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# THE BEIJING ELECTRON POSITRON COLLIDER

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Abstract Since the first e+e- collision was realized in October, 1988, the peak luminosity has been upgraded to 7 x $10^{30}/cm^2 \cdot s$ at 2.2 GeV. Construction and commissioning of the BEPC are briefed in this paper.

## INTRODUCTION

The Beijing Electron Positron Collider (BEPC) is the first high energy accelerator ever built in China with the energy ranging from 1.4 to 2.8 GeV. This project was officially approved by the Chinese government on April 24, 1984 and designated as one of the state key projects the same year. On October 7, 1984, the ground was broken and on October 16, 1988, the first e+e- collision was realized, which claimed its initial accomplishment of this project. There are two purposes for building the BEPC. The first one is to carry out research on particle physics, namely, research on charmed physics and lepton physics. In spite of numberous events accumulated for years at SPEAR in this energy region, experimental results showed that there are still many interesting problems which deserve exploration but higher luminosity is required. The designed luminosity of the BEPC is 1.7 x $10^{31}/cm^2 \cdot s$ at the energy of 2 x 2.8 GeV, twice the luminosity of SPEAR. The second purpose is to provide synchrotron radiation in VUV, soft x-ray and hard x-ray for scientific resear ch and applications in other sciences. The characteristic wavelength is between 2.6 Å and 44 Å and central brightness is 4 x $10^{13}$ photons/s•mm•-mrad•1% BW.

Now the peak luminosity of the BEPC has reached 7 x 10 $^{30}/cm^2 \cdot s$ at 2.2 GeV. Assembly of the Beijing Spectrometer was completed in September, 1988 and the J/$\psi$ peak was found on June 22 this year. The installation of the four synchrotron radiation beam lines were accomplished in the middle of April, 1989 and the commissioning is underway.

## CONSTRUCTION AND COMMISSIONING OF BEPC

Figure 1 is the layout of the BEPC which consists of the injector, the storage ring, the Beijing Spectormeter and the synchrotron radiation light laboratories.

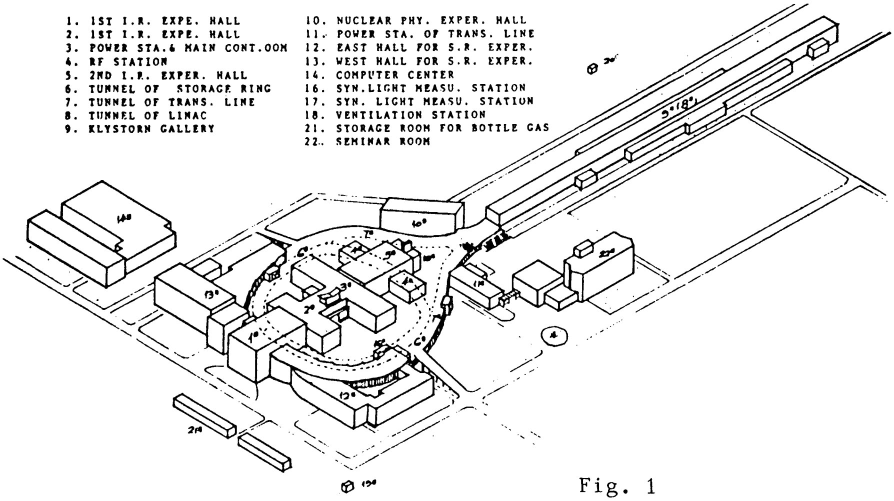


Fig. 1

Injector - Electron Linac

Table I shows the main parameters of the electron linac. This linac is 202 m long. The first part is the 30 MeV pre-injector. Located at the 150 MeV section are a movable tungsten target and a pulse magnetic concentrator for positron production and collection. What follows is the main part of the accelerator which accelerates electrons and positrons to 1.1 - 1.4 GeV.

