DEVELOPMENT OF LINEAR ACCELERATORS IN CHINA

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Summary

In this paper, a brief account of the development of linear accelerators in China will be given. Firstly, some small scale electron linac and microtron projects, with energy below 30 Mev, will be mentioned chronologically to serve as background to understand the later developments. Secondly, some R & D efforts, such as RFQ, helical wave-guide resonator, S.W. structure, T.W. resonator etc. that had been carried out in various institutes, will be discussed. Lastly, four major linear accelerator projects now under construction in China will be briefly described.

(1) Introduction

The development of accelerators in China began only after the founding of PRC in 1949. Up to now, more than one hundred and forty accelerators have been developed, such as: High voltage generators, Van de Graaffs, Tandem, betatrons, conventional and isochronous cyclotrons, electron linear accelerators, microtrons, proton linear accelerator, etc. All of them are low energy ones with energy less than 30 Mev. However, they served their purposes of making contribution to the development of science and technology in China and laid the foundation for larger accelerator projects.

Among them, linear accelerators, because of their particular usefulness in application and research, enjoy unrivalled development. As evidences, four major linac projects are underway at present. It is hoped that through this talk you can get a general impression about the linac activities in China.

(2) Electron Linear Accelerators and Microtrons —— Historical Background and Present Status

It might be a little surprising that the first linear accelerator (Fig.1) built in China is a 30 Mev electron machine with microwave power produced by a high power klystron developed together with the accelerator. This work was carried out in the city branch of the Institute of Atomic Energy (IAE) by a group headed by the author, and the approach to this task was mainly a matter of circumstances. When this project was started in late fifties, purchasing from abroad was very difficult and not much of the advanced technologies associated with the construction of electron linac can be relied on the industry. So we had to proceed rather unorthodoxly and make all non-standard components by ourselves. Since we had no high power microwave tubes available at that time, we decided to build a high power klystron for this purpose because we thought klystron is not much more difficult to build than a high power magnetron, but it has better potential for future development. Since limited by means of large scale numerical computations and by the availability of precision microwave measuring instruments, we decided to build an accelerator structure with $\beta=1$ following Stanford MKII fashion so that all we needed is to keep the mechanical tolerances. To mention another thing to remind you of the circumstances, we had to go so far as to make some standard S band wave guide sections by electroforming process in our own laboratory.

After years of struggling and some interruptions, this machine was finally put into operation in 1964. It consisted of a 3.6 m long constant impedance accelerating tube operated on $\pi/2$ mode, a rudimentary diode electron gun and a continuously pumped 3 cavity high power klystron which gave 12.6 MW during first operation.[1]

Now, after 20 years of service, and after suffered several disastrous accidents, colour rings appeared on the discs of the accelerator tube and carbonization of oil film occured over all the coupler surfaces due to oil contamination, this accelerator is still going strong as a useful, reliable radiation source for many fields of application. It gives peak current of 180 ma (BBU limit) at 29 Mev with 15 MW input. If any experience can be drawn from this primitive machine, it may be the fact that a delicate, precision device can also be pretty rugged and forgiving in a way.

Following this 30 MeV machine, the activity in IAE on electron linac become dispersed. Besides we had put a 3.5 Mev microtron concurrently and a 4 Mev electron linac a little later into operation, we worked in cooperation with Nuclear Medical Apparatus Factory, Shanghai to produce 10 Mev electron linacs (DZY-10 series)[2] for therapeutic application with first model completed in 1974, and with Pioneer Electric Machinery Factory, Shanghai to produce a 10 Mev machine for non-destructive material testing in 1982. At the suburban branch of IAE, a 14 Mev experimental model of short pulse high current electron linac was tested in 1980-81. (Fig.2) The city branch of IAE was reorganized as Institute of High Energy Physics , IHEP, in 1973 and in this new institute, we started the construction of a 35 Mev proton linac in 1979 and we have already finished the 10 Mev section[3] in 1982.

For the development of high energy physics in China, it was decided to build a 2.2/2.8 Gev electron, positron collider, BEPC, in IHEP, so we had also built a 30 Mev preinjector electron linac to be used in the collider last year. Besides, various R and D work such as RFQ, REC permanent magnet for linac focussing are also being developed.

