The Development of China's Accelerators I Experienced

Shouxian Fang

May 16, 2013

Outline

- **The hovering period of China's accelerators (1958-1978)**
- **Rapid development period of China's high energy accelerators in later 30 years (1978 – now)**
  1. ***Beijing Electron Positron Collider (BEPC) and BEPCII***
  2. ***Shanghai Synchrotron Radiation Facility (SSRF)***
  3. ***Accelerator driven subcritical reactor for wast transmutation***
  4. ***China Spallation Neutron Source (CSNS)***
  5. ***Proton accelerator therapy***
- **Summary**

My Personal Experience

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).

The First 20 Hovering Years of China’s Accelerators

- Development of high energy physics and 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, Chinese government had already considered the development of China’s nuclear physics.
- In 1957, I was sent to the Lebedev Physical Institute of Soviet Union for advanced study. The main task was to design a 2 GeV electron synchrotron.(people doubt that quantum fluctuation of SR would limit the maximum energy can be reached in electron synchrotron <5GeV?) This scheme seems to be more suitable for the then situation of China.

- 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 (CERN 28 GeV PS not competed). This was a very adventurous scheme and was dropped.

- Thanks to the great advancement in the isochronous cyclotron (sector focusing cyclotron) at Joint Institute of Nuclear Research of Dubna, with their help, a 450MeV isochronous cyclotron was adopted and designed. The scheme was more suitable for our national capability at that time.

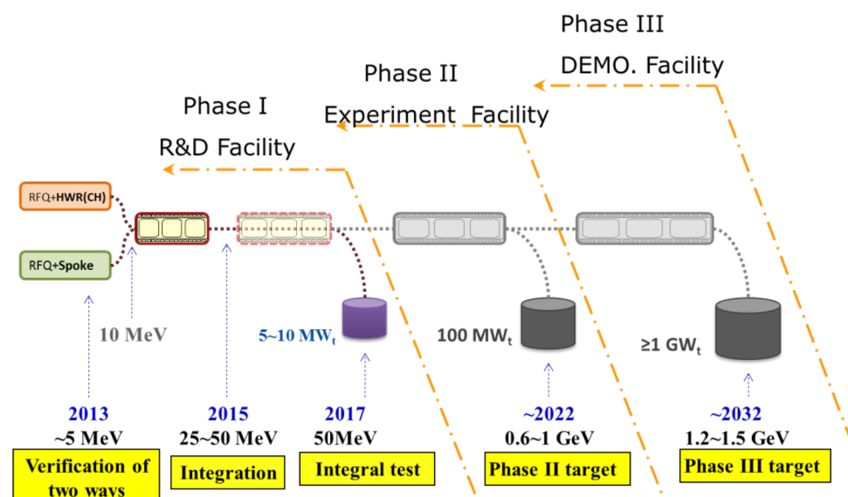
- My design and research efforts were still kept on going in China at next 5 years. I published some interesting papers related to isochronous cyclotron theory. Among them, the most important one is my first paper "the finding of the non-isochromatic phenomenon in isochronous cyclotron", which is due to the transverse free oscillation, thus, making it impossible for the particles to always synchronize with the RF field, and limiting the maximum current can be reached in this kind of cyclotrons.

- **Later, the Cultural Revolution began and the Sino-Soviet relations was broken, I had to stop my research work. It followed that this project discontinued. In the ten years' cultural revolution and the ensuing years, the Chinese community of high energy physics had proposed and designed a few of proton accelerator schemes, such as**
  - **6 GeV proton synchrotron**
  - **800 MeV proton linac**
  - **50 GeV proton synchrotron**

  But none of them materialized.

- **From the late 1950's to the early 1980's, China's high energy accelerators had hovered for over twenty years.**

Rapid Development of China's high Energy Accelerators in Later 30 years



- In the early 1980's, China had entered the era of reform and opening to the world, and China's dream of constructing high energy accelerators had finally come true.
- The proton type accelerator, which had been long preferred was given up.
- According to the existing physical window, the BEPC, which was considered to be suitable for the economic capability and keeping accelerator advanced in technology was selected, the correct decision-making is the key to the success.

1. Turning Point of the China’s High Energy Accelerators Development – Beijing Electron Positron Collider

BEPC

BEPC

- The energy of BEPC is 2.5 GeV, (return to origin 1957 2GeV, synchrotron vs Collider) and the designed luminosity is $1 \times 10^{31} cm^{-2} s^{-1}$ @1.89GeV with a total investment of about only $90 million.
- The purpose of building BEPC: basic research on charm and tau lepton physics, applied research on synchrotron radiation. "One machine for two purposes".
- The construction of BEPC started on October 7, 1984 and was accomplished on October 16, 1988 on schedule and within budget.
- its luminosity is the highest in the world in the same energy region at that time.

BEPC constructed in 1984 –1988 with beam energy: 1 – 2.8 GeV

- Physics Run： Luminosity $10^{31}cm^{-2}s^{-1}$ @ 1.89GeV, 5 month/year
- Synchrotron Radiation Run： 140mA @ 2.2 GeV, 3 month/year

Bird's Eye View of BEPC

Major Challenges:

- the difficulties in terms of China’s weak industrial foundation.
- 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, within the framework of PRC- USA HEP annual meetings. (For ex. the life time of first klystron was only one month)

- The lattice design of BEPC was very successful. Considering BEPC was a small collider with a circumference 240 meters, the design philosophy I adopted which was different from that used for traditional large colliders, the non-dispersion and arc areas were blended to form a quasi-periodic lattice, thus improved the overall performance. This is due to the "dynamic aperture" of the machine had been enlarged.

- This idea came from the experience gained during my designing of the lattice of the new high intensity antiproton ring AC at CERN with E.J.N. Wilson in 1982.

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

Physics Results from BEPC

- In the next decade, many important physics 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.

