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Improvement and Application of the Beijing Proton Linac

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The main characteristics, the performance improvement, the current status, and the applications of Beijing Proton Linac (BPL) are described in this paper.

In August 1985, the 35-MeV Beijing Proton Linac got its first beam [1]. During the following three years, improvements have been made and the machine has been used for various researches. The main characteristics, improvements and application of BPL are described in this paper.

1. MAIN CHARACTERISTICS OF BPL

The main technical parameters of BPL are listed in Table 1. Table 2 gives a comparison between the designed beam performance and the measured one. It shows that the performance of the operation beam has met the design requirement, and that the measured beam momentum spread and emission are much better than the design [2-4].

The main characteristics of BPL are as follows.

1) All the energy gain of BPL is obtained with a cavity. This was designed in order to take advantage of the existing 5 MW RF power supply and to save the budget when we were upgrading the energy from the original 10 MeV to the present 35 MeV [1]. Table 3 compares the performance of BPL cavity with the cavities in overseas laboratories. It shows that the energy gain, the average beam power and the accelerating cell number in BPL's single cavity are higher than those in overseas laboratories.

2) Unlike other proton linacs, BPL does not serve as an injector of any synchrotron, but is

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Table 1
Main parameters of BPL.

Input/output energy	90.75/35.5 MeV
Length of accelerating cavity	21.83 m
Inner diameter of cavity	949.4-909.0 mm
Frequency	201.25 MHz
Number of Accelerating cells	104
Average E-field on axis	1.65-2.60 MV/m
Synchronous phase	$-40^\circ \sim -25^\circ$
RF pulse power (for 60 mA beam)	4.89 MW

directly used for fundamental researches and applicational experiments. Thus it should provide a high average beam current. This means that a higher pulse current, a higher repetition rate and a larger beam pulse length are required. Furthermore, in order to meet the requirements of different experiments, there must be a wide range of the beam parameter, the pulse beam current of the BPL ≤ 60 mA, an adjustable repetition rate of 1, 2, ..., 12.5 Hz, and a beam pulse length of 30-120 μs. As a standing wave accelerating structure machine, the output energy of BPL is basically fixed at 35.5 MeV or so, while the lower output energy can be obtained through the absorber with water or aluminum.

3) BPL cavity is characterized by a double periodic structure. The accelerating period involves drift-tubes, while the coupling period, which is used for field stabilization, involves post couplers. In BPL, due to the higher energy gain, the difference of the particle velocities between input and output and the difference of the cell lengths between the corresponding cells are larger, therefore the accelerating structure is only a quasi-periodic one. In addition, because of the longer cavity and a bigger number of cells, the adjustment of the E-field on the axis as well as the stabilization of the field are very difficult. On one hand, the required macroscopic distribution of the E-field along the axis must be guaranteed and the local field deviation controlled; on the other hand, the field should also be stabilized. The adjustments in the above two aspects may affect each other. In order to overcome these difficulties, we used three groups of post couples with different dimensions, adjusted the penetration of the coupler in the cavity and the tap direction at the end of the coupler in the cavity, and measured the field distribution and stability through bead perturbation controlled by a micro-computer. After this process repeated more than 100 times, the rms deviation of field for all cells reduced about 3.15%, the frequency difference between the nearest high mode and working mode increased from 74 kHz to 169 kHz. The beam test has proved that the final field distribution and stability can meet the designed beam performance requirements [5].

2. BPL'S PERFORMANCE IMPROVEMENT

2.1 Improvement of the Injector

The injector of BPL is a Cockcroft-Walton-type high-voltage accelerator, with the output energy of 750 keV, beam current ≥ 200 mA and H.V. stability $\leq 0.1\%$ [6]. It uses a high gradient (30 kV/cm) accelerating column of air structure, which has double gaps (three electrodes), an inner diameter of

Table 2
BPL's beam performance.

	Energy (MeV)	Pulse current (mA)	Pulse length (μs)	Momentum spread ($\Delta p/p$)	Normalized emission (π-mm-mrad)
Designed	35.51	60	50 ~ 100	±0.6%	6 ~ 8
Measured	35.5	60	50 ~ 100	±0.3%	≤ 4

Table 3
List of single cavity performance.