TABLE I Main parameters of the electron Linac

| | Designed Value | Value Obtained |
|---|---|---|
| e- energy | 1.1 - 1.4 GeV | 1.1 - 1.55 GeV |
| pulse electron current | 0.2 - 5 A | 5 A |
| pulse width | 2.5 ns | |
| pulse repetition rate | 50 times/s | 12.5 times/s |
| No. of klystrons | 16 | |
| No. of energy doublers | 13 | |
| klystron power | >20 MW | 15 - 24 MW |
| energy multiplification factor | 1.51 | >1.4 |
| working frequency | 2856 MHz | |
| energy spread ΔE/E | 0.6% | 0.8%(e- beam)<br>1.0%(e+ beam) |
| bunch phase spread | $<5^0$ | |
| bombarding energy for positron production | 150 MeV | 150 MeV |
| thickness of tungsten target | 5mm | 6mm |
| length of pulse magnetic concentrator | 12cm | |

| | | |
|---|---|---|
| maximum field strength of the consentrator | 26,000 Gs | |
| minimum field strength of the concentrator | 3,000 Gs | |
| emittance of e+ beam | 0.22MeV/c.cm | 0.22MeV/c.cm |
| e+ yield | 0.02 e+/e- GeV | 0.02 e+/e- GeV |
| current intensity of e+ beam | | 3-6 mA (at 1.2 GeV)<br>9 mA (at 130 MeV) |
| max. current intensity of electron beam | 0.2 A | 1 A |

The most difficult components for manufacturing are the 56 S band accelerator sections composed of disk loaded waveguides, 16 klystrons with the maximum output power of 30 MW each and their modulators whose pulse voltage is 270 KV and the pulse width is 3 $\mu$s and energy doublers with a quality factor of $10^5$. They were all manufactured by the machine shop of the Institute of High Energy Physics and Chinese industries.Test showed that they all reached the designed requirements.

Up to the first half of 1986, all the components of the linac had been completed. Installation started in May. However, the installation was rather slow because civil engineering construction was still underway, conditions in the tunnel were very poor and we lacked experience in this kind of work. It was not until September 1987 was the installation completed. From October, 1987 and to the end of 1988 three rounds of commissioning had been conducted. The total operation time amounted to 240 days and nights, one third of which were spent on its own commissioning and two thirds of which were spent on providing beam for the commissioning of the storage ring. Table II is the milestone during the commissioning of the electron linac. The preliminary performances are given in Table I.

TABLE II Milestone during commissioning of Electron Linac

| | |
|---|---|
| Feb.1987 | Commissioning of the 250 MeV section started |
| Apr.21, 1987 | At the end of 250 MeV section, a positron beam of 80 MeV and 0.38 mA was obtained and soon was accelerated to 100 MeV and 2.5 mA. |
| Mid-Oct.1987 | The first round of commissioning of the whole linac started. |
| Nov.30,1987 | For the first time an electron beam of 800 MeV and 30 mA was obtained at the end of the linac and soon was upgraded to 1.17 GeV and 240 mA. |
| Mid-Apr.1988 | The second round of commissioning started |
| Mid-May,1988 | Energy of the electron beam reached 1.2 GeV and the intensity 800 mA. |
| June 27, 1988 | For the first time a positron beam with energy 1GeV and current 1mA was obtained at the end of the linac. Soon they were increased to 1.1 GeV and 6mA. |
| Sept.18,1988 | The third round of commissioning started. |

Generally speaking, the performances are satisfactory as the designed requirements have all been met. Particular mention should be made of the the current intensity of the electron beam which is far greater than the designed value. All the key components are in normal operation. Although the maximum output power of the klystron has reached up to 30 MW during testing, it was limited to less than 20 MW during the initial stage of commissioning for the sake of safety. All the 16 klystrons have worked over 7,000 hours, but no damage has been found. Their lifetime is much longer than has been expected. All the key components of the modulator are also in normal operation. The only problem is that some of its minor parts are easy to damage during the early stage causing shutdown of the linac, which remain to be improved. The multiplification factor is only about 1.4, less than the designed value. The main reason for this is that the temperature control of the constant temperature water system is based on the wall temperature of the accelerator section. Therefore, the temperature of the energy doubler can only be controlled within $0.5^{0}$ C, which must be improved later. Although the positron yield has reached the designed value, it is still too low, which should be increased by one factor, i.e. to 12 mA - 15 mA. To this end, the current intensity of the electron gun will be increased to about 7 A in the near future and large aperture focusing magnets will be installed to increase the capture of positrons. As to the conversion between electron and positron acceleration, sometimes it is several minutes short and sometimes it is much longer. To solve this problem, the closed loop phase control system must be used and the number of high sensitive beam monitors increased along the linac. We expect to achieve the conversion within 2 - 3 minutes each time.

