THE DEVELOPMENT OF CHINA'S ACCELERATORS I HAVE EXPERIENCED

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Abstract

The development of China's high energy accelerator for half a century falls into two stages, namely the first 20 hovering years (1958-1978) and the later 30 years of rapid development (from 1978 till now). I was lucky enough to have experienced the whole process, witnessed, and to some extent, joined in the decision-making, getting the projects approval, the designing, the construction and development of China's five large scientific facilities undertaken by the Institute of High Energy Physics (IHEP) in Beijing and Shanghai Institute for Applied Physics (SINAP).

A brief review is given of the previous stage of history regarding the consideration of China's high energy accelerators in the first 20 years. A short presentation is also given of the later 30 years concerning the rapid development of the Beijing Electron Positron Collider (BEPC and BEPCII), the completed BEPC-based Shanghai Synchrotron Radiation Facility (SSRF), the Chinese Spallation Neutron Source (CSNS) under construction, the high intensity proton accelerator (ADS) used for nuclear waste transmutation and the proton therapy machine in the R&D stage.

INTRODUCTION

The achievement of China's high energy accelerator described in the following is attributed to China's policy of reform and opening to the outside world in the late 1970's, the ensuing rapid economic development, the attention paid to science by the Chinese Government, and extensive and effective international cooperation. It is also due to the support of my colleagues and their unremitting efforts and most importantly, the correct decision making. Without the above-mentioned factors, it is impossible to make such great achievements.

THE FIRST TWENTY HOVERING YEARS OF CHINA'S ACCELERATORS

Development of high energy physics and high energy accelerator has been the long cherished undertaking of several generations of Chinese scientists. As early as in the late 1950's soon after the foundation of new China when the national economy was still difficult, the Chinese government had already considered the development of China's high energy physics. In 1957, I was sent to the Lebedev Physical Institute of the Soviet Union for advanced study. The main task was to design a 2 GeV electron synchrotron. Now, this scheme seems to be more suitable for the then situation of China as the investment was not too much and the energy was modest at that time. But, as everyone knows, because of the expensive high energy accelerator and advanced technologies, its development would inevitably be influenced by the state political and economic conditions. In 1958, under the influence of ideological trend of China's great leap forward, this scheme was considered not big enough and thus was not approved. Instead, a 15GeV proton synchrotron was designed. Obviously, this was a very adventurous scheme, and finally it was dropped. Thanks to the great advancement made in the isochronous cyclotron at Dubna Joint Nuclear Research Institute, with their help, a 450MeV isochronous cyclotron was designed. This scheme was more suitable for our national conditions at that time. Even in the so-called three-year economic difficulty period (1960 -1963) in China, my design and research efforts still continued. During this period, I had published some interesting papers related to isochronous cyclotron theory. Among them, the most important one is my first paper [1] on the finding of the non-isochromatic phenomenon in isochronous cyclotron, which is due to the transverse free oscillation, thus making it impossible for the particles to always synchronize with the RF field, and limiting the maximum current which can be reached in this kind of cyclotrons. Later, the Cultural Revolution began and the Sino-Soviet relation was broken. I had to stop my research work. It followed that this program discontinued. In the ten years' Cultural Revolution and the ensuing years, the Chinese community of high energy physics had proposed and designed quite a number of proton accelerator schemes, such as the 6GeV proton synchrotron, the 800MeV proton linear accelerator and the 50GeV proton synchrotron, but none of them materialized. This is due to the wrong decision-making and the opportunities chosen in the wrong time. However, although a lot of time and work were wasted, I was tempered in practice, with my knowledge on accelerator accumulated and widened. In a word, from the late 1950's to the early 1980's, China's high energy physics accelerators had hovered for over twenty years.