The BEPC Upgrading Project（BEPCII）

- In the late 1990's, after 10 years of the completion of BEPC project, the strategy for further 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 carefully study, I found
  1. the design was not mature enough as well. The high luminosity mode is ok, the other two modes – mono-chromatic and polarization - are difficult to realize in engineering.
  2. It needed a too large investment relative to the economic capability of China at that time

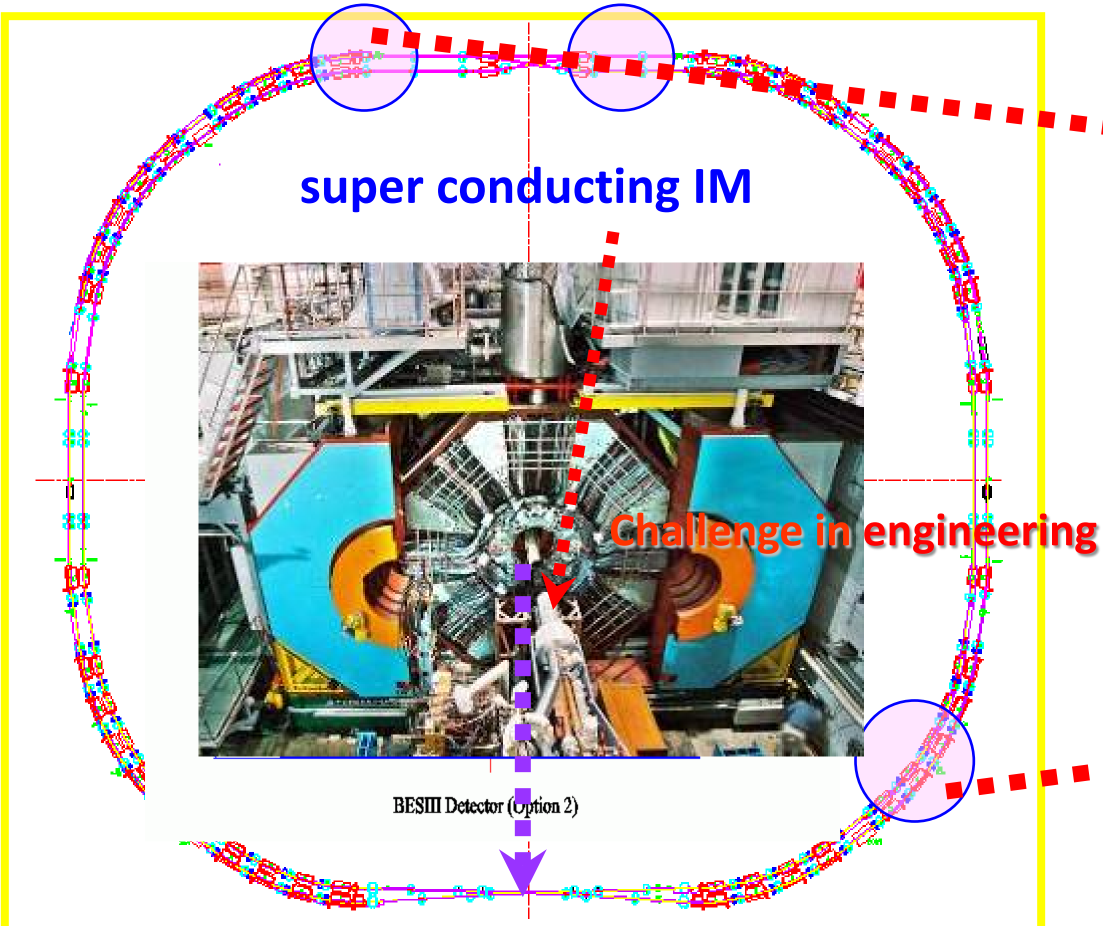
Single Ring to Rouble-ring

- **A single ring（pretzel）upgrade scheme with an improvement of luminosity by a factor of 10 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 that it is possible to realize collision by large angle in a rather short circumference (BEPC). Facing the competition of CESRc, we decided to adjust the BEPCII from single ring to double-ring scheme with large angle collisions. the design luminosity was increased by an another order, while the investment was only $30million more than the original $50 million. It still can be approved.**

- 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. The design luminosity would be 1xE33/cm2/s at 1.89 GeV.
- It was a very difficult scheme due to short circumference and narrow tunnel and Limited investment.
- So, BEPCII need more innovative and challenging in physics design and engineering technologies.

1. Challenge in Engineering



double-ring High Lumi.

1. Build two rings inside existing narrow tunnel.

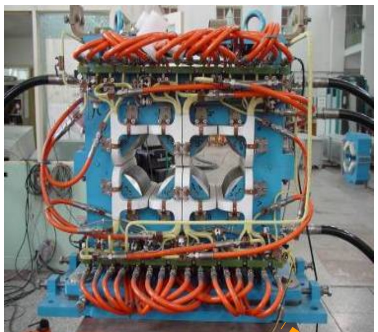
2.One machine for two purpose adopted a bridge at the north IR to connect the two outer rings, thus making the two-half rings in the east and west to form a synchrotron radiation ring.

3. collision region only ±14 m long （KEKB±40m ）very crowded

e+e- collision was on July 2008

Special Technologies in Collision Region

Special mag., vacuum chamber and most compact and complex superconducting mag.(BNL) were developed.



double aperture Q

Septum mag. In Colli. Region

Compact sc insertion mag.in Colli. Region

Special vaccum cham.

Vaccum chamber

2. Challenge in accelerator physics

- To speed up the construction and to save the investment. We had to found a storage ring lattice, which can kept the positions and direction of all the original synchrotron radiation beam lines unchanged in the narrow tunnel.it is quite difficult job.

- Various measures were adopted to fight against Single beam collective effect.