Accelerator	Country	Energy gain (MeV)	Pulsed beam power (MW)	Average beam power (kW)	Number of cells
BPL	China	35	2.1	2.6	105
LINAC-2	CERN	20	3.0	0.9	44
BNL-(H^-)	USA	27	0.6	1.8	60
FNAL(H^-)	USA	27	0.7	0.6	60
KEK	Japan	20	2.6	0.26	80
SACLAY	France	20	0.34	0.14	80
RHEL	UK	20	1.6	0.8	40
DESY	Germany	20	0.4	0.05	44

600 mm and 2 m in length. The ion-source is a high-current pulsed douplasmatron. The readout and adjustment of the source parameters are performed through laser fibers and a micro-computer. The normalized beam emission from the injector is 2.4 πmm-mrad in the case of 200 mA for 75% particles. The injector is operated stably and reliably as a result of the improvements described in the following.

1) The discharge outside the column was eliminated by installing two high voltage insulators at the end of the nylon rope used to hang the column at the end. We also installed a metal ring with the diameter of 25 cm below the insulator and above the column, which improved the outside field distribution and eliminated coronas.

2) The air pressure in the column was controlled within the best range (6.7×10^{-3} — 4.7×10^{-2} Pa) to avoid the inside-discharge. We installed an X-ray detector near the column which was used to control and adjust the high voltage with the signal from the detector.

3) An oxide cathode of ion source was used with a lifetime of above 600 hours. The hydrogen with purity of 99.999% was provided with a device we had made by ourselves.

4) To meet the requirements for high-current operation, we improved the bouncer system. Our measurement indicated that the high voltage dropped about 40 kV due to the beam loading with 200-mA beam current and 100-μs pulse length. In this case, the output energy of proton at the pulse tail was about 710 keV. These protons would arrive at the first accelerating gap of the drift-tube cavity 2.5 ns later than the normal protons (750 keV) after flying through the drift space of 1.1 m from the buncher to the entrance of the cavity. This is tantamount to being at the RF phase about 180° later than the normal protons, therefore they would be lost. The acceptable voltage drop for the protons to avoid falling in the decelerating phase is about 10 kV. To compensate for the serious beam loading

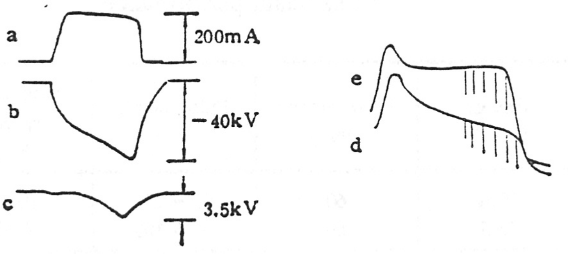

Fig. 1
The effect of bouncer. (a) Beam waveform at the output of column; (b) voltage drop without compensation; (c) high voltage waveform with compensation; (d,e) 35 MeV beam waveforms without and with compensation, respectively.

and to ensure a good particle transmission efficiency, we developed a new bouncer, which compensates for the voltage drop with a remainder ≤ 3.5 kV, as shown in Fig. 1(c). In this way, the beam current drop was compensated considerably at the end of the pulse, as shown in Fig. 1(e) [7].

Fig. 2 gives the transmission efficiency without buncher for different input energy. It shows that the calculated transmission (with the multi-particle simulation code PARMILA) is in accordance

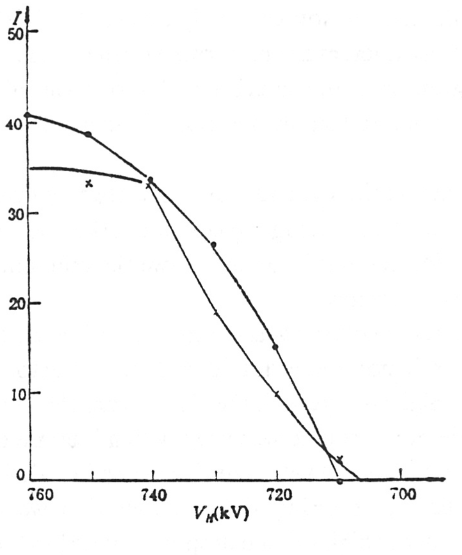

Fig. 2
Beam transmission efficiency of the accelerating cavity with different input energy: • calculated; × measured.