## The Storage Ring

The storage ring has a circumference of 240 m and is racetrack-shaped. Magnets of various kinds are located on the orbit to control the motion of the particles as shown in Figure 2. Both on the southern and northern side of the ring is a 5m long area for physics experiments. Electrostatic separators are placed on both sides of the area. On the east and west side is the e+ e- injection area where injection elements are installed. Table III shows the parameters of the storage ring. The characteristics of the storage ring are as follows:

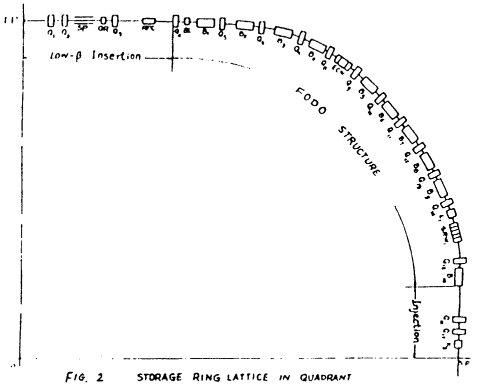


FIG. 2 STORAGE RING LATTICE IN QUADRANT

Unlike the typical designing method for large colliders of separating the dispersion suppressor from regular cell arc, a compact structure was found. In the comparatively short circumference, there are eight 2 m long straight sections out of which four are for the installation of

TABLE III Main parameters of the storage ring

| Designation | Designed Value | Value Obtained |
|---|---|---|
| energy(GeV) | 1.6-2.8 | 1.6-2.2 |
| circumference(m) | 240.4 | |
| peak luminosity($\text{cm}^{-2}\cdot\text{s}^{-1}$) | $(1.8\text{-}17)\text{x}10^{30}$ | $(2\text{-}7)\text{x}10^{30}$ |
| current(mA) | 12.5-65 | 12.5-30 |
| No. of particles | $(0.6\text{-}3.3)\text{x}10^{11}$ | $(0.6\text{-}1.5)\text{x}10^{11}$ |
| No. of bending magnets | 40 | |
| No. of quardruploes | 60 | |
| No. of insertion quardrupoles | 4 | |
| free length for experiments | 5m | |
| revolution frequency(Mhz) | 1.247 | |
| horizontal tune | 6.18 | 5.8 |
| vertical tune | 7.12 | 6.8 |
| horizontal emittance(mm.mrad) | 0.66 | 0.24-0.45 |
| hori. chromaticity | -11.2 | -10.4 |
| vert. chromaticity | -17.7 | -19.7 |
| momentum compression factor | 0.038 | 0.040 |
| coupling coefficient | 0.277 | |
| total beam lifetime(hrs) | 4.6-6.7 | 4-6 |
| hori. damping time(ms) | 4.6-8.6 | |
| max. strength of magnetic field(Gs) | 5159-9028 | 5159-7093 |
| bending radius(m) | 10.345 | |
| hori. beta at I.P.(m) | 1.3 | 1.3 |
| vert. beta at I.P.(m) | 0.1 | 0.085 |
| max. dispersion function(m) | 3.9 | 3.7 |
| No. of harmonics | 160 | |
| RF frequency(MHz) | 1.9953 | |
| total RF power(KW) | 200 | 40-60 |
| No. of bunch/beam | 1 | |
| peak RF voltage(MV) | 1.35 | 0.3-0.8 |
| S.R. loss/turn(KeV) | 522 | 56-200 |
| S.R. power/beam(KW) | 34 | 0.7-6 |
| synchrotron tune | 0.021 | 0.016 |
| r.m.s energy spread | $7.4\text{x}10^{-4}$ | $4\text{x}10^{-4}$ |
| r.m.s half bunch length(cm) | 3-5 | |