  - Strictly control impedance budget to limit the bunch lengthening
  - Using bunch to bunch feedback system 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

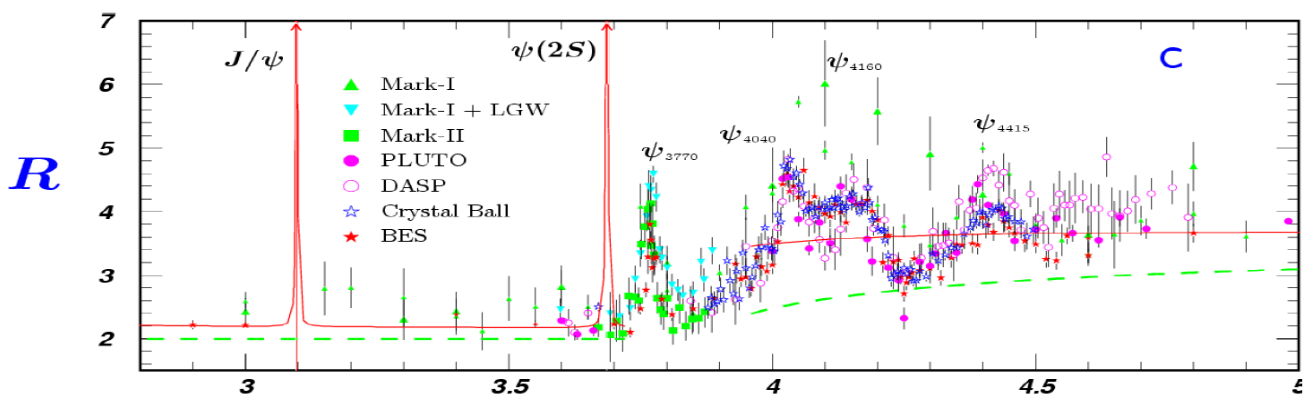
BEPCII/BESIII Luminosity

- The BEPCII started in 2004. The first e^+e^- collision was obtained on July 19, 2008. The luminosity reached $3.3 \times 10^{32}/cm^2/s$ at 1.89GeV and it was promoted to $6.5 \times 10^{32}/cm^2/s$ in April, 2010.Now , rise to 7.1×10^{32} $/cm^2/s$.
- the peak luminosity is improved by 65 times, the daily data taking rate of $\psi''$and J/ψ was increased about 90 times and 120 times.
- Large amounts of hadron events were obtained. Many physics experiments have been done on BEIII.

The BESIII Experiment at the BEPCII: status

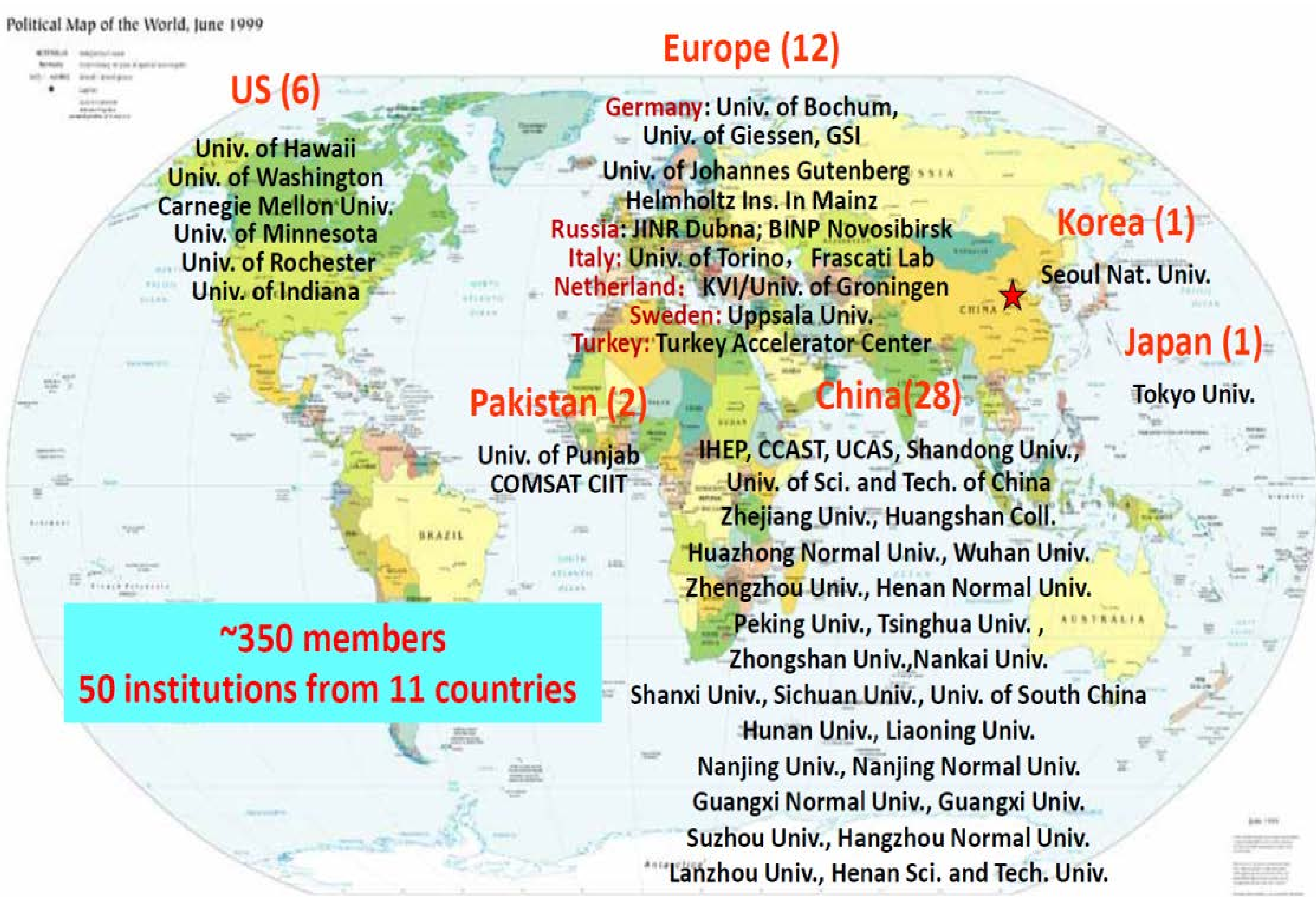
BESIII: current data samples and data goals