A group of physicists in the Physics Department of Nanking University started to show interest in electron linac in early sixties and they completed a 0.7 Mev model powered by a small magnetron in 1966 for training purpose. With experience thus gained, they designed and constructed, together with factories in Nanking area, a 20 Mev TW electron linac with feed-back for medical application. (Fig.3) This machine got its first beam in 1978.[4][5] The steep beam loading characteristic of the electron linac with feed-back suits the requirements that relatively high energy and low current are needed for electron beam therapy while relatively low energy and high current are needed for γ-ray therapy. To counter the deterioration of energy spectrum associated with the longer buildup time, they incorporated a magnetic chopper to cut-off the front edge of the electron beam from the gun which proved to be compact and effective. To improve the operational stability besides using double-cavity for frequency stabilization, a feed-back loop phase tracking system to guarantee good energy-frequency behaviour was also employed.

In 1981, they completed the design and manufacturing of a 5 Mev electron linac for non-destructive material testing and now they are engaging in the design and construction of a 20 Mev electron linac for research in chemistry, biology and solid state physics.

Qinghua University, as a major engineering and technical institute in China, also has devoted considerable efforts in electron linac development. Working together with other organizations in Beijing area, they produced an operational radiation-therapy machine with

8 Mev (100 ma current) in 1975[6] and has treated more than 3000 patients up to now. In 1979, Beijing Medical Equipment Research Institute and Qinghua University succeeded in putting a 4 Mev irradiation machine[7] into operation. (Fig.4) It can accelerate an average current of 230 μa with average beam power close to 1 KW. Recently, Qinghua University has completed a 10 Mev machine on their campus for teaching and research, and also had participated in the construction of a 4 Mev, 100 ma side coupled S.W. electron linac in 1982 and is now working on an axial-coupled S.W. electron linac.[8]

Besides linac, a 25 Mev microtron[9] which will be used for dosimetry research, was jointly developed by other organizations and Qinghua University. This machine provides 6-24 Mev energy and 16 ma. pulsed current at the 27th orbit when the rf power is 1.85 MW from a magnetron. Up to now, only internal beam has been measured with beam diameter about 6 mm, work on beam extraction is being carried out. (Fig.5)

(3) Research and Development Efforts

(a) Helical Resonator

An extensive R & D work on helical wave guide accelerating cavity has been carried out in the Technical Physics Department of Peking University since 1973 [10][11] with the intention of using it as an energy booster for heavy ion beam from an electrostatic accelerator. This kind of accelerating cavity is well known for its compactness, easy of fabrication, lower cost and suitable for accelerating low energy heavy ions. Although its pondermotive oscillation problem makes Spiral Resonator or Split Ring Resonator a better choice, they stick to this approach for circumstantial reasons.

After some experimentation with low power buncher cavity, accelerating cavity etc. to gain experience, they succeded in performing a high power model testing in 1982. The cavity is 0.65 m long containing two 17cm long 8 cm diameter helices. The operating frequency is 28.8 MHZ, Q is 970 and Z is 22 MΩ/m. With 19 KW RF power excitation, a 300 Kev proton beam was accelerated to an energy of 620 Kev. The power threthold for pondermotive oscillation was found to be 5.5 KW, so this experiment was carried out under pulsed condition.[12] Now, this cavity is used together with a 3.2 MHZ chopper to form a high efficiency bunching system to produce 1.2 ns light ion beam for physics experiments.[13]

(b) RFQ

RFQ, because of its many attractive features, also draws attention from my colleagues at IHEP. An "Alternating half short" (AHS) four vane structure (Fig.6) has been proposed[14] to improve the coupling between different quadrants so that better performance can be expected. The results of model measurements show that for the same manufacture tolerances and operating frequency, the field flatness in the azimathal direction for the AHS structure is much better than that for the standerd four vane structure, and the mode separation between the working mode and its neighboring one for the former is 3 times larger than for the latter.

