THE PROGRESS OF LOW ENERGY PARTICLE ACCELERATORS IN CHINA

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Abstract

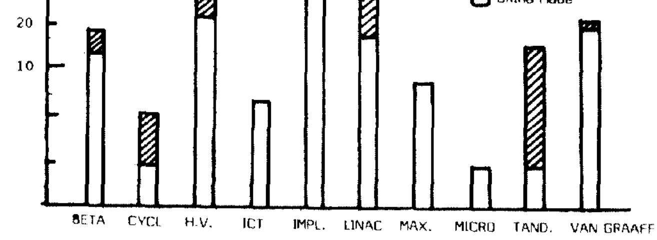
A brief account on the development of particle accelerators in China is given. Features and performance of typical accelerators are described. R & D efforts are also included.

Introduction

It was 30 years ago when Prof. Zhao Zhong-yao and his group put China's 1st 2.5 MV Van de Graaff accelerator into operation at the city branch of Institute of Atomic Energy [1]. A little later, 25 Mev Betatrons and 1.2 m cyclotron imported from USSR started working at Peking Univ., Tsinghua Univ. and IAE respectively. Inspired by the needs of basic research and the achievements of nuclear energy, a variety of accelerators were studied and constructed by universities and research institutes in the early period. Among them, the 30Mev electron linac,developed by Prof. Xie Jia-lin's group,was the highest in energy and was put into operation in 1964 [2]. Subsequently the industry produced various types of accelerators e.g. cascade generators, electrostatic accelerators, betatrons and cyclotron etc. By the end of the first decade, the number of accelerators totaled up to about 50 and thus laid down the basis necessary for future development.

The development of accelerator technology in the recent decade turns out to be active and fruitful. New projects for basic research including Beijing Electron Positron Collider, Lanzhou Heavy Ion Research Facility, Hefei Synchrotron Radiation Facility, the 6 MV Tandem accelerator and the 4.5 MV Van de Graaff accelerator etc. all are approaching their completion. Thanks to international collaborations, the design and construction of these accelerators are much facilitated. Meanwhile, a great number of small accelerators aiming at applications in the fields such as radiotherapy, micro electronics, radiation processing and ion beam analysis etc. have emerged to meet the strong needs from medical treatments and various industries. According to recent incomplete statistics, the number of accelerators totals up to 270 [3], and about 2000 scientists and engineers are engaged in this field, among them 800 are members of China Society of Particle Accelerators.

The number of various accelerator species is plotted in Fig.1.



The rapid development of ion implantation technology stimulated mass production of high voltage multiplier as implantor. So far 76 sets of 150-600 KV implantors have been produced in China and 22 sets imported from abroad [4]. The medical treatment is also a field where extensive applications of accelerators are absolutely necessary. Up to now, 45 electron linacs and 8 betatrons have been installed in the nation for radiotherapy [5]. To meet the needs of medical isotopes, existing cyclotrons have been producing short-lived isotopes from time to time. Moreover,an imported compact cyclotron CS-30 and a 35 Mev proton linac are dedicated to medical isotope production. Applications of electron accelerators to the field of radiation processing appear to be quite profitable. The manufacturer in Shanghai and Chengdu made million yuan (RMB) profit out of cable irradiation. In addition, more than 20 electron accelerators are used for producing foamed polyethylene, vulcanized silicon rubber and for paint curing and etc. [6]. However, the installed capacity of beam power totaled 182 kw which is obviously too low to meet the requirements from the industry. The number of small tandem Van de Graaff accelerators are growing rapidly because of extensive use of ion beam analysis. The 2 MV tandem developed by Lanzhou Institute of Modern Physics was put into operation in 1986, and the other 12 made by NEC and GIC in U.S.A. are also in operation. They are mainly used for studies in environmental science, archaeology, material science and etc.

Ion Implantors

There are 4 factories and 10 institutes engaged in the manufacture and development of ion implantors. 59 sets of 200 KV implantors have been produced in Beijing, Baoji and Changsa since 1976 [4]. The typical products are listed in Tab.1. All of them are equipped with pre-acceleration analyzer, in general a 90° double focusing magnet with a resolution $M/\delta M=100$.

