1	WEIDA
ZJ-10	TW	10	X, E	21	SMNIF
XHA-600C	SW	6	X	10	XHMED

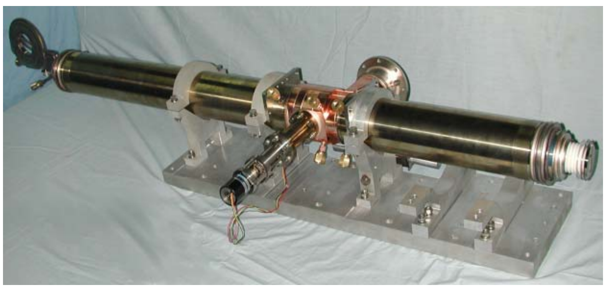

Figure 1: 20 MeV SW medical acceleration tube with an "energy switch".

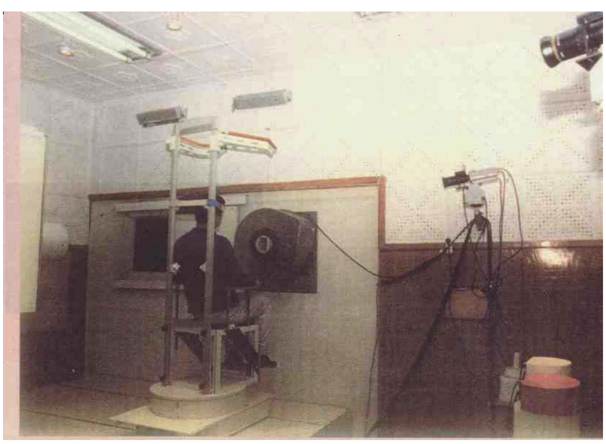

Figure 2: Neutron therapy treatment room at IHEP.

This facility has enabled many experiments on neutron radiophysics, neutron preclinical radiobiology, the effects of neutron radiation, etc. Since 1991, this facility has also been used to treat patients with more than 600 patients, including a Taiwan patient been treated. The clinical results show that the neutron radiotherapy is effective for some cancers such as salivary gland cancer, prostatic adenocarcinomas, soft tissue sarcoma, bone sarcoma, metastatic cancer in the head and neck, malignant melanoma, and pancreatic cancer.

Some proton therapy facilities are currently under consideration.

3 ELECTRON ACCELERATORS FOR IRRADIATION PROCESSING

Another field which has been rapidly developed is the electron-beam irradiation processing applications. Irradiation processing applications still concentrate mainly on heat-shrinkable materials(tube, film), wire and cable consuming most of the beam power and the annual output value (about 80~85%). Irradiation processing is also used for other applications, such as coating curing, radiation chemical materials and radiation sterilization, but not on a production scale. For all these applications the beam energy is below 4 MeV. Several 8~14 MeV travelling-wave electron linacs are employed to modify the properties of semiconductor devices.

By the middle of 2001, the total of about 70 irradiation accelerators had been installed, with about 44 of them being domestically manufactured. The currently installed machines are listed in table 2, with their accelerator types, beam energies, beam currents, number, manufacturers, etc. Figure 3 gives a picture of a Dynamitron-type machine made by IHEP. Figure 4 shows a view of another Dynamitron-type machine made by SINR.

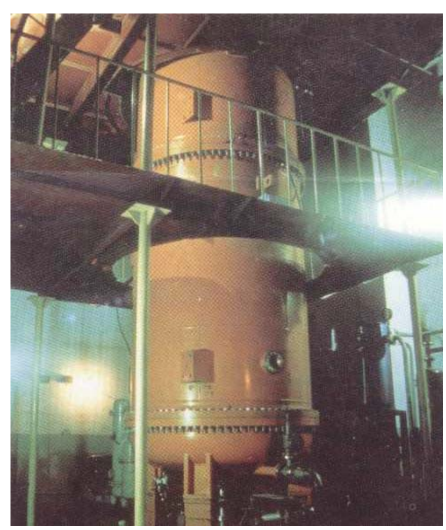

Figure 3: 3.0MeV GNJ Dynamitron-type machine made by IHEP.