To apply RFQ for heavy ion acceleration, Peking University helix resonator study group has cold tested a split ring supported four rod electrode RFQ system.[15] The measured results are: resonant frequensy in 80 MHZ, Q, 1500, ρ, 42.8 KΩ-m, and the radial and axial electric field distributions are satisfactory. (Fig.7)

(c) Accelerating Structure and System

In their 20 Mev linac with feed-back, Nanking University group[25] found that if they adopt variable coupler to control the amount of feed-back, almost all machine characteristics, such as beam loading, efficiency, capture, energy spectrum, frequency stability can be significantly improved in theory. Also a new version of feed-back type linac, using traveling wave resonator for acceleration of electrons bas been studied.[16] Primiary analysis of a model accelerator indicates that rather good energy spectrum can be obtained with resonable capture efficiency with very low injection voltages. A related idea for small electron linac is to use two parallel accelerating cavity chains coupled at both ends to form a standing wave ring. The electron beam passes thru one coloum first and then with the help of a bending magnet, enters the second column.[17]

A modified version of split ring resonator using longitudinal rods to connect the mutually coupled split rings together has been tried out by Peking University group.[15] It may be called "Integral coupled split ring resonator". Model measurements indicate the π mode impedance of this structure is comparable with ordinary strongly coupled split ring resonator while the mechanical rigidity, mode seperation and field flatness are much improved.

With the advent of S.W. electron linacs, a bi-periodic accelerator structure with arrow-shaped cross-section coupling cavities had been proposed[18] and a 4.5 Mev model accelerator is going to be completed in the near future at IHEP.[19]

(d) REC Permanant Magnet Focussing Device

Because rich in rare earth resources in China, some work on REC quadrupole for linac focussing has been done. A 16-piece fixed field PM quadrupole had been built. Some of the specifications are:

PM material:	Ce-Co-Cu
Aperture:	30 mm
Outer Diameter:	50 mm
Gradient	1998 gs/cm

At 60% aperture, harmonic contents equals to 0.8%. They are mainly 3rd and 6th harmonics. Ferro fluid technique has been found useful in displaying field configurations.

Four variable gradient PM quadrupoles are now under construction. Each consists of two lenses —— one placed inside the other (Fig.8). Rotating both lenses by the same amount in opposite directions, the resultant gradient can be varied. These quadrupoles are made of $SmCo_5$ with maximum gradient 3100 gs/cm and 40mm aperture. They will be installed in the external beam line of the 30 Mev Linac mentioned before.

Theoretical study of multipole field with multipiece structure and gradually varied magnetizations has been done since 1979. Assuming uniform magnetization of individual megnet piece and by applying harmonic analysis, 2D and 3D analytical field expressions have been derived[20]. The 2D results are the same as those derived by Halbach[21] though the derivations are different. For 3D case, a rigorous expression has been obtained by us though some digital integrations still needed, while under some approximations, Halbach gave a completely analytical expression for the calculation of fundamental component.

(e) Theoretical Work

In connection with the work of short pulse, high intensity electron linac at IAE, problems concerning the design, such as transient beam loading effect, radial and longitudinal space charge effect etc. had been extensively worked out.[22][23][24] An interesting result of these analyais is as following. If, for a given accelerator structure, we define a beam loading parameter which is proportional to the charge per pulse and inversely proportional to the field amplitude, then it can be shown that the γ, φ phase space separatrices become narrower and gradually shift upward with increasing beam loading parameter. This means that for increasing charge per pulse, higher injection energy is required and capture efficiency is reduced.

In connection with the injector to be used for BEPC at IHEP, some thought has been given to improve BBU threshold and pass band characteristics for the long pulse mode of operation.[25] The generally adopted method is to detune the HEM_{11} mode by wall deformation of some earlier cavities, however, this would also cause phase error for the accelerating mode. If some holes were introduced at proper radial position on the discs of these cavities, it can be shown that it is possible to give HEM_{11} detuning but negligible disturbance to the accelerating mode.

Among others, study of transporting beam of centrosymmetric instead of elliptical phase space distribution[26] and of controlling the beam emittance growthin linac[27] have also been carried out.

(4) Four Major Linac Projects in China

(a) 35 Mev Proton Linac[28]

As mentioned above, IHEP is working on a 35 MeV proton linac and has already completed the first 10 Mev section. This accelerator will be used for short-lived radioisotope production and fast neutron therapy study.