	Previous data	BESIII present & future	Goal
J/ψ	BESII 58M	1.2 B 20* BESII	10 B
ψ'	CLEO: 28 M	0.5 B 20* CLEOc	3B
ψ''	CLEO: 0.8 /fb	2.9/fb 3.5*CLEOc	20 /fb
Above open charm threshold	CLEO: 0.6/fb @ $\psi(4160)$	2011: 0.4/fb @ $\psi(4040)$ 2013: 1/fb@4260, 4360	5-10 /fb
R scan & Tau	BESII	2012: 12/pb@2.23,2.4,2.8,3.4 25/pb τ scan 2013, 2014: @4260, R scan, …	



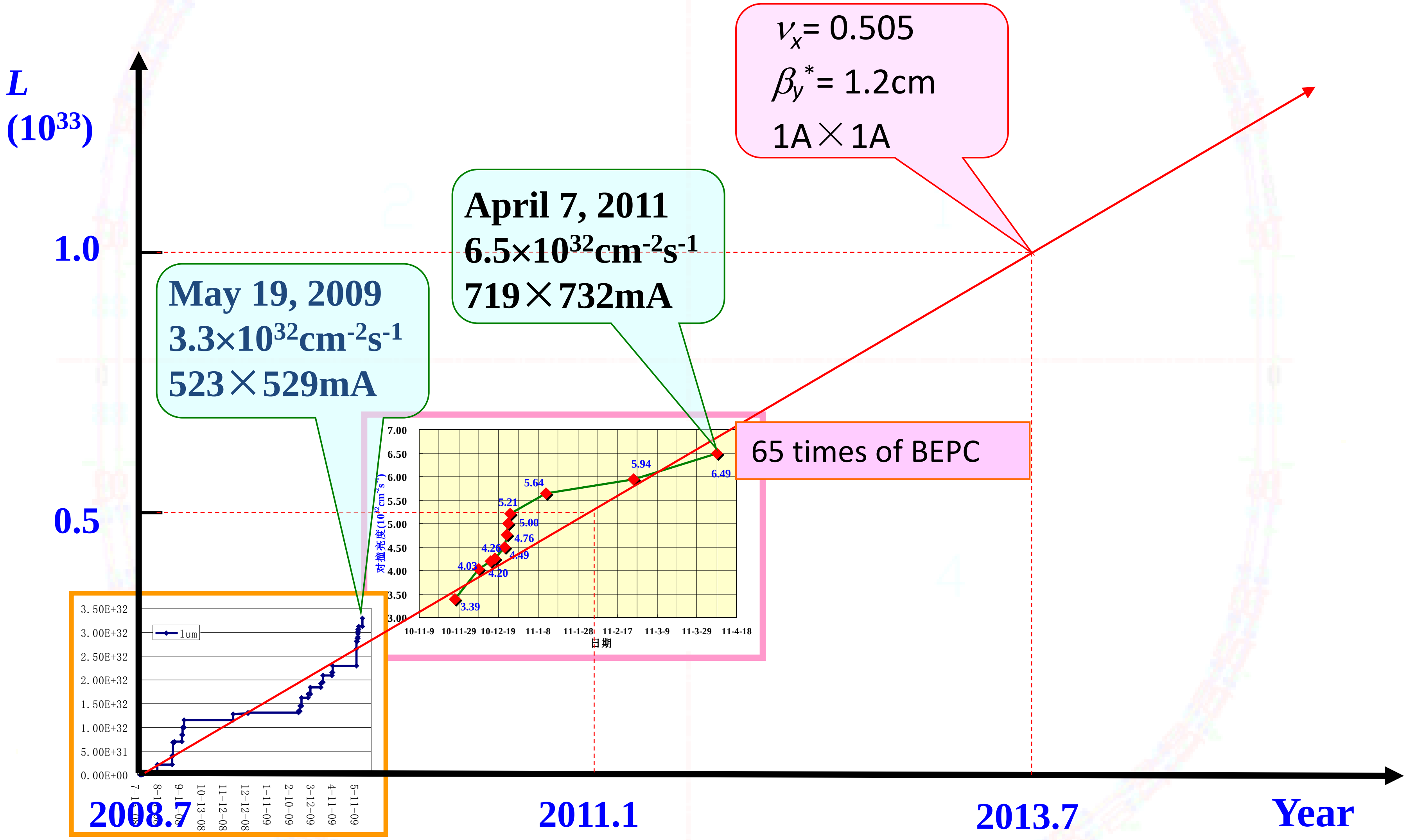
Source: Xiaoyan Shen
April 12, 2013

Extensive international cooperation with 350 members from 50 institutions of 11 countries.



- **It is indeed a very difficult project, even in the construction process, many people are worried whether it could be built to achieve high luminosity. Thanks to the design experiences and industrial foundation which was far better than the 1990's, many new technologies and new processes were quickly developed and applied.**
- **Finally we get success, the BEPC II project completed according to the designed specifications and the schedule, within budget and with high quality.**
- **It is not an original tau charm factory but it really is a high luminosity tau charm factory.**

Peak Luminosity Trend



Main parameters achieved (collision mode)

Parameters	Design	Achieved	
		BER	BPR
Energy (GeV)	1.89	1.89	1.89
Beam current (mA)	910	800	800
Bunch current (mA)	9.8	9.0	9.0
Bunch number	93	80 – 88, 120	80 – 88, 120
RF voltage (MV)	1.5	1.5 – 1.7	1.5 – 1.7
β_y^* (m)	0.015	0.014 – 0.015	0.014 – 0.015
Lifetime (hrs)	3.5@910mA	~1.8@720mA	~1.8@720mA
Beam–beam parameter	0.04	0.0354	
Luminosity ($10^{32}cm^{-2}s^{-1}$)	10	7.08	

Note: some parameters are not reached simultaneously.