wigglers for synchrotron radiation use. The other four straight sections are for placing emittance control wigglers so that the luminosity may decrease proportional to energy square. The present structure is not sensitive to nonlinear field and has a large dynamics aperture, it will ensure the stability of beams and lay a foundation for the attainment of high luminosity. The aperture of the vacuum chambers of the storage ring is 56 x 120mm$^2$, much larger than that of the same kind of acclerators. And what's more, the wall of the vacuum chambers should be as smooth as possible so that transverse impedance Z/n will be only 1/5 of SPEAR, thus greatly improving the threshold of fast head tail instabilities. The majority of the components of the storage ring were fabricated in China.

### A. Magnet and Power Supply

The cores of 60 quardruploes and 40 bending magnets were stacked with laminations with a thickness of 0.50mm each. Measurement showed that the integral field discrepancy between magnets was smaller than the designed value by a factor of 2. That is $\Delta BL/BL = 3 \times 10^{-4}$, $\Delta GL/GL = 6 \times 10^{-4}$. Eight insertion quardrupoles were made by Hitachi with the arrangement of KEK and shimmed by our experts together with our KEK friends and later reshimmed at our Institute. Finally we got $\Delta GL/GL = 6 \times 10^{-4}$. Four wigglers had been accomplished and measurement showed that they reached the designed parameters.

Current stabilty of the 175 power supplies of 17 kinds reached $10^{-4}$ during long-term operation. The ripple coefficient of the output voltage $<10^{-3}$ and the tracking accuracy between power supplies during the ramping process reached $10^{-4}$.

### B. RF System

Owing to the limitations of the technical conditions at home during the designing stage, the frequency of the RF system was chosen to be 200 MHz. The system is composed of 2 cavities. Each cavity is powered by four combined 30 KW RF transmitters. In developing the cavities, we overcame a lot of difficulties.The cavity is made of copper clad steel. As a water jacket was used and strict cleaning technologies were adopted, the vacuum of the cavity reached $5 \times 10^{-9}$ Torr. The breakdown of the ceramic window was avoided by using the imported 99 ceramic sputtered with 100 A TIN and water cooling around it. To quicken the development of ceramic window, we asked SLAC to manufacture two windows. Not until Jan. 18, 1988 was the power of 25 KW fed into the cavity for the first time. Now both cavity are in normal operation when 30-40 KW are input to it. Although it can meet the requirement during the early commissioning, it needs speedy improvement.

### C. Vacuum System

After the Al vacuum chambers extruded by a US manufacturer were shipped to China, the pumping hole, the bending, the welding, cleaning and so on were done by Chinese industries. In addition, 100L/s and 500L/s ion pumps were developed in China. As strict regulations were drawn during installation, we succeeded in conducting the vacuum pumping test of the 240 m long vacuum chamber with over 400 flange interfaces one week after the installation with static vacuum reaching $10^{9}$ Torr. After clening by the beam during the commissioning, the base pressure reached $5 \times 10^{-10}$ Torr and the dynamic vacuum was $7 \times 10^{-11}$T/ma at 2.2GeV.

### D. Injection System

The main components of the injection system, such as the 2 Lambertson magnets, the 4 electostatic separators and 6 kickers have all reached designed specifications. The thickness of the Lambertson magnet is less than 5mm. The field uniformity in the good field region of the Lambertson magnets is better than $2 \times 10^{-3}$, the leakage is $< 1 \times 10^{-3}$. The voltage of the electrostatic separators is up to 60 KV. The rise time of the rectangular waveform of the kicker is 200ns, the fall time 400ns and the flat top width 300ns.