This linac has a 750 Kev Cockcroft-Walton accelerator with duo-plamatron ion source as pre-injector. A low energy beam transport line of 6.45 m long follows the pre-injector. There are two bunchers preceding the accelerating tank working at the fundamental and second harmonic frequencies respectively. The accelerating tank consists of 6 sections with a total length of 21.83 m, tank diameters 949.4/909.0 mm, and number of unit cells totalled 104. The average accelerating field varies from 1.65 MV/m to 2.60 MV/m. while the synchronous phase changes from -40° to -25°. The RF system of this linac consists of two TH 116 hypervaportron triodes operated at 201.25 MHZ. To suppress the unwanted parasitic modes, RF power is fed through two ports at 1/4 and 3/4 tank length respectively.

The 10 Mev portion had already been completed and it deliverd the first beam of 14 ma in Dec. 1982 without buncher. A maximum current of 70 ma was obtained in Sept. 1983 with one fundamental frequency buncher at ~100 us pulse width. One interesting phenomena associated with this linac is that when there is microdischarge at the accelerating column, the buncher cavity will multipactor and one beam pulse will be lost. We are in the process to understand this phenomena and to eleminate it. (Fig.9)

(b) 100 Mev Short Pulse, High Current Electron Linac[29]

The applications of short pulse, high current electron linac in neutron physics and other fields are well known. Time of flight measurement dictates short pulse and high current while the energy spread is not critical in this case.

The linac consists of two pre-bunchers, one buncher and 5 quisaconstant gradient accelerating sections , with a total length of 17.5 m. This project is now in the advanced development stage. High current (10A) and high repetition rate (1000 PPS) are the major design objectives for nano-sec pulses.

(c) 200 Mev Electron Linac Injector for the 800 Mev Storage Ring

In Hefei Synchrotron Radiation Laboratory, a 800 Mev storage ring is under construction and a 200 Mev electron linac will be used as its injector. The reasons that they prefer a linac rather than a booster electron synchrotron are mainly the availability of linac technique and hardwares in China and the simplicity and flexbility of linac injector. This linac consists of nine constant impedance accelerating sections, 3.1 m long each, operated on 2π/3 mode. Including the electron gun, pre-buncher, buncher etc., the total length of the linac is 40.1 m and supplied by five 15 MW klystrons. As injector, pulse current of 50 ma, pulse width of 1 μs, energy spread of ±1% and pulse repetition rate of 50 pps are adequate.

At the present, a 30 Mev linac had been constructed both as a prototype and as the first section of the injector.[30] It was put into operation in July, 1981 and preliminary measurements in dicate the performance was satisfactory. (Fig. 10)

(d) 1.4 Gev Electron Positron Linac Injector for BEPC[31]

The 2.2/2.8 Gev $e^{\pm}$ collider BEPC requires a linac to provide both electrons and positrons. Since 200 MHZ RF accelerating system will be used in the storage ring , the bucket size limits the pulse length of electrons and positrons to about 2.5 ns, so this linac is mainly operated on a transient mode.

For the case when positron beam is desired, electron beam with about 1/10 of the total injector energy and current of several amperes is made to strike a tungsten target to produce positrons and electrons through cascade showers. The positron beam, with intensity less than 1% of the incident electron beam, and with emittance matched to the acceptance of latter linac sections with magnetic focusing device, is accelerated to the final injection energy of the storage ring. For the case when electron beam is desired, the positron producing target is retracted from the beam line and the electrons emitted from the gun are accelerated directly to the same final injection energy by controlling the phases of accelerating fields. The electron current is of course, limited by the deterioration of energy spectrum casused by transient beam loading.

The total length of this injector linac is about 200 m consisting of 56x3.05 m long constant gradient sections operating at 2π/3 mode. To cut down the cost of this linac a pulse compression scheme[32] to enhance the peak power at the expense of pulse width is employed. This device significantly increase the klystron peak power input to the accelerator structure, so that the number of high power klystron can be reduced to 16. As is well known, injector linac generally has stringent energy spread requirement. It is $\pm 6\times10^{-3}$ in this case. The phase spread of electron or positron bunch has to be kept within about 5° for 75% of the captured beam. Thus, sophisticated design efforts are made for the realization of this aim.