Table 1

Type	Year	Voltage (kv)	B^+Yield (μA)	Uniformity
J95-200/ZM	1980	20-200	100	< 3 %
J59200B/2K	1981	30-200	120	≤ 1.4%
LC — 2B	1984	30-200	150	= 5 %
ZLZ — 200	1985	30-200	250	≤ 2 %

Typical accelerating tube developed by Beijing Institute of Automation for Machinery consists of stainless steel electrodes bonded with high boron glass rings. The gradient of a surface break down is 4.5-5 kv/cm and the strength against pulling 61.3 kg/cm. Extensive studies have carried out on ion sources for implantors, e.g. Penning, Duoplasmatron, Calutron, micro-wave source and etc., so as to raise the ion yield, to extend the ion species and to improve the beam quality. The ionizing efficiency of

Freeman type source was enhanced at IAE by putting molybdenum screens on both ends of the ionization chamber [7]. For a BF_3 discharge the proportion of $B^+$to the total yield=38.5%, while I=30 mA at gas consumption of 3.5 cc/min, and the source life time >10 hr. A number of compact Penning source with permanent magnets was developed by Peking University's group [8]. Total yield of a typical side-extraction source is 1-2 mA with the proportion of N^+ 60~70% and B^+ 40-50%. Rich content of multiply charged ions has been found.

The implantor SD-400 [9], constructed by Shangdong University in 1985, has an energy range of 50-400 kev and a resolution $M/\delta M > 200$. In order to minimize the path length of ions while keeping resolution high they made good use of an unsymmetrical double focusing magnet with a radius of 56 cm for pre-acceleration analysis. An electrostatic quadruple doublet is set in front of the magnet so that the emittance of the injected beam can matched in both directions to form a real image. The path length of ions from source to target is about 6 m.

The C-600 implantor [10] developed by Shanghai Institute of Metallurgy accelerates ions of A=1-210 amu. to an energy 200-630 kev. Typical target currents are $Ar^+ \approx 200\mu A$, $P^+ \approx 105\mu A$, $Mg^+ \approx 75\ \mu A$, and $Cd^+ \approx 65\mu A$. The HV terminal is about 7 m high from the ground and is linked by an infrared optical telemetry system transmitting 40 signals with the controlling panel. The heavy ion source model 820 can work with gas, liquid or solid state samples and provide more than 20 species of ions. The accelerating tube is totally 1.76 m long, divided into 4 sections. Each consists of titanium disk shaped electrodes bonded with 95% Alumina ceramic rings. The tube is working under a clean vacuum of $3x10^{-7}$ tor and can sustain a voltage as high as 850 kv during the "cold" test. The analyzing magnet is set after the acceleration. With a gap of 4 cm and a radius of curvature of 1.2 m the magnet has a resolving power $M/\delta M = 208$. The transmission efficiency from the tube output to target ≈ 80%. Five beam lines are available.

Recently, high current implantors for modification of materials have been developed by Sichuan Univ., Beijing Normal Univ., IHEP and etc.

High Voltage Electron Accelerators

Most of the electron HV accelerator are used for radiation Processing. The JJ-2 accelerator produced by Vanguard factory was the basic model in 1960's. It is a 2 MV electrostaic accelerator with 200 μA output current and 40 cm scanning width. However, to make the processing cost effective an average beam power higher than 5 kw is necessary. For this purpose,BIAMI developed series of ICT products including 0.3 Mev/30mA, 0.6Mev/30 mA, 1.5 Mev/10 mA and etc., while Vanguard developed a 2Mev/10mA model GJ-2 for cable irradiation [11]. It is a Dynamitron providing a scanning width of 80 cm and field flatness 85%.The cable is winded by pullies in a pattern of "8" during the exposure . Besides, they produced a new model of cascade generator providing 500 Kev/40mA beam with a 1 m scanning width and uniformity > 85%. Moreover, an electron curtain accelerator of 200 Kv/30 mA will be available commercially for radiation paint curing. It is expected that the production of high power accelerators for industrial irradiation will continue growing, more and more radiation centers will be established in the near future.

Pulsed high current generators have been developed to meet the requirements of flashing radiography [12] as well as the research of ICF and excimers by National Academy of Engineering Physics [13]and IAE [14]. The specifications of basic facilities are listed in table 2.