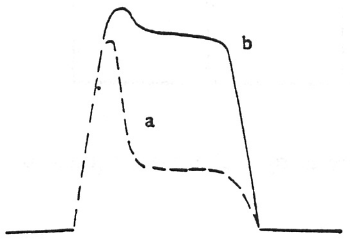

Fig. 3
Typical beam waveforms.

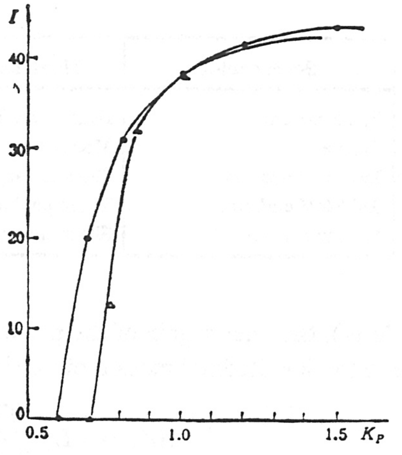

Fig. 4
Beam current vs. RF power:
• calculated; Δ measured.

with the measured one.

The injector has been operating stably and reliably for about eight years. Its current average discharge rate is less than once per 24 hours.

2.2 Improvement of the RF Power

BPL has an RF power supply which works at a frequency of 201.25 MHz with an output power of 5 MW. The final amplifier is a triode TH-116 imported from France. The pulse modulation is performed with a hard-tube modulator, which has the advantage of providing a fine RF waveform in the case of a high repetition rate and long pulse length. The RF power is fed into the cavity by two symmetrical ways through the feed couplers outside the ceramic windows for the convenience of adjustment. The power supply can control frequency, amplitude and phase servo-loops in order to stabilize the accelerating field in the cavity.

The quantity and the quality of the output RF power from the supply can significantly affect the beam performance. Through calculation and measurement, it is known that one needs 2.8-MW power to establish the "normal" (or "designed") E-field amplitude, and needs 4.9 MW to accelerate a 60 mA beam. In the beginning of each operation period, we first set the RF power at the medium value (e.g., 3.5 MW), and adjust the beam optics with the quadrupoles in the region of the cavity input to match the beam emission with the accelerator acceptance and to obtain the maximum peak in the current waveform (Fig. 3(a)). Then we add more RF power to the cavity to increase the peak value and to widen the upper part of the current waveform (Fig. 3(b)). In this case, the quality of the current waveform is mainly dependent on the quantity and quality of the RF power.

In fact, for the standing wave accelerator BPL, if the RF power fed into the cavity is higher than

Table 4
BPL's beam diagnostic system.

Beam quality	Measurement device	Quantity
Pulse current	Beam transformer	16
Profile	Multi-wire target	11
750 keV emission	Slit-multi-layer target	4
350 MeV emission	Three profiles	1
Energy and spread	Slit-multi-wires	1

P_s (P_s = 2.8 MW), the energy gain of the particle in an accelerating cell almost equals the design value W_c due to the longitudinal motion of particles

$$\Delta W_c = eL_c\sqrt{\frac{P}{Z_s}}T_c\cos\varphi_c = \text{const}.$$

where L_c, Z_s, T_c, φ_c are the cell length, the shunt impedance, the transit-time-factor and the accelerating phase of the particles at the midgap, respectively. Increasing the RF power into the cavity only leads to an increase of the synchronous phase, i.e., the increase of width of the stable longitudinal phase region of $3|\varphi_c|$, so that more particles can be accelerated steadily due to the more RF power. Fig. 4 shows the relationship between the beam current and RF power (the horizontal coordinate K_P is the relative power factor), and that the measured value is in accordance with the calculated one with the code PARMILA [8].

Within the limit of the maximum RF power from the supply, there are three ways to improve the efficiency and quality of the RF power to obtain the maximum pulse and average beam current: 1) forward compensation, which overcomes the drop of the field amplitude due to the beam loading, as shown by the dash curve in Fig. 5(a), so that all particles in the 100-μs pulse length can be accelerated with almost the same field amplitude (as shown by the real curve in Fig. 5(a)); 2) minimizing the reflective power from the cavity during the beam pulse, i.e., in the high current operation, and setting the coupler position such that the standing wave rate is minimized during the beam pulse (Fig. 5(d)); 3) using the feedback loops of the amplitude and frequency to make the accelerating field stable and reliable during the long-period operation [9,10].