Since the filling of the storage ring will only take about 1/6 of the beam time of the injector linac, high energy nuclear physics experiments to use the rest of linac beam time are also contemplated. For this purpose, beam pulse longer than 1 μs will be used and the linac will be operated on steady-state mode. The pulse compression device must be shut-off and BBU effect will come into play. However, it is estimated that up to 100 ma peak current might be accelerated if appropriate measures were incorporated in the design of the accelerating structure as mentioned before.

Acknowledgements

The author wants to acknowledge Dr. Chen Chia-erh and Dr. Liu Nai-Quan for reading the manuscript and other colleagues for providing the photographs and reference materials

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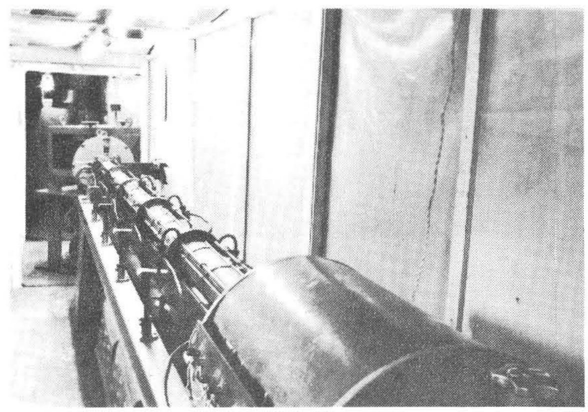

Fig.1 The first electron linac in China —— a 30 Mev machine at IHEP.

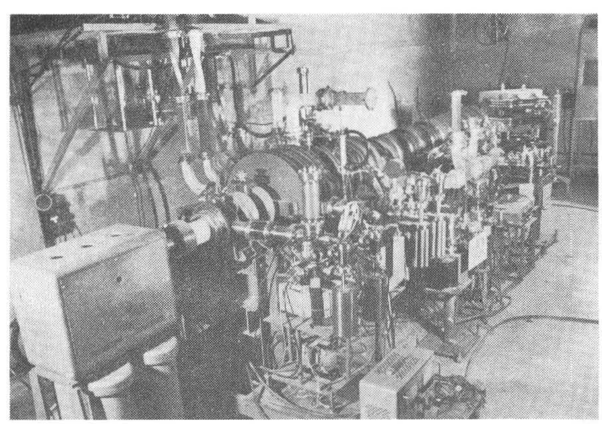

Fig.2 A 14 Mev prototype of IAE 100 Mev short-pulse, highcurrent linac.

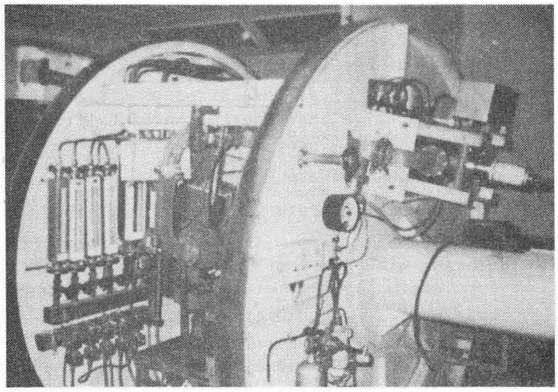

Fig.3 Nanking University 20 Mev electron linac with feed-back for medical application

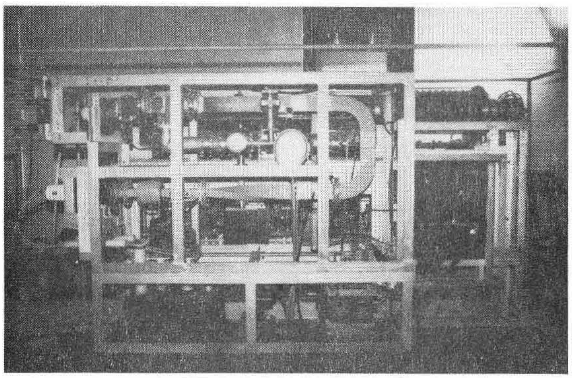

Fig.4 A 4Mev, 1KW beam power irradiation machine designed by Qinghua University and others