Figure 4: 3.0MeV Dynamitron-type machine made by SINR.

The total beam power is about 3300 KW. The annual value of the irradiation processing was more than 2,000 million Chinese Yuan in 2000. Figure 5 shows the increasing status of irradiation processing accelerators and their beam power in China.

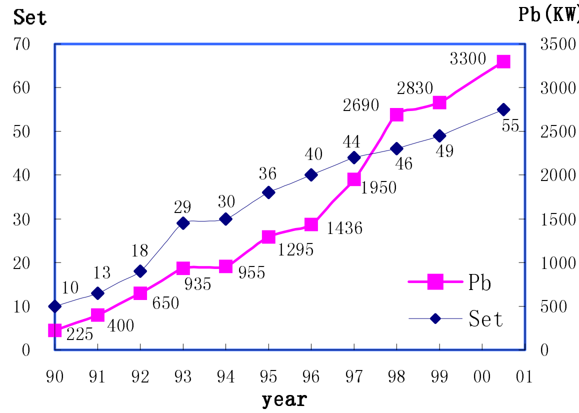

Figure 5: irradiation processing accelerators which beam power exceeds 5KW and their beam power.

4 ACCELERATORS FOR PRODUCTION OF RADIOACTIVE ISOTOPES

The third field of accelerator application is the production of radioactive isotopes. In recent years, proton accelerators for producing radioactive isotopes were developed rapidly. The first, in 1994, was a 30 MeV intense current proton cyclotron (CYCIAE 30)

Table 2: accelerators for irradiation applications

Category		type	Energy (MeV)	Current (mA)	Number	Manufacturer
D.C. high voltage accelerator	Dynamitron	Dynamitron	3.0	40	4	RDI(U.S.A)
			2.0	30	1	RDI(U.S.A)
	Radio-frequency cascade generator (Dynamitron-type)	GJ-2	2.0	10	18	Shanghai（China）
		KFG-1	2.5	30	4	Beijing Kefu(China)
		KFG-2	3.0	20	8	SINR（China）
		GNJ-3.0	3.0	20	2	IHEP（China）
	High voltage rectifier type (with an iron-core)	ELV-8	2.5	30	8	(Russia）
		ELV-4	1.5	20-30	4	(Russia)
	High voltage transformer rectifer type	EPS-3000	3.0	30	1	Nissin-High voltage (Japan)
		EPS	0.8	400	2	Nissin-High voltage (Japan)
	Isolated-core transformer	FDJ-0.3	0.3	30	2	BRIA
		FDJ-0.6	0.6	40~50	3	BRIA
		FDJ-1.2	1.2	6~10	1	BRIA
		Vivirad	3.0	40	1	Vivirad(France)
		Vivirad	2.0	40	1	Vivirad(France)
	Long filament type		0.2	20	1	BRIA
Pulsed resonance accelerator	Single cavity standing wave accelerator	ILO	2.0	10	3	(Russia)
			2.0	10	1	CIAE(China)
	Traveling wave electron linac	BF-5	4.0	0.15	2	BMEI(China)
			14.0	0.2	1	CIAE(China)
			4~14	0.45	1	Nanjing U.(China)
			10	0.20	1	YunhuanEATRI(China)

Figure 6: 30MeV Cyclotron (CYCIAE-30) made by CIAE.