### E. Control System

The design of the BEPC control system was developed on the basis of the SPEAR new control system. One VAX 11/750 is used as the main control computer with a 4MB memory and a 912 MB disk and other periferals. There are 3 control consoles. Each is composed of graphics display, touch panels and programmable knobs. A VAX-CAMAC Channel (VCC) with data transmitted by serial optical fibre is used in this data acquisition and processing system. There are about 500 CAMAC modules and 700 interface modules connected to about 900 equipments and devices of the collider. The timing system was designed on the basis of that for the storage ring at KEK. Its jitter time was < 200ps. What's more we have developed the hardware and software.

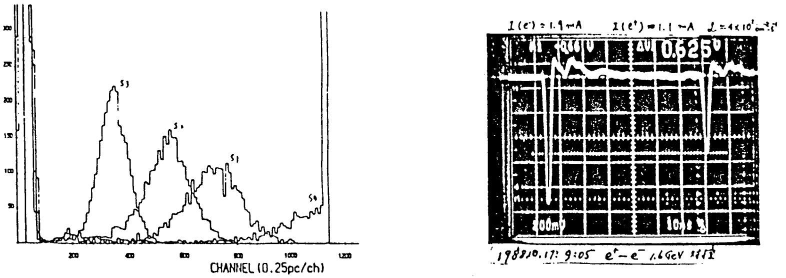
With the exception of the RF cavities, nearly all the components of the storage ring were delivered to our Institute in the first half of 1987 and had undergone strict test before they were moved into the tunnel. In the middle of 1987, installation began. Based on the experience accumulated in installing the linac, it went on quite smoothly. As the time for installation was shortened, the delayed schedule caused by civil engineering construction was compensated. In November, 1987, the installation of all the components with the exception of the RF cavities was accomplished. In Jan., 1988, the first RF cavity was fabricated and installed in the storage ring. At the same time, nearly 200 power supplies of the beam transport lines and the main ring were put under the control of computer. And the vacuum in different regions and status of the vacuum pumps could be displayed in the central control room. The COMFORT, LATTICE and ORBIT software for the configurations of acceleration came into use. Three rounds of commissionings had been conducted from May, 1988 to July 10, 1989. Table IV is a milestone of the commissioning of the storage ring.

TABLE IV Milestone of storage ring commissioning

| | |
|---|---|
| May 5, 1988 | First round of commissioning started |
| May 19, 1988 | First stacked beam with RF acceleration field was obtained, but the intensity was only a few $\mu A$. |
| June 18,1988 | Misconnection of the power supplies between quardrupole 1 and quardrupole 2 was found out. After correction, the intensity of the storage ring shot up to 50 mA. The lifetime was 1 hr at 1.1 GeV. 19 power supplies were synchronously tracked and controlled by computer. The beam energy was from 1.1 GeVto 1.6 GeV. |
| July 3, 1988 | Positron beam was successully stacked with intensity reaching 12 mA and energy ramped from 1.1 GeV to 1.6 GeV and a beam loss of 7%, better than had been expected. The machine had to be shut down because of the muggy weather and high humidity. |
| July-Sept. | Perfection and modification of some systems |
| Early October | Second round of commissioning started |
| Oct. 16,1988 | Realization of first e+ e- collision at 1.6 GeV with peak luminosity reaching 8 x $10^{27}/cm^2 \cdot s$ |
| Oct. 18,1988 | 2 mA positron and 3 mA electron beam were brought to collider with peak luminosity of 8 x $10^{28}/cm^2 \cdot s$ obtained at 1.6GeV |

| | |
|---|---|
| Nov. 6, 1988 | Luminosity reached 1 x $10^{30}$ $cm^{-2}$ $s^{-1}$ at 1.6GeV and the lifetime was about 4 hr. |
| Mid-Dec.1988 | Peak luminosity increased to 2 x $10^{30}$ $cm^{-2}$ $s^{-1}$, intensity of e+ e- 16 mA |
| Jan.-Apr.1989 | Perfection of some sub-systems, BES was moved into collision region |
| April 5,1989 | Third round of commissioning started |
| May 29, 1989 | Luminosity reached to 7x$10^{30}$ $cm^{-2}$ $s^{-1}$ at 2.2GeV |
| June 22,1989 | J/$\psi$ peak was found |