Table 2

Inst.	Model	V(mv)	I(kA)	t(ns)	Dose	Use
NAEP	FL-1	6-8	75-100	85	950	Flash radiograph
	EPA-1	.4-.7	4	90		Microwave FEL
	EPA-2	0.5	120	70		Excimer Studies
IAE	No.1	1	80	80		Excimer & Beam
	No.2	.65	150	40		Physics

Micro-wave FEL amplifier experiments were carried out on EPA-1 [15]. A 100 A, 50 ns pulse beam, 4 mm in diameter with axial momentum spread 0.2% was injected into a cylindrical optical cavity. The Wiggler field generated by 1 m long bifilar helix was a circulary polarized magnetic field with $\lambda w=3.45$ cm. At an input level of 30 w, more than 1.4 Mw radiation of 34.5 GHz was observed (Fig.2).

Fig.2 The FL-1 Accelerator

Heavy Ion Electrostatic Accelerators

The 2 MV tandem at Inst. of Modern Phys. Lanzhou is the first workable tandem Van de Graaff made in China and has run stably since 1986 [16]. Its terminal voltage can be adjusted in the range of .3-2 MV with a fluctuation < ±1 KV. The beam current at the analyzing magnet exit is 1-3 μA and the spot size 3 mm. the laddertron developed by IMPL runs at a linear velocity of 12 m/s and can sustain a gradient of 2.06 MV/m. typical charging current is 440 μA. The bakeable titanium-ceramic (95% Alumina) accelerating tube ensures a very clean and high vacuum for acceleration, the gas leakage of the tube is 10^{-9}tor-l/sec. The tube consists of 6 sections and has an effective length of 1.15 m in total with the mechanical strength against pulling : 500-900 kg/cm. Apart from the above, the 6MV tandem designed and constructed by Shanghai Institute for Nuclear Research has been installed and commissioned, their laddertron, duoplasmatron source and 60kev injector have passed the acceptance test [17].

The tandem HI-13 of HVEC was put into operation at IAE, Beijing in Oct. 1986 [18]. So far, more than 10 ion species have been accelerated. The highest voltage of 13.4 MV was reached with the acceleration of proton beam. Experiments were carried out smoothly with Q3D and neutron TOF spectrometer and other equipments. The transmission efficiency along 40 m long beam lines appears to be 95%. However, as the beam utilization efficiency of the present buncher is as low as 2/70, so that a higher efficiency beam pulse system has to be considered. In addition an EN-18 tandem of HVEC was transferred from Oxford to Peking University in 1986. It is being commissioned and hopefully it might be able to get the first beam by the end of this year. The other 11 tandems of 1 MV, 1.7 MV, 3MV produced by NEC and GIC are in operation for ion beam analysis in the nation.

As for single ended Van de Graaff accelerator, the 4.5MV machine at Peking University has been installed after a long delay due to the building construction [19]. It is expected to get the beam this year. A high efficiency beam pulsing system is equipped in the terminal electrode. the BUE is enhanced by a factor of 1.47 by superimposing the 9th harmonic onto a conventional sine wave chopper[20]. Moreover, a short focused double drift harmonic buncher is installed to ensure the BUE OF bunching to 66% [21]. These compose one of the unique features of the accelerator (Fig.3).

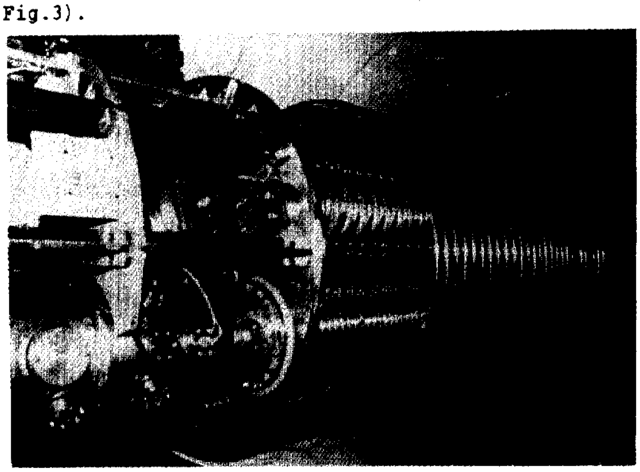


Fig.3 The 4.5 Mv Van de Graaff Accelerator

Cyclotrons

HIRFL is one of the major accelerator projects in China, which is composed of a SF injector cyclotron (K=69) and a Split Sector cyclotron (K=450). The SF cyclotron has been in operation since 1987 with typical parameters as following: [22]