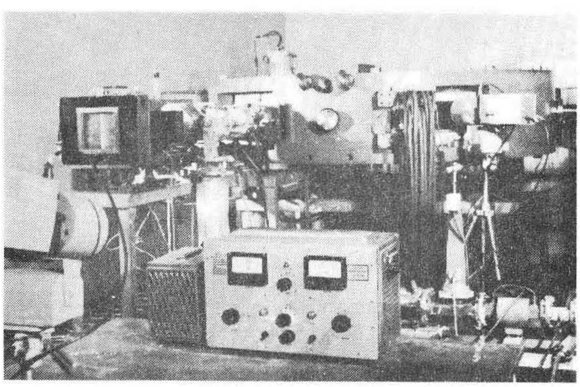

Fig.5 A 25 Mev microtron for dosimetry research

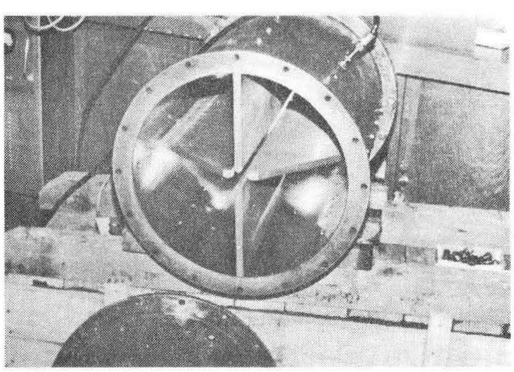

Fig.6 AHS RFQ developed in IHEP

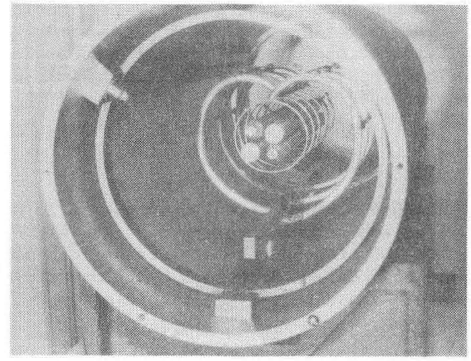

Fig.7 Split-ring RFQ developed by Peking University

Fig.8 Adjustable gradient samarium-cobalt quadrupole lens developed in IHEP

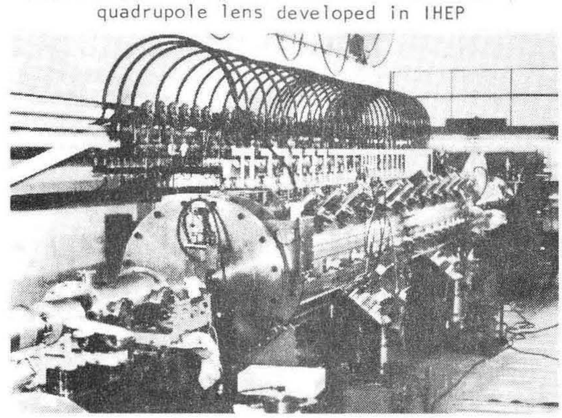

Fig.9 10 Mev section of IHEP 35 Mev proton linac

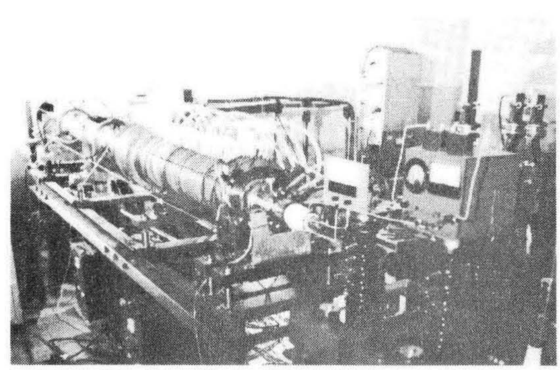

Fig.10 30Mev pre-injector of HESYRL storage ring