2.3 Improvement of the Beam Diagnostic Technology

BPL has a complete beam monitoring system [11]. It can diagnose most of the beam parameters, e.g., the pulse current by using the current transformer with a core of Mo-Permalloy thick tape; the average current on the target by using the current integral; beam profile and position by using multi-wire devices; low energy 750 keV beam emission by using the device which consists of a slit and a multi-layer target; middle energy (35.5 MeV) beam emission by using three profile monitors; beam energy and energy spread by using a set of slit-analyze magnet-multiwire. This monitoring system is equipped with a micro-computer and its own software. It collects the signals and processes and displays the data or diagrams of beam performance. The whole system has about 30 monitor-probes (Table 4), which are reasonably distributed in the beam line. In addition, important improvement was also made in the measuring

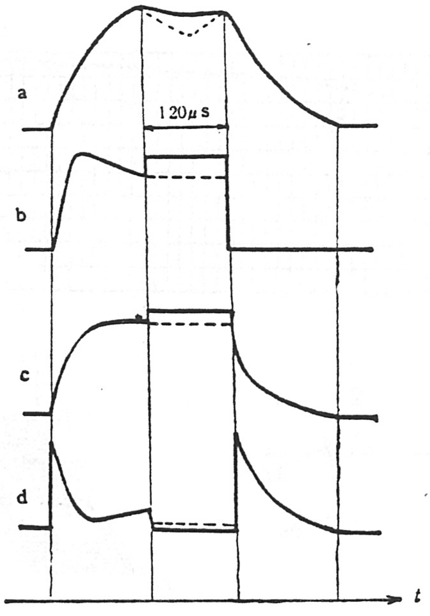

Fig. 5

Some waveforms of RF system. (a) RF field waveform in cavity; (b) output waveform from modulator; (c) forward waveform from the final amplifier; (d) reflected waveform from the cavity.

technology, such as calibrating the energy analyzer with the uniform magnetic field [7], controlling the emission measurement error by three profiles with conditional numbers [7] and analyzing the real emission of the protons at the output of the injector by using syntactic pattern recognition, which can eliminate the influence of such ions as H_2^+ and H_3^3 on emission [12]. This has played an important role in improving the operation of the machine. Figs. 6, 7, 8 and 9 are the beam performance diagrams displayed by a micro-computer.

2.4 Improvement of Control System

BPL's control system consists of the central console and CAMAC interfaces which are connected with local accelerator stations [13, 14]. With a timing system, the ion source, RF power supply and magnetic power supply work synchronously. The control system was improved as follows.

1) Three terminals were used to adjust the magnetic power supply, check the parameters of the RF power supply and adjust the ion source, respectively. It makes it faster and easier to adjust the whole accelerator.

2) The software for adjusting magnets and steering coils was improved. It makes it faster and easier to adjust the power supply. Before the machine is turned off, all current values of more than hundred power supplies are stored into the data-base of the computer, then these

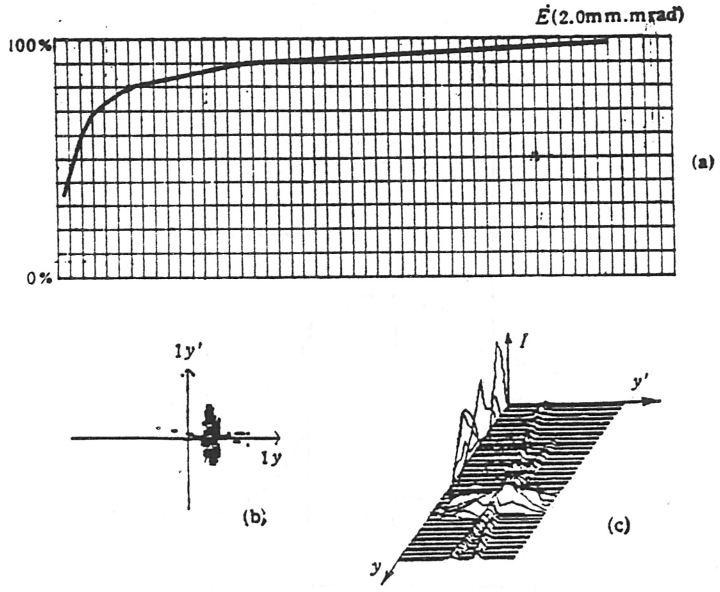

Fig. 6
750 keV beam emission. (a) Emission value vs. particles' percentage; (b) emission with 75% particles in $y-y'$ plan; (c) emission diagram vs. particles' percentage.