constructed by CIAE (Chinese Institute of Atomic Energy), whose beam energy could be adjusted from 15 MeV to 30 MeV, with the maximum target current of 370 μA. The machine has been specially designed to produce medium and short-lived radioisotopes for medical use. The radioisotopes include ^{18}F, ^{201}Tl, ^{57}Co, ^{67}Ga, ^{123}I, and ^{103}Pd. In Sichuang University, a domestically produced 13.5 MeV cyclotron has also been used to produce radioisotopes, such as ^{57}Co, ^{109}Cd, ^{211}At, and ^{199}Tl. In the Shanghai Institute of Nuclear Research Academia Sinica, a 30 MeV proton cyclotron was imported from IBA company, Belgium in 1997 to produce ^{18}F, ^{67}Ga, ^{89}Sr, ^{123}I, ^{188}W, ^{188}Re, and ^{201}Tl. Among these radioisotopes, ^{18}F, ^{67}Ga, ^{89}Sr, ^{123}I, ^{188}W, ^{188}Re, and ^{201}Tl are used as diagnostic medicines. During 1998~2000, seven sets of 11 MeV compact negative hydrogen-ion cyclotrons (RDS-111) were imported from the CTI company (Computer Technology Imajin) in the U.S.A. to produce short-lived positron-emitting isotopes for use in PET and as radiolabeled compounds. They were installed at General People Liberation Hospital, Consonancy Hospital, Shanghai Huashan Hospital, Beijing Xuanwu Hospital, and the People's Hospital of Guangdong Province, etc. The short-lived positron–emitting isotopes produced by the machines include ^{11}C, ^{13}N, ^{15}O, and ^{18}F. The RDS-111 targets are gas targets and liquid targets. The beam current on the target is about 40 μA. The accelerated negative ion beam is extracted at the extraction radius by passing through a thin carbon stripper foil to remove the electrons to produce a proton beam. The extraction efficiency from the foils is approximately 99%. Figure 7 shows the RDS-111 cyclotron for PET use.

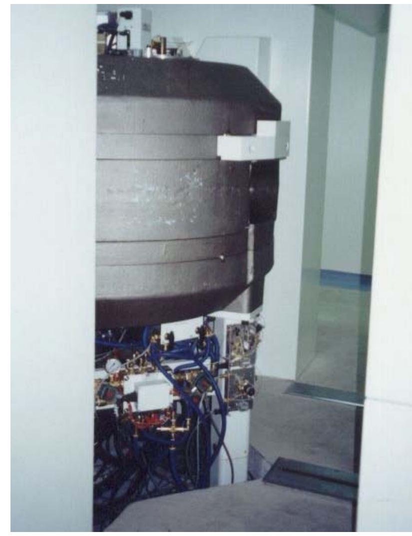

Figure 7: RDS-111 cyclotron installed at a hospital.

5 ELECTRON ACCELERATORS FOR REMOVING SO_2 AND NO_x FROM FLUE GAS

Another important application of accelerators in China is for electron-beam flue gas treatment (EFGT). The emission of coal-fired boiler flue gas containing large amounts of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) is a serious air pollution problem. In China, the SO_2 emitted in coal-fired power plants flue gas is more than 20 million tons per year. The government considers this to be a serious problem and requires decreased emissions of coal-fired flue gas. New techniques for effective SO_2 and NO_x removal from flue gas are urgently needed. There are various SO_2 and NO_x removal technologies, of which the EFGT technology is one of the most promising technologies. Experiments to remove SO_2 and NO_x with EFGT method were started in 1984 in the Shanghai Institute of Nuclear Research (SINR), Academia Sinica. In the early 1990's, interest in the EFGT method expanded very quickly. Recently about 10 institutes, universities and power plants have been involved in development of this technology.

In 1999, China Electrical Power Ministry, in cooperation with the Ebara corporation, Japan, set up an 100 MW model plant for removing SO_2 and NO_x from flue gas using EFGT method at the Chengdu Electric Power Plant. The system has a treatment capacity of 300,000 NM^3/h flue gas using two sets of high voltage electron accelerators (800KV, 2×400mA). The system runs very well with byproducts (ammonia sulfate and ammonium nitrate) used as fertilizer .

In the same year in Mianyang, Sichuan, a pilot plant was constructed to develop the technology for treating flue gas with the EFGT method by CAEP (China Academy of Engineering Physics) at a coal-fired electrical power station. The pilot plant can treat 3000~12000 NM^3/h flue gas with a 800 KV, 45 mA high voltage electron accelerator. The plant has operated reliably for more than 1000 hrs. The SO_2 removal efficiency exceeded 92% and the NO_x removal efficiency reached 75%. Figure 8 shows the pilot plant for removing SO_2 and NO_x .