RAPID DEVELOPMENT OF CHINA'S HIGH ENERGY ACCELERATORS IN THE LATER THIRTY YEARS

The Turning Point of the Development of China's High Energy Accelerators – Beijing Electron Positron Collider (BEPC)

In the early 1980's, China had entered the era of reform and opening to the outside world, and China's dream of constructing high energy accelerators had finally come true. Since the opinions and suggestions of experts, mainly from abroad had been accepted, according to the existing physical window, the scheme, which was considered to be suitable for the economic condition and keeping advanced in accelerator, was selected, and this is BEPC. It can be said that the correct decision-making is the key to the success.

The energy of BEPC is 1 to 2.5GeV, and the designed luminosity is $1x10^{31}/cm^2/s$ at 1.89GeV with a total investment of about only \$90 million. Fig.1 is the bird's eye view of BEPC.

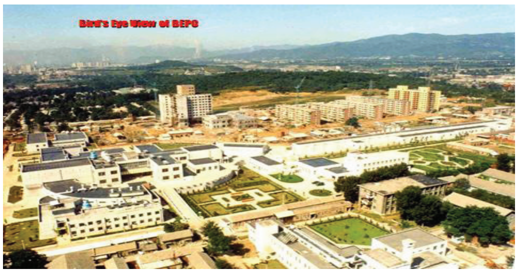

Figure 1: Bird's eye view of BEPC.

The purpose of building BEPC is mainly to carry out the research on charm and Tau lepton physics, and the applied research on synchrotron radiation. It is a machine for two purposes". The construction of BEPC started on October 7, 1984 and it followed that the first collision between electron and positron was realized on October 16, 1988. All these were accomplished only in 4 years. And moreover, its luminosity is the highest in the world in the same energy region at that time.

By overcoming the difficulties in terms of China's weak industrial foundation and the COCOM restrictions on China's importing of high technologies and related products, we succeeded in developing most of the key equipment by relying on our own efforts with the help of our friends worldwide, especially, under the framework of PRC- USA HEP annual meeting**s.**. It should be noted that even when we lacked experience in every respect, we succeeded in making a special lattice design of BEPC. Considering BEPC was a small collider with a circumference of only about 240 meters, I adopted a design philosophy which was different from that used for traditional large colliders. According to this idea, the non-dispersion and arc areas were blended to form a quasi-periodic lattice. Now we understand this is due to the 'dynamic aperture' of the machine had been enlarged and thus improved the overall performance [2]. This idea came from the experience gained during my designing of the focusing lattice of the new high intensity antiproton ring AC at CERN with E.J.N. Wilson in 1982 [3].

In addition, different from the design ideas for large colliders, I moved the skew quadrupoles for correcting the transverse coupling from the long straight section near the interaction point to the injection region [4]. The transverse coupling was therefore reduced effectively in this way. So in the early commissioning, the luminosity of BEPC quickly met and exceeded the original design specifications [5].

In the next decade, many important results were obtained, including the precise measurement of tau mass, the measurement of the hadron R-value in the c.m.s. energies between 2-5 GeV, the decay properties of ψ', etc. All these put China's research on tau- charm physics in a front position around the world

In 1986, I was nominated as the Project manager of BEPC, and thus responsible for the whole BEPC project. This widened my knowledge on accelerator theory and technology, and this also improved my ability of management.

The success of BEPC was also attributed to the strong support from the Chinese Government and the international cooperation. BEPC was designated as a state key project during its construction, which received strong support from Deng Xiaoping and coordinated collaborative efforts throughout the country. In addition, Deng's visit to the United States of America in 1979 promoted the signing of the PRC-US agreement on cooperation in the field of high energy physics, which created a good environment for international cooperation.