Ion	B(kG)	F(MHz)	V(kV)	Rex(cm)	E(MeV/A)	I(eμA)
$^{12}C^{4+}$	14	7.1	60	75	5.9	1.1
$^{16}O^{5+}$	15	7.1	60	75	6.0	1.4

Carbon ions are to be accelerated in SSC to 100 Mev/A while Xenon 5 Mev/A with an intensity of 10^{10} - 10^{12} pps. The main magnet consists of four 52° sector, each weights 2000 tons, with a field up to 16KG. there are 36 pairs of trim coils mounted inside the gap. When the input RF power is 240 Kw, 100-250 Kv is generated by each of two 26° sector cavity in two valleys, the operation frequency of which can be adjusted in the range of 6.5-14 MHz. The vacuum chamber contains pole tips, trim and harmonic coils, accelerating cavities, as well as inflection and extraction devices in a high vacuum and thus has a rather peculiar shape with a total volume up to 100 cubic meters. Nevertheless, the giant was evacuated to a vacuum as high as $6x10^{-8}$ tor. last year, which was one of most difficult yet well done tasks during the commissioning. So far they have finished the shimming of the magnet. The field inhomogeneity measured at median radius was 21 gauss and reduced to 1 gauss after careful shimming. However the perturbation due to the inflecting channels can be as high as 17 gauss in the region of injection after incomplete compensation. The center variance of the orbit in the field is about 3 mm. SSC is expected to get its first beam by the end of 1988 for the experiments of nuclear research (Fig.4).

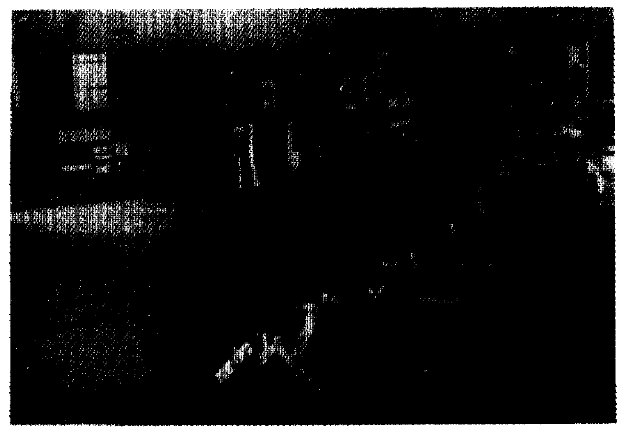


Fig.4 The Accelerator SSC

The majority of conventional cyclotrons built in 1960s have been upgraded. For instance, the 1.2m cyclotron of Shanghai Institute for Nuclear Research was reconstructed in 1982 and thus it turned from a fixed energy machine (6.8 Mev proton) to a variable energy isochronous cyclotron providing proton beam in the range of 10-30 Mev , deuteron 10-16 Mev and Alpha beam 10-32 Mev. The energy spread of the extracted beam was minimized to 0.43% by computer optimized orbit programming based on the measured electro-magnetic field distribution.

Besides cyclotrons a microtron DHJ-25 [23] for dosimetry research was jointly developed by Tsinghua University and BIAMI. It provides electron beam in the energy range of 5-27 Mev, and 18 mA pulsed current at the 27th orbit when the RF power is fed from a 2 Mw magnetron. The beam current extracted at 25 Mev, reached 18.9 mA with a spot size 2x2 mm and energy spread < ±1%. The dose rate of 25 Mev X-ray is in the range of 400-1000 R/min-m.

Linear Accelerators

The majority of linear accelerators in China are for medical use. Among them BJ-4 and NDZ-20 are two recent products developed by Beijing Institute of Medical Equipments and Department of Physics, Nanking University respectively. The former is a compact, economical 4 MV therapy system [4] suitable for installing in a small treatment room. The length of the entire assembly is only 38 cm. and the gun, side-coupled cavity, RF window and the target are brazed altogether and sealed off under very clean and high vacuum. As a result it works with high reliability, long life and convenience. Under a peak power of 2.6 MW. BJ-4 provides 4 Mev X-ray with a dose rate of 500 R/min-m.