Despite the careful examination of the connections of the power supplies during the installation, the mistake as mentioned in Table III as not found out. About 20 days were spent on finding out this mistake during the first round of commissioning. The second round of commissioning was plain-sailing. Figure 3 shows the e+ e- signals obtained by BCT when the electron and positron collided on October 18, 1988 and the Bhabha scattering events recorded by the luminosity monitor. Even the beam monitoring system was not perfect and the accuracy was not high, the peak luminosity of the BEPC had been increased from 8 x $10^{28}/cm^2\cdot s$ to 2 x $10^{30}/cm^2\cdot s$ at 1.6GeV by the end of 1988 and to 7x$10^{30}/cm^2\cdot s$ at 2.2GeV in late of the May 1989. All the lifetime was about 4-6 hr. For detailed parameters see Table III. Although preliminary results of commissioning demonstrate that the machine is good in terms of its performances and has great potentiality, it is an arduous task to improve the hardware and software in order to ensure their long-term, stable and reliable operation. In addition to the RF cavity, systems to be improved urgently are BPM, SLM, tune measurement for betatron oscillation frequency and the control software of computer.



Counts of Bhabha scattering events of luminosity monitors

Signal of electron and position beam

Fig. 3

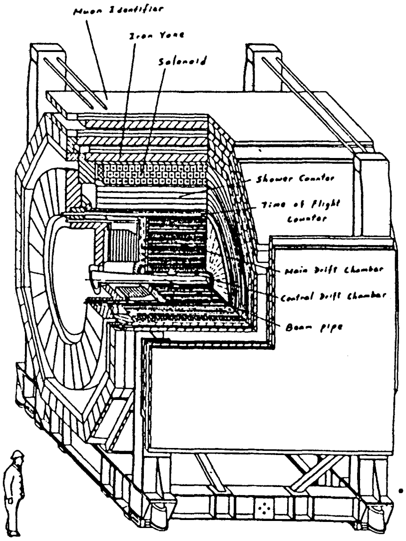
The Beijing Spectrometer

Owing to the budget limitation, only one of the two interactions is used for high energy physics experiments. So far just one large detector -

the Beijing Spectrometer has been built. Its design principle is as follows:

1. large solid angle coverage;
2. good charged particle momentum resolution and identification;
3. high detection efficiency for photons with lower energy cutoff, with good position resolution and energy resolution.

This spectrometer consists of a central drift chamber, a main drift chamber, a time-of-flight counter, a shower counter, a muon identifier, a magnetic coil and iron yoke (see Figure 4). It is also supplied with a gas system, a fast electronics system and a data acquisition system. It is 6m high and 7m wide,weighing 480t. It is the first time for such a large and complex detector with high precision to be built in China.The main drift chamber is a 2.2m long Al barrel with a diameter of 2.3m.The thickness of each of the two end plates is 4cm. On the two end plates 20,000 holes with a precise position of 50μm and the hole diameter error of 18μm are to be drilled.And 20,000 gold-plated tungsten wires are to be strung between the corresponding holes of the end plates Besides, there is strict demand on the tensity of each wire and the properties of the current leakage. Only when these conditions are met can the energy resolution and position resolution of $\sigma_x<200\mu m$, $\sigma_z<3$-4mm be ensured. The shower counter consists of the barrel part and the end cap.As the foundation of the barrel, the inner Al barrel has a diameter of 2.6m and is 4.2m long. It is made of 4 cm thick Al sheets after bending,which is a difficult process. The barrel shower counter is composed of 24 layers of aluminium-lead-aluminium sandwich weighing more than 40 t, which have to be bound together with steel ban-ds. The barrel part of the time-of-flight counter totals 5.6 m long. Of the end part, the scintillator is 2.8 m long and 5 cm thick. There are altogether 48 such scintillators. The time resolution of TOF is 200 ps.