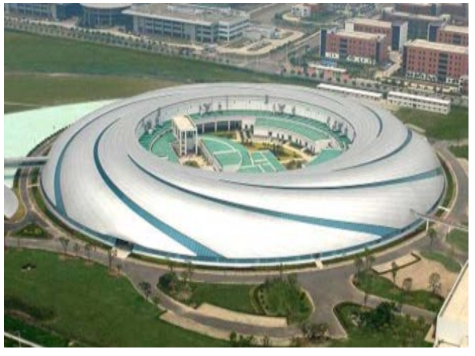
There is still room for improvement of the luminosity.

2. 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 by parasitical mode.**

- **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.**

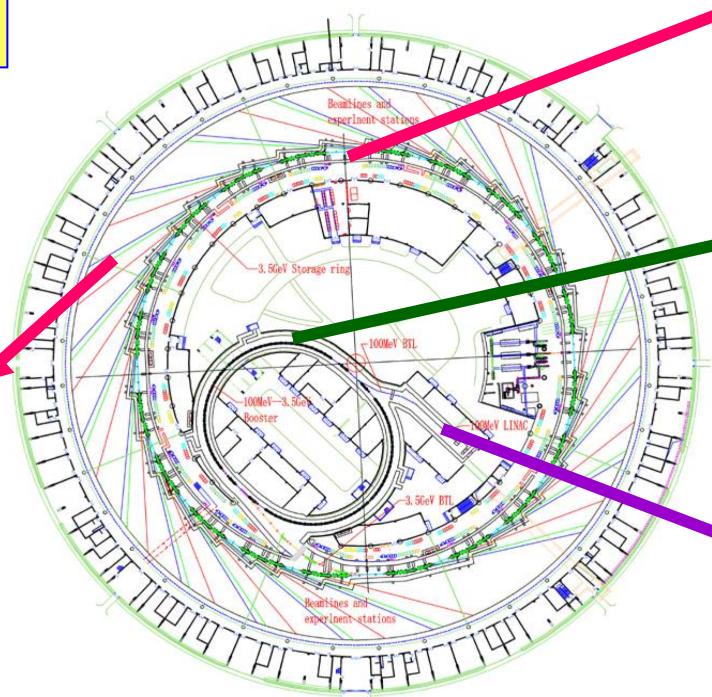


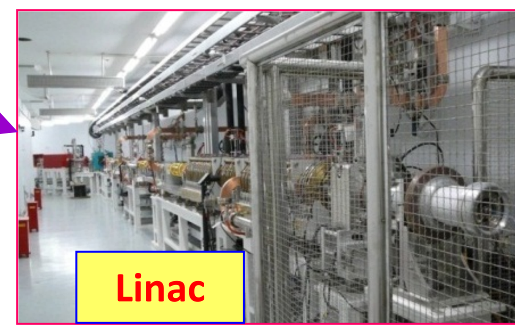
- Fortunately, my proposal received the strong support from the Shanghai Municipal Government, hence the third generation light source was built in Zhangjiang , Shanghai.

- As Chairman of Science and technology Committee, I had played an important role in getting the project approved and in the designing and constructing period I had held review meetings for its scientific goal, physical design, key technical route… etc.

SSRF

First seven beamlines





SSRF

- The SSRF is an 3.5 GeV third generation light source. This project began its user operation in May 6, 2009.
- The operation of the SSRF is very reliable, and many improvements in performance have been mad, for examples, the lower emittance of 2.88nm-rad at 3.5 GeV and top-up operation with sub-micron orbit stability.

It has served more than 4800 users from all over the country, and achieved fruitful experiment results with about 750 journal publications.

◆ The photon beam time is heavily overbooked by users, and the existing seven beam lines can only provide 20% of the beam time that user requires.

◆ There are another 21 new beam lines being planed. 16 public beamlines is approved by the government. By 2020, nearly another 40 beam lines will be in operation at SSRF.