NDZ-20 is a 20 Mev TW electron linac with a feedback loop [25][5]. It's equipped for X-ray and electron beam therapy (table 3).The feedback of the traveling wave facilitates varying the output energy in a wide range: electron beam 5-20 Mev. and X-ray 5,15 (or 8,16) Mev. In this way it is able to provide a variety of depth dose profiles to satisfy various requirements of different treatment. It was found that the system efficiency as well as the beam loading characteristics can be optimized by using a coupler with variable feedback ratio . To limit the extra energy spread of the beam caused by long build-up time associated with the feed-back process, a pair of magnetic chopping coils are used to cutoff the front edge of the beam before entering the waveguide and it works successfully (Fig.5).

Table 3

Type	BJ-4	NDZ-20		DZ-10	
		X-ray	e-beam	X-ray	e-beam
Energy(Mev)	4	10,15(8,16)	5-12	8	6,8,10
SSD(cm)	80	100	100	100	100
Dose rate (R/min-m)	500	300-500	300-1000	500	500
Spot size(mm)	2	3.5		2	
Uniformity(%)	±3	±3	±5	±3	±5
Structure	side coupled	TW feedback		Travel. wave	
Frequency (GHz)	2.998	2.856		2.998	
RF Power(MW)	1.6	4.5		1.8	
Total length (m)	0.38	2.58		2.33	

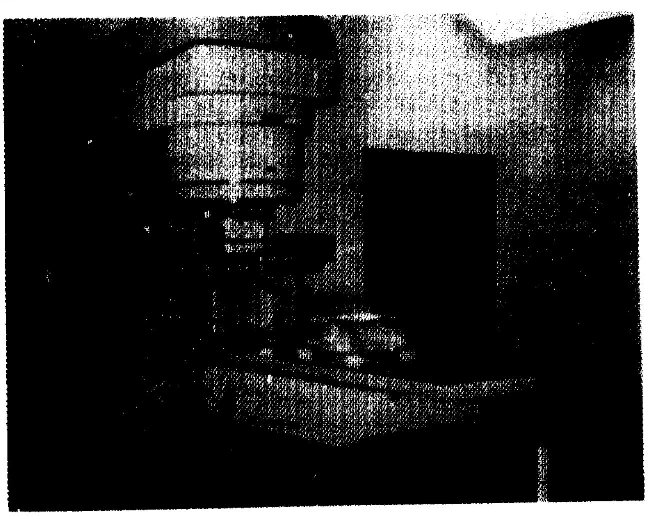


Fig.5 The NDZ-20 Electron Linac

The proton linac of IHEP is also dedicated to medical applications. Proton beam can be accelerated to 35.5 Mev with a peak current of 70 mA and transported down the 35 m beam line to two target halls equipped for short lived isotope production and neutron therapy respectively [26]. With an average beam current of 75 μA, it is able to provide annually several tens Curies of medical isotope like ^{11}C, ^{67}Ga, ^{201}Tl and etc. The first batch of ^{201}Tl was produced in 1987. Moreover, by bombarding proton beam on Be target, 20 Mev neutrons can be produced at a dose rate of 145 rad/min-m.

The preinjector of the linac consists of a 750 KV cascade generator with a duoplasmatron source and a double drift harmonic buncher which is set in front of the Alvarez tank. The total length of the tank is 21.83 m and divided into 6 sections with totally 104 cells. The linac is tuned to 201.25 MHz and the average accelerating field varies from 1.65-2.6 MV/m at 5MW RF power. To suppress the unwanted TM_{001} and TM_{012} modes two RF feeding ports located at 1/4 and 3/4 tank length are used. LASL type resonant couplers are mounted inside the tank with a periodicity one per two drift tubes so as to get the stabilized field. As a result the mode separation increases from 74 KHz to 139 KHz [26].