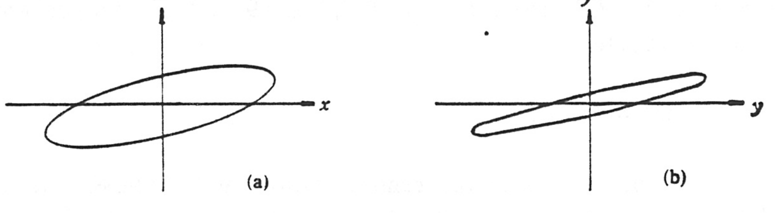

Fig. 7
The normalized emission at the output of linac (measured with three profiles).

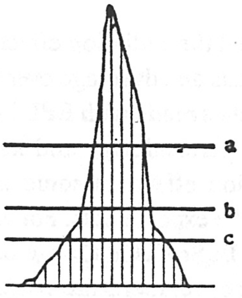

Fig. 8
Typical beam profile.
(a) 70%FW = 5.0442 mm;
(b) 80%FW = 6.6718 mm;
(c) 90%FW = 9.6900 mm.

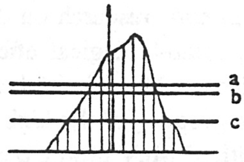

Fig. 9
Beam energy and energy spread.
(a) 70% particle, $\Delta E/E = \pm 0.36\%$;
(b) 80% particle, $\Delta E/E = \pm 0.40\%$;
(c) 90% particle, $\Delta E/E = \pm 0.60\%$.

currents reduce to zero one by one automatically. In the beginning of the next operation, the current values of all the power supply were set by the software. This procedure saves much time to readjust the power supplies. In the data-base, we have several sets of parameters which are used for different operation purposes. In addition, we also improved the timing system and added the protective circuits which ensure the power supply in case the timing pulse has an error, e.g., a high repetition rate.

3) We improved the acquisition modules, saved a great number of imported NIM modules and increased the control and monitoring efficiency.

3. BPL'S STATUS AND APPLICATION

In May 1989, BPL passed the technical appraisal by the Chinese Academy of Sciences (CAS). The appraisal committee confirmed that the technical specifications and performance parameters of BPL had met or surpassed the design requirements [15]. In August 1989, BPL and its application research project was inspected and accepted by CAS. The stability and reliability of the BPL operation have been improved year by year. It can be operated reliably for a long term. The average output current can be adjusted in the range of 0.1-40 μA depending on the experimental requirement. However, in order to increase the operation efficiency and reduce the operation cost, we need to upgrade the ion source so as to overcome the beam oscillation in the case of longer pulse (e.g., 100-150 μs), reduce the RF equipment wear and tear and improve the operation reliability in the future.

BPL is used to produce the short-lived radio-isotopes for medical treatment, neutron cancer therapy and other fundamental and applicational researches. BPL can produce about 30 kinds of radio-isotopes, in which ^{201}Tl, ^{67}Ga, ^{11}C have been successfully produced and tested. In the research of the neutron cancer therapy, we have obtained the neutron beam, with 35.5 MeV proton beams hitting the ^{9}Be targets, which have an average energy about 20 MeV and a dose rate of 1 rad/min $\cdot$ μA at a distance of 1.2 m from the target in the forward direction. These parameters can meet the clinical treatment requirements. We also conducted researches in radio-physics and radio-biology by using neutron beams. For some kinds of tumors, we compared the radiation effects between the neutron and γ-ray treatment. The result shows that the neutron has an advantage over the γ-ray [19].

Other fundamental or application experiments and researches made with BPL include nuclear physics experiments, research on the mechanism of high T_c superconductor and its performance improvement, radio-biological effect by protons, and irradiation effect on some materials with neutron and proton. Many fruitful results have been obtained in the experiments. For example, it was found that the property of the high T_c superconductor material $Bi_2Sr_2CaCu_2O_7$ can be improved by irradiation with 35 MeV proton beams, so that the zero-resistance temperature could be increased by about 10 °K and the current density by a factor of four [20].

BPL will make even more contributions to accelerator technology and its application in China.

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