Experimental tests at the Institute of Nuclear Energy, Tsinghua University and the Shanghai Institute of Nuclear Research have also produced very satisfactory results.

An 800 KV, 2×300 mA and an 800~1200 KV, 80 mA high voltage electron accelerator are under development in the Shanghai Institute of Nuclear Research and the Lanzhou Institute of Modern Physics, Academic Sinica. The 800~1200 KV 80 mA accelerator at Lanzhou is shown in Figure 9.

Figure 8: pilot plant constructed by CAEP for removing SO_2 and NO_x in Mianyang, Sichuan

Figure 9: The 800~1200 KV 80 mA accelerator at LIMPR

6 ELECTRON LINACS FOR THE CUSTOMS CONTAINER INSPECTIONS

A new application for accelerators is for container inspection at customs. Smuggling in China has been a serious problem. The smuggling of contraband goods, arms and drugs is not only an important security problem, but also affects the national income by affecting import and export taxis. Usually, container inspections rely on manual inspections, which necessitate that only a few percent of the containers are inspected. This is no longer acceptable with the increasing numbers of containers being transported. An automated inspection system is necessary, such as that found in airports for inspecting personal luggage. To meet these requirements, three types of large container inspection system for customs have been developed by Tsinghua University in cooperation with Tsinghua Tongfang Nuclear Technology Co., LTD.

The systems use high-energy X-rays from a linear accelerator to scan the container with detectors to record the radiation intensity passing through the container. The electrical signals produced by the detectors are then amplified and digitized. Finally, the X-ray image of the container is displayed on a video monitor for the customs officer. The system provides a fast inspection procedure without opening the container.

The three types of large container inspection systems are “the fixed type”, “the relocatable type” and “the mobile type”.

The fixed type system has a 9 MeV travelling wave linac as a radiation source situated in a shielded room with cement walls two meters thick. The 9 MeV linac is driven by a 3.5 MW klystron which has a 0.4 m long bunching section and a 1.8 m long main accelerating waveguide. The bunching capture efficiency is more than 75%. The beam pulse current is about 120 mA which heats the tungsten target causing it to radiate 40

Figure 10: 9 MeV TW linac from the electron gun side.

Gy/min·m X-rays. A triple-quadrupole magnetic lens is employed in front of the target to further focus the accelerated beam to 1.5 mm diameter. Figure 10 shows a view of the structure of the 9 MeV TW linac from the electron gun side.

The first fixed type inspection system was installed at the Tianjin seaport customs in the end of 1999. Figure 11 gives a view of the building and working field for this system.

Figure 11: building and working field for the inspection system at the Tianjin seaport customs

By the middle of 2001, other eight sets of fixed type systems had been installed at seaport customs in Dalian, Qingtao, Shanghai, etc.

However, most ports have insufficient space to install the fixed type inspection system and they have less containers to inspect. Therefore a mobile, flexible, self-shielded, compact system was also developed which was mounted in a truck. This system had an X-band 9.3 GHz 2.5 MeV on-axis coupled standing-wave linac as the radiation source. The accelerating guide length is only 15 cm and does not have any external magnetic focusing coil. The mobile system is shown in Figure 12. Three sets of these systems have been installed in Guangdong ports.

Figure 12: mobile container inspection system

For medium size ports, the "fixed type" system is too expensive and the "mobile type" system is too limited. So a "relocatable type" system was developed which can be placed in a simply-shielded cement-block building but possesses more penetration power than the mobile one. A S-band 6.0 MeV standing-wave linac was chosen for its radiation source. A double-housing gantry structure is employed in this system (Figure 13) with the radiation head mounted on one side of the gantry. Two sets of these systems have been installed in Xiamen and Guangdong Customs.

Another 26 sets of these three systems will be installed at other ports in the next two years.

Figure 13: relocatable type inspection system

7 ELECTRON LINACS FOR RADIOGRAPHY

About 20 sets of electron linacs are used for radiography at heavy industrial companies in China. Among them, 11 sets are domestically produced, with electric beam energies of 3, 4 and 9 MeV.

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