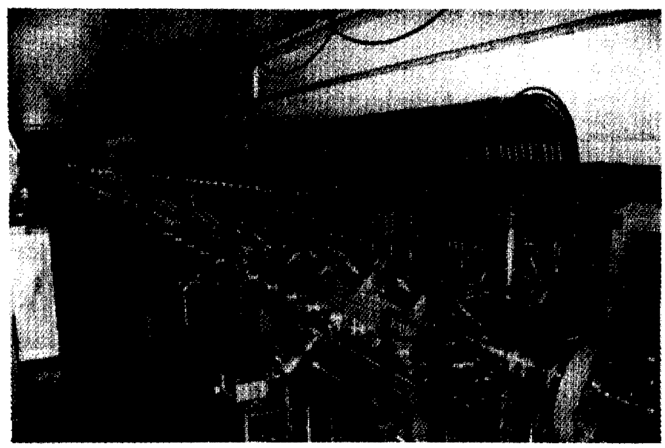


Fig.6 The 35 MeV Proton Linac

Apart from medical applications, there are several linac projects carried out for basic research. As FEL studies arouse great interest in recent years, IHEP decided to upgrade their 30 Mev linac for the first phase of their Compton regime FEL research project [27]. The parameters of the linac are: E=10-30 Mev, I(bbu)= 300mA, T(e-beam)= 4μs, T(modulator)= 5μs $\delta\gamma/\gamma = 0.5\%$, $\delta f/f = 10^{-6} - 10^{-7}$. The longitudinal motion of the electrons in a 3.05 m long constant gradient wave guide has been simulated by computation under the condition of 200 mA beam current and 12 MW RF power input. The longitudinal phase space and factors affecting the output energy spread, e.g. initial phase and energy spread, phase fluctuation of injected electrons and etc. have been carefully studied.

The high brightness preinjector is one of the key Items of linac based FEL project. IHEP is developing a microwave gun for this purpose. It is expected to provide 20 A pulsed current with 4° phase width and an emittance of 30 mm-mrad at an energy of 0.9 ± 0.1 Mev. On the other hand, IAE planned to develop co-axial planar grided gun combined with 1/24 and 1/6 subharmonic buncher so as to reach a peak current of 100 A(t=20 ps) with energy spread $< \pm 1\%$. With their grided pierce gun, 19 A peak current of 2.4 ns has been obtained in a bench test when the pulsing voltage reached 82 KV [28]. The cathode-grid geometry will be studied further and scandate cathode will be tried so as to upgrade the performance of the gun.

The linear induction accelerator is the other important approach to produce energetic high intensity beam. NAEP has completed the first induction accelerator in China. It consists of 7 inducting cells and is capable of accelerating 4 KA beam 90 ns beam to 1.5 Mev [12]. They are going to upgrade the machine and carry out FEL amplifier studies.

As for heavy ion linacs, with the support of NSFC, Peking University's group has developed a 4-rod structure excited by integrated split-ring resonators which can be operated in the range of 14-100 MHz[29][30]. Typical results of model test are: Fo = 27.26 MHz, Q=1190, Specific resistance r = 135.6 KΩ. Both the axial and radial field distribution are satisfactory. We are planing to construct a RFQ either for ion implantation or to use as a preinjector for our EN-18 tandem to accelerator ions like C, Be, B, Al and etc. to 300-500 Kev for the AMS project supported by NSFC. Apart from the above,the group has also been engaged in developing post acceleration boosters for D.C. accelerators. A variety of low Beta resonators including Helix, Tapperd helices, Spirals, Split-rings designed, constructed and tuned to 28 MHz or 108 MHz. A model cavity containing two 17 cm long helices turned out to be able to accelerate 300 Kev proton to 620 Kev when the RF input power is 19 KW and frequency 28.8 MHz [31]. The cavity has been in routine operation as a postbuncher providing 1 ns deutron beam for neutron TOF experiments. In addition, two helical cavities and a split-ring cavity w ere constructed and installed on the beam line of EN-18 Tandem to provide a boosting voltage of 3 Mv [32].

Conclusion Remarks

Particle accelerators in China has progressed smoothly since 1978. While there will be great efforts in the near future to make best uses of these existing facilities, more and more new projects for industrial and medical applications will be f unded. On the other hand, new ideas and technologies will be highly encouraged to develop few advanced accelerator projects in China either for basic research or application purpose.

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