The Upgrading Project（BEPCII）

In the late 1990's, after 10 years of the completion of the BEPC project, the strategy for developing China's high energy accelerators faced an important decision. When the tau charm factory was proposed in the world, most people thought that it might be a good scenario for further development of BEPC. But after careful study, I found that it needed a too large investment, and the design was not mature enough as well. In addition to high luminosity mode, the other two modes - monochromatic and polarization - are difficult to realize in engineering. Thus, according to the economic conditions of China at that time, a single ring upgrade scheme with an improvement of luminosity by an order of magnitude was proposed. This upgrade project was known as BEPCII. Later, at the end of 2000, large angle collision was successfully realized at KEKB in Japan, which reveals us it is possible to use this technology to realize collision in a rather short circumference. Facing the competition of CESRc scheme announced by Cornel we decided to adjust the BEPCII from single ring to double-ring scheme with large angle collisions. Although it was a difficult scheme, the design luminosity was increased by another order of magnitude, while the investment was only \$20 million more than the original \$60 million, thereby laying a foundation for the competitive capability of BEPCII today.

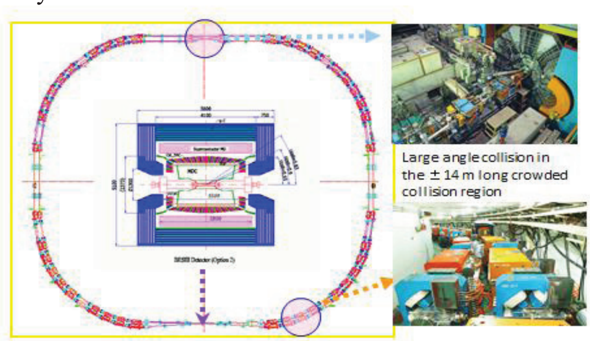

Figure 2: Layout of BEPCII double ring.

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BEPC II is a double-ring collider. The new ring was built inside the existing ring in the BEPC tunnel. Two halves of the new ring and two halves of the old rings cross at two interaction regions, as shown in Fig. 2. The design luminosity would be $1\times10^{33}/cm^2/s$ at 1.89 GeV.

Compared with the BEPC, BEPCII was more innovative and challenging in physics design and engineering technologies ten years ago. In the lattice design, BEPCII had to reach the above mentioned luminosity and in the meantime it still needed to keep the original function of "One machine for two purposes". The latter requirement made the design more complicated. We had adopted the structure of a bridge at the north IR to connect the two outer rings, thus making the two-half rings in the east and west to form a synchrotron radiation ring. This design is unique to the similar projects in the world. In physics design, we worked out an optimized storage ring lattice, which not only met the required high luminosity but also kept the positions and direction of all the original synchrotron radiation beam lines unchanged in the narrow tunnel. This had saved investment and made it possible to construct the machine quickly as well.

In engineering, it was very difficult to realize the double ring scheme in the original small cross-section BEPC tunnel. A series of technological problems were caused and had to be overcome. In order to realize large angle collision in the only ±14 m long collision region and rapid separation after collision, special magnets, vacuum chambers and compact and complex superconducting insertion magnet were developed. With the exception of the 500 MHz superconducting RF system and the cryogenic system imported abroad, most of the components required were developed by us, etc. Moreover, the impedance budget was strictly controlled to limit the bunch lengthening, bunch to bunch feedback system was used to damp the coupled bunch instability due to HOMs of RF cavity, resistive wall and ion effect, TiN was coated in antechamber of e+ ring to control electron cloud instability etc. [6]. Thanks to the industrial foundation which was far better than the 1990's, many new technologies and new processes were quickly developed and applied. All these made the BEPC II project completed according to the designed specifications and the schedule, within budget and with high quality. Table 1 shows the main parameters of BEPC-II and those achieved in operation.

The BEPC upgrade project started in 2004. The first e+e- collision was obtained on July 19, 2008. The luminosity reached $3.3x10^{32}/cm^2/s$ at 1.89GeV and it was promoted to $6.5x10^{32}/cm^2/s$ in April, 2011, and during this period，large amounts of hadron events were obtained. Compared with the peak luminosity of BEPC before upgrading, it was improved by 65 times, the daily data taking rate of ψ″was increased by about 90 times and that for J/ψ increased by 120 times respectively. It maintains the advanced position among similar accelerators in the world. Many physics experiments have been done on BES III. Extensive international cooperation has been carried out with 350 members from 50 institutions of 11 countries. According to the current operation, there is still room for further improvement of the luminosity [7]. In March of this year, the luminosity was enhanced to $7.1x10^{32}$ $/cm^2/s$ at 1.89GeV.