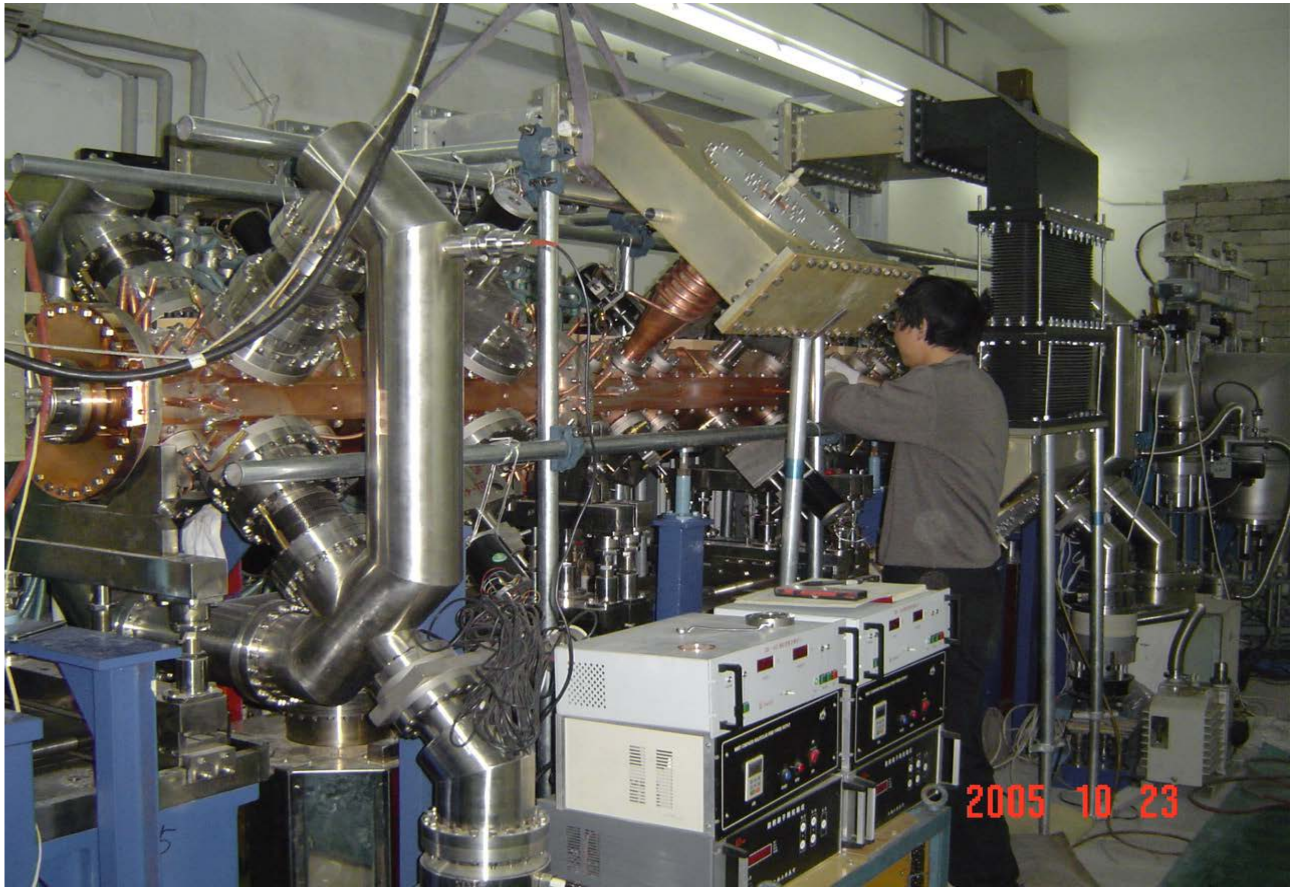
Upgrade of the SSRF storage ring is being considered to meet the increasing user demands.

3. Accelerator driven subcritical reactor (*ADS*) for nuclear waste transmutation

- **In 1999 Prof. Dazhao Ding (China Institute Atomic Energy) and I proposed the project of "Basic research on the physics and technology of the Accelerator Driven Subcritical Reactor (ADS) on Clean Nuclear Power System" for using ^{238}U and ^{232}Th as nuclear fuel.**
- **The Chinese Government approved the R&D plan of ADS.**

As the major advisor, 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 designing and developing the high duty RFQ accelerator and to establish superconducting RF lab in IHEP.



A 3.5MeV RFQ of four-vane type built at IHEP with an output beam of 46mA at 12% duty factor In 2006

ADS focuses transmutation of nuclear waste

Later, considering the rapid development of China's nuclear power industry, high level radioactive waste processing has become one of the key issues for the sustainable development of China's nuclear energy. I organized an expert advisory committee to compare the priorities for developing ADS and fast reactor. The final report pointed out, "In the strategy of sustainable development of our nuclear energy, while fast reactor focuses on nuclear fuel breeding. ADS is a reasonable choice as for the transmutation of nuclear waste."

ADS

Pilot science Project of the CAS

This conclusion was adopted by the CAS (Chinese Academy of Sciences). Thus the focus of the ADS strategy was shifted from nuclear energy to nuclear waste transmutation. To quicken the development of this project. 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.