Cut away view of the BES detector

Fig. 4

The BES magnet is 5.1 m long and 6.9 m high and wide, weighing 30 t. The outer diameter of the solenoid coil is 4.14 m, weighing 31 t. It is one of the biggest coils in the world.

The BES electronic readout system is very complex. After the signals detected by the BES are amplified or discriminated, they are kept in a sample-and-hold circuit or converted (i.e. time signals converted into analog signals) and readout later by a multiplexed intelligent ADC (i.e. the BADC of SLAC). The BES has 19,964 readout channels. A VAX11/785 will be used for the on-line data acquisition. We follow the SLAC MARK-III on-line system with a VAX-CAMAC Channel (VCC).

The BES magnet was accomplished at the end of 1986 and its solenoid coil finished in February, 1987. In the spring of 1988, all the big detectors of the BES were accomplished in the detector laboratory. In May 1988 they were moved into the experimental hall and assembled. In October 1988, the BES was successfully assembled and the cables were laid, followed by the system integration test with the electronic readout system and the computer on-line system. On October 23, 1988, the track of cosmic ray was detected by the drift chamber and TOF. The BES was moved into the interaction point on May 3, this year, and the commissioning started. After careful scanning the $J/\psi$ peak was found on 22 June, up to now, more than 50 thousands $J/\psi$ events have been collected.

Synchrotron radiation laboratory

Two SR experimental halls will be built around the southern half of the storage ring, each has 7 ports. As the first step, 3 beam ports, 5 beam lines and 7 experimental stations will be built. The storage ring will operate in parasitic and dedicated mode. Table V shows the characteristic parameters of the two modes.

TABLE V. Characteristic parameters

| | Parasitic mode | Dedicated mode |
|---|---|---|
| electron energy E, GeV | 1.6-2.8 | 1.1-2.8 |
| characteristic wave length $\lambda_c$, Å | 14.1-2.63 | 43.7-2.63 |
| electron beam current I, mA | 13-65 | 150 |
| synchrotron radiation power $P_a$, kW | 0.7-34 | 1.9-78 |
| horizontal emittance $\epsilon_x$, mm•mrad | 0.21-0.67 | 0.03-0.12 |
| bunch half length $\sigma_z$, cm | 5.1 | 1.8-4.6 |
| central brightness B $\lambda_c$, photons/s•mm•mrad•1% BW | $10^{11}$-$10^{12}$ | 4.1-4.9 x $10^{13}$ |

BL-1 is a white beam line from the wiggler beam port. An x-ray topography station and a medicine station are built there. BL-2 is an unfocused monochromatic beam line from the wiggler beam port for EXAFS and diffuse scattering experimental stations. BL-3 is an x-ray beam line for diffraction station and small angle scattering station. BL-4 is a VUV/-soft x-ray beam line for a two level photoemmisison spectrometer. BL-5 is for lithography.

So far the front ends of the 3 beam ports and the first 4 beam lines have been completed. In mid-April this year, the commissioning of the four beam lines successfully started. The synchrotron light has been successfully observed from the reflection mirrors placed at the front parts of these beam lines. The fifth beam line will be built at the end of this year.

Acknowledgment

The work and achievements mentioned in this paper are the crystallization of the painstaking efforts exerted by those who have been involved in the BEPC construction for the past few years. I would like to express my great appreciation of their great contributions.

I also appreciate very much all the helps given by the world community of high energy physics.Particular mention should be made of the big contributions to the progress of the BEPC by the PRC/US Joint Committee of High Energy Physics.

Thanks also go to ANL, BNL, FNAL, LBL, SLAC, KEK, CERN and DESY. Since the BEPC is similar to SPEAR and the BES to MARK-III, SLAC has been much involved in the collaboration.

Professor T. D. Lee of Columbia University has made very valuable and great contributions to our project. Without his painstaking efforts, this project could have hardly moved. Special thanks also go to Professor W. K. H. Panofsky who has been giving us many important helps and advices.

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