Table 1: Main Parameters Achieved

Parameters	**Design**	**Achieved (BER, BPR)**
Beam energy(GeV)	1.89	1.89, 1.89
Beam current (mA)	910	911, 800
Bunch current (mA)	9.8	≥10, ≥10
Bunch number	93	80~88
β_y^* @IP (cm)	1.5	1.4~1.5
Inj. rang (mA/min)	200/e^-, 50/e^+	>200, >50
Trans. tune (x/y)	6.53/5.58	6.506/5.58 6.51/5.585
RF voltage (MV)	1.5	1.5~1.7
Beam-beam parameter	0.04	0.035
Luminosity ($cm^{-2}s^{-1}$)	10×10^{32}	7.1×10^{32}

Shanghai Synchrotron Radiation Facility (SSRF)

When discussing about the further development of BEPC, I felt that with the rapid increase of SR users, it would be more and more difficult to satisfy their requirement parasitically. Therefore I proposed that a dedicated synchrotron radiation facility be built at IHEP while upgrading the BEPC. But IHEP management was worried that building a SR facility at IHEP would slow down the development of high energy physics. Fortunately, my proposal received a strong support from the Shanghai Municipal Government, hence the third generation light source was built in Zhang Jiang High Tech Park of Shanghai, known as SSRF. I served as Chairman of the Science and Technology Committee of the SSRF Project and had played an important role in getting the project approved and in the designing and constructing periods I had held various review meetings for its scientific goal, physical design, key technical route, etc. All the design goals were reached quickly after its successful construction and commissioning in 2008 and 2009. The operation of the SSRF accelerator complex is very reliable, and many improvements in performance have been made, including the obtainment of the lower emittance of 2.88nm-rad at 3.5GeV, the vertical emittance of 3 pm-rad and top-up operation with sub-micron orbit stability [8]. Performance upgrade of the SSRF storage ring, including the 3.0 GeV operation energy and super bend based lattice, are being considered to meet the increasing user demand. There are another 21 new beam lines being planned, 16 of them are public beam lines which are approved by the government. By 2020, there will be nearly 40 beam lines in operation at SSRF.

Application of High Intensity Proton Linear Accelerator in Nuclear Energy

It is a bounden duty to transform the high tech achievements obtained in basic research into application. As energy is the bottle neck in developing our national economy, I paid attention to the role of the high tech played in the development of nuclear energy.

Accelerator driven subcritical reactor (ADS) for nuclear waste transmutation. In 1999, in order to make better use of the uranium resources, some of my colleagues at the Atomic Energy Research Institute and I put forward a project entitled "Basic Research on the Physics and Technology of the Accelerator Driven Subcritical Reactor (ADS) on Clean Nuclear Power System" to the government, and its R&D plan got approved. As the major advisor to this project, I help define the roadmap and choose the accelerator scheme and responsible for the study of the high intensity proton accelerator at IHEP. I made a lot of efforts in pushing the design and construction of a high duty factor RFQ accelerator and in helping establish a superconducting RF laboratory at IHEP.

In 2006, a 3.5MeV RFQ was commissioned at IHEP, with a 46mA output beam at 12% duty factor and transmission rate of large then >93% [9].

Later, along with the rapid development of China's nuclear power industry, the processing of high level radioactive waste has become one of the key issues for the sustainable development. I organized an expert advisory committee to set up the priorities for developing ADS and compare with fast reactor. The final report pointed out, "About the strategy of sustainable development of China's nuclear energy, while fast reactor focuses on nuclear fuel breeding, ADS is a reasonable choice for the transmutation of nuclear waste." This conclusion was adopted by the CAS (Chinese Academy of Sciences) directors. Thus the focus of the ADS strategy was shifted to the transmutation of nuclear waste from nuclear energy production. A project entitled "Study of the Key Technologies for Accelerator Driven Nuclear Waste Transmutation" was approved by CAS in 2011 as a strategic pilot science project. I had served the general advisor to this project. The ADS key technologies mainly include the overall design, high intensity accelerator, high power spallation target and sub-critical reactor.