ADS

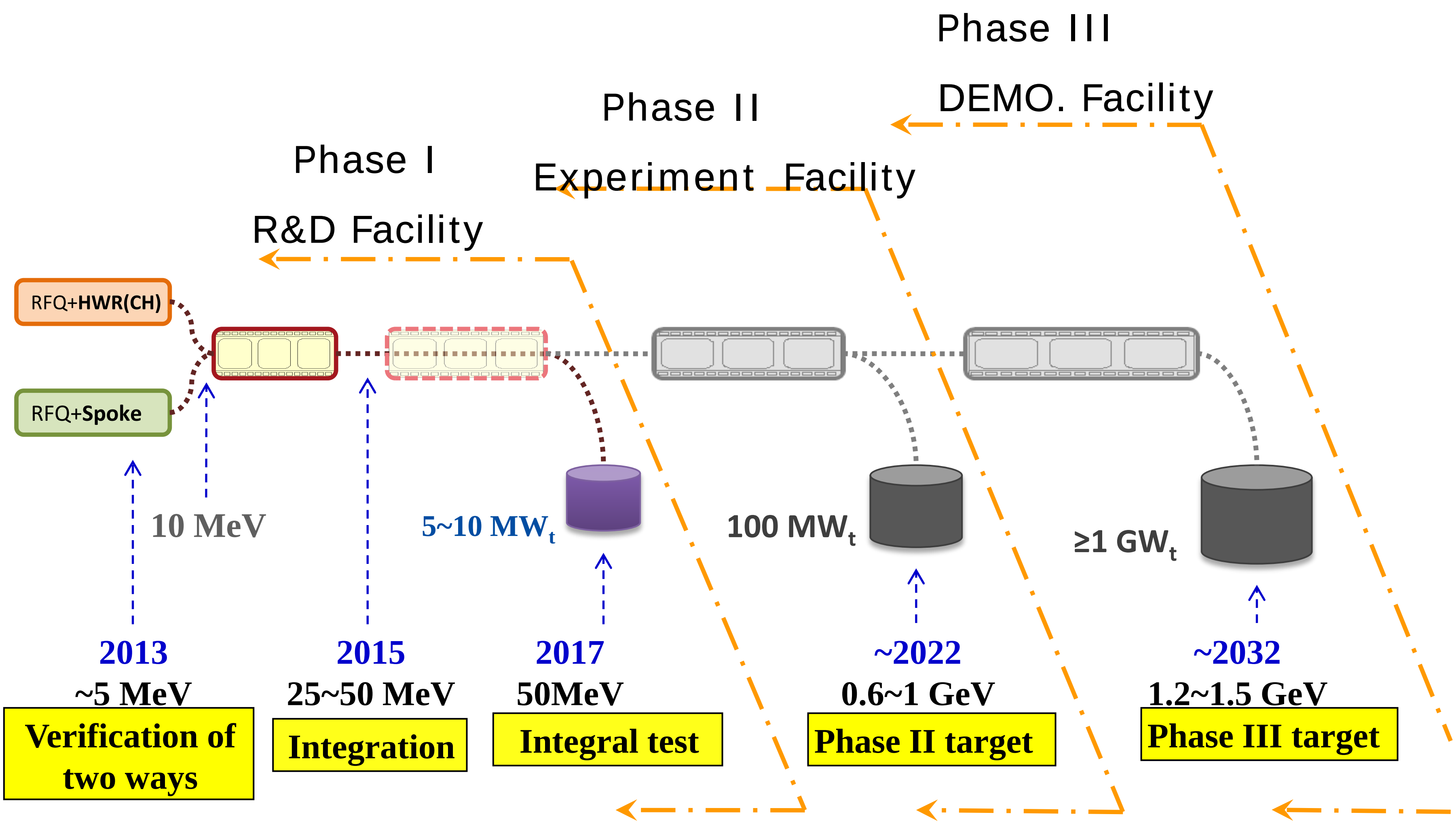
Three Development Phases

This is a rather challenge 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 super conducting proton linac which will be developed jointly by IHEP and Institute of Modern Physics (IMP). The relative key technologies in CW proton linac are extremely challenging to us.

ADS

Three Phases Roadmap of Chinese ADS



A D S

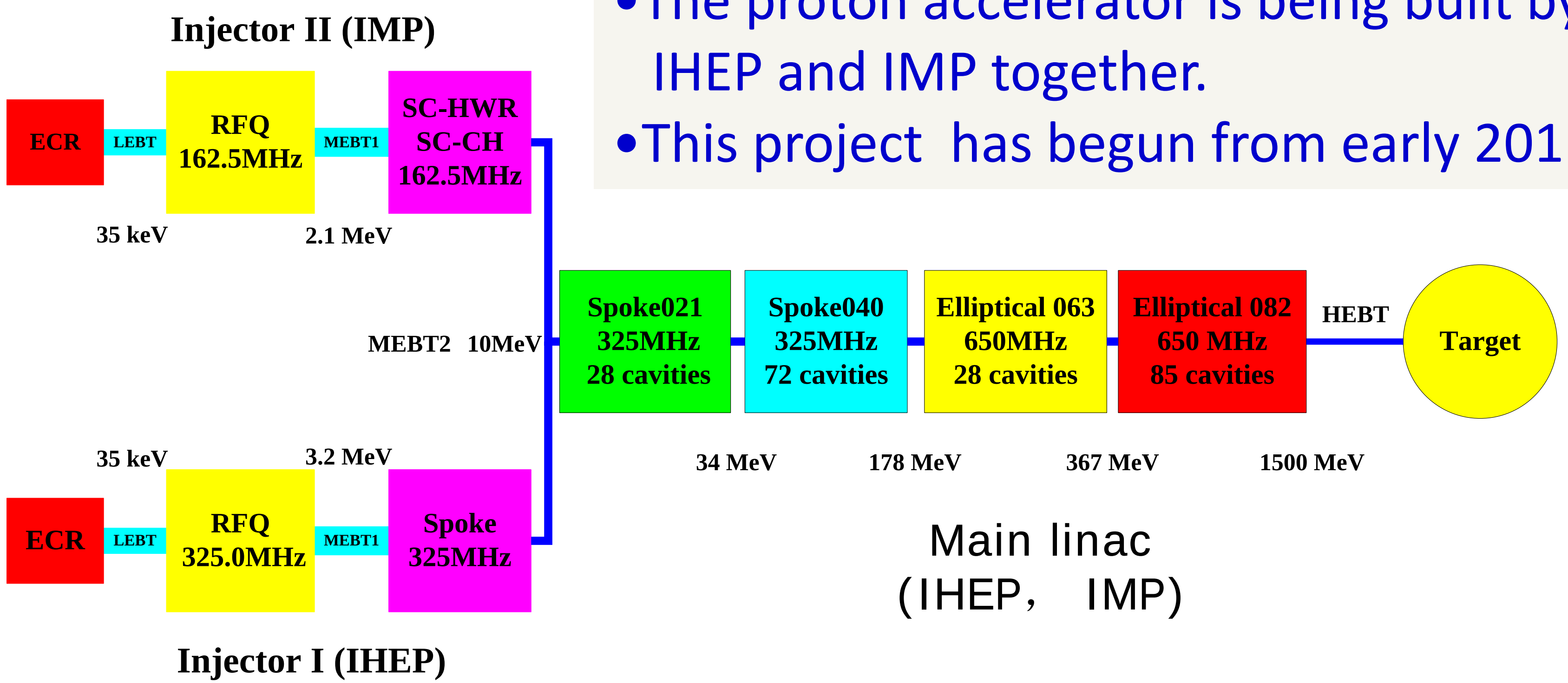
ADS Proton Beam Specifications

Particle	Proton	
Energy	1.5	GeV
Current	10	mA
Beam power	**15**	**MW**
Frequency	162.5/325/650	MHz
Duty factor	**100**	**%**
Beam Loss	**<1 (0.3)**	**W/m**
Beam trips/year	**<25000** **<2500** **<25**	**1s<t<10s** **10s<t<5m** **t>5m**

A D S

Layout of Accelerator

- The proton accelerator is being built by IHEP and IMP together.
- This project has begun from early 2011.