This is a rather challenging plan, which aims to build a 1000-MW (thermal) ADS demonstration facility in about 20 years. The scope design defines a 1.5-GeV 10-mA CW superconducting proton linac which will be developed jointly by IHEP and Institute of Modern Physics (IMP). The Schematic for ADS linac is given in Fig.3. Up to now, the conceptual physics design of the linac has been completed, together with the advancement in technical R&D studies. The 10 MeV 10 mA test stands based on two different design schemes pushed independently at IHEP and IMP also advance quite well see the presentation by Professor W. L. Zhan in this conference [10].

The scheme of the ADS injectors at IHEP is shown in Fig.4. Here I will only mention the considerations in choosing the IHEP scheme for the injectors. The RF frequency for the injector is 325 MHz, it is the same as the one for the low energy part of the main linac, it is also similar to the previous RFQ we built, so we can use almost mature technique but with conservative design to meet the RFQ CW operation. Compared with the injector scheme of 162.5 MHz, another advantage of this solution is that only one frequency jumps from 325 MHz to 650 MHz at about 178 MeV is needed for the whole linac. This is considered better for longitudinal match, and its lower bunch charge in the main linac section is good for alleviating space charge effects.

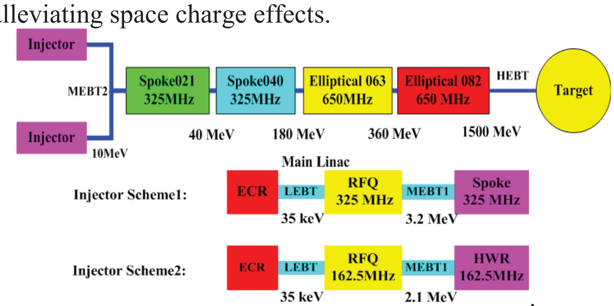

Figure 3: Schematic for ADS linac.

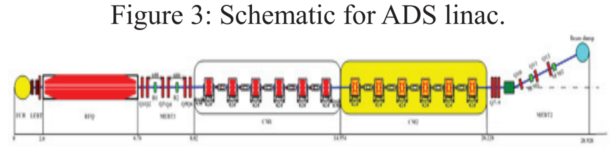

Figure 4: Test stands for the ADS injectors at IHEP.

China Spallation Neutron Source (CSNS). Pulse spallation neutron source is an important tool for the development of some of today's frontier disciplines. Starting from the late 2000, a series of discussions and symposiums were organized by me to clarify the necessity, possibility and the design principle for the China's future spallation neutron source. Finally, it was proposed that this machine be a world-class, but modest one within China's financial capability, which will provide a multi-discipline platform of scientific research for national institutions and industries, so the beam power was chosen to be 100 kW in the first phase with a potential for further upgrades [11]. Moreover, the accelerators and target technologies developed in construction CSNS will be a solid foundation for further development of ADS. Not only did I play an important role in pushing the designing of this project and getting it approved, but also took part in its physics design. Now I serve as Chairman of the Science and Technology Committee for this project.

The CSNS consists of an 80MeV H^- linac and a 1.6 GeV rapid cycling synchrotron (RCS) producing a proton current of 62.5 μA (100 kW) at a 25Hz repetition rate, as shown in Fig. 5. It should be able to be upgraded to 500 kW beam power in its second phase. Its proposal was approved in September 2008. Most of the key R&D items of accelerator have been carried out since 2006, and were completed. Mass production of accelerator components has started. CSNS is located in Dongguan City, Guangdong Province. The construction started in April 2010 and the ground breaking ceremony was held on 20 Oct. 2011. Civil engineering started in May 2012. The total investment is about 250 million US dollars.