A D S

- **Before 2017,a test facility with 50MeV 1-10mA will be built. The relative key technologies are severe challenges for us. To leave a margin, It has two 10 MeV injectors ,based on two different design schemes pursing independently at IHEP and IMP advanced quite well.**
- **Up to now, The conceptual physics design of the linac has been completed, together with the advancement in technical R&D studies. Details have been reported by Professor W. L. Zhan.**
- ***Here I will only mention the test facility developed by IHEP.***

ADS

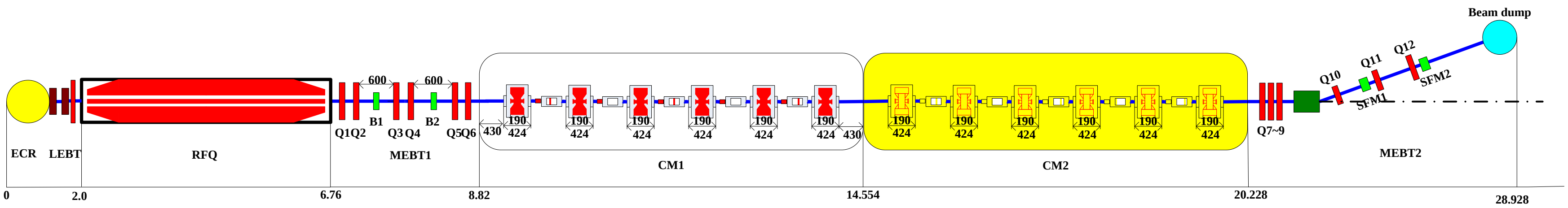
Injector development and superconducting cavities at IHEP

- **At IHEP, the efforts are focused on the injector development and superconducting cavities in the main linac. I helped in defining the design scope.**
- **The RF frequency for the injector-I scheme by IHEP is 325 MHz, which is similar with the previous RFQ frequency, so as we can use almost technique but with conservative design to meet the CW operation. Another advantage is only one frequency jump from 325 MHz to 650 MHz in the main linac section, and this is considered better for longitudinal match, lower bunch charge good for space charge effect and better for reducing beam losses.**

A D S

Current status

Now the project has entered the stage of component fabrication. The 1st and the 4th section of RFQ has been fabricated and advance well. We are very glad that we have succeeded in developing the spoke cavity with β=0.12 which was considered the most difficult part.

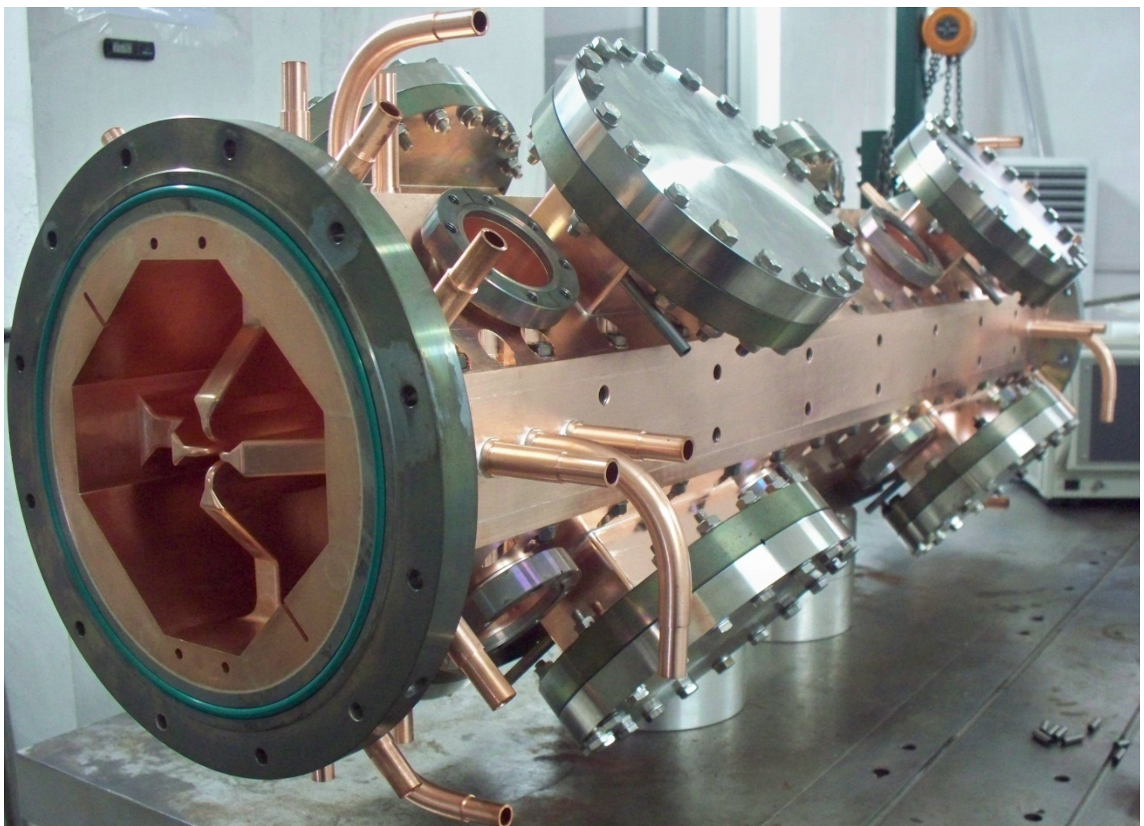