It will be completed at the end of 2017. [12]. Details have been reported by Dr. S. Y. Fu in this conference.

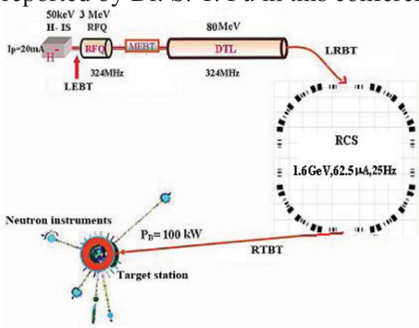

Figure 5: Layout of the CSNS.

Application of Proton Accelerator in Cancer Therapy

The number of patients is rapidly increasing in China. According to unofficial statistics, there are 3.2 million new patients suffering from this disease each year, of which about half need radiotherapy. Proton accelerator is one of the most advanced radiation therapy equipment for dealing with cancer efficiently. Technologically，proton equipment for medical treatment is similar to CSNS. Thus IHEP can bring its characteristics into full play. So from 2007, I made great efforts in pushing and leading the designing and research of proton accelerator for medical treatment. Finally, it is undertaken by SINAP. It will be supported by the Shanghai Municipal Government and put in use in a new cancer treatment hospital called Jiading Ruijin Hospital. For the time being, the preliminary design has been completed.

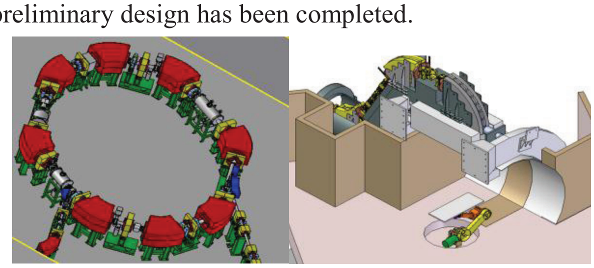

Figure 6: Proton synchrotron and 180° compact gantry.

The proton accelerator includes a synchrotron of 250 MeV in maximum energy, an injector of 7 MeV consisting of an RFQ and a DTL linac, with a repetition rate of 0.5 Hz. The slow extraction using the third order resonance is adopted and the beam spill length can be adjusted from 0.1 to 10 s. The irradiation methods should be able to reflect all the major progresses worldwide. So only the spot scanning method is adopted in the facility. To accommodate the requirement of this method, the extraction energy can be changed by about 100 steps between 60 MeV and 250 MeV. It only has one fixed nozzle and one gantry nozzle in the first stage of project, Isocentric 180^0 compact gantry coupled with robotic patient couch is adopted. The design philosophy must be in accordance with the RAMI principle (Reliability, Availability, Maintainability, Inspect ability), and it will be completed within less than 4 years, and its investment is about $60million.[13]. The proton synchrotron and Isocentric 180^0 compact gantry are shown in Fig.6.

SUMMARY

Today I am given an award, to be more exact, this award is given to the Chinese community of high energy accelerators. It is an encouragement and spur to the best representatives of accelerator builders who have made outstanding contributions to the construction of China's high energy accelerators in the past decades. The development of China's particle accelerator is inseparable from international cooperation. In the 30 years since the construction of BPEC, IHEP has established a relationship of extensive cooperation with all the major high energy physics and synchrotron radiation laboratories in the world, such as CERN, SLAC, BNL, FNAL, LBNL, KEK, INFN, DESY, PAL, etc. IHEP has received valuable support from them. Here I would like to express my sincere thanks to my colleagues and all our foreign friends who have helped us.

Although we have made a big stride in accelerator construction, there are still large gaps compared with the accelerators of the advanced countries in Asia and the world. We know that we still have a long way to go. With the development of our economy, we hope that in the next decades we will exert our great efforts to make our due contributions to the development of accelerators in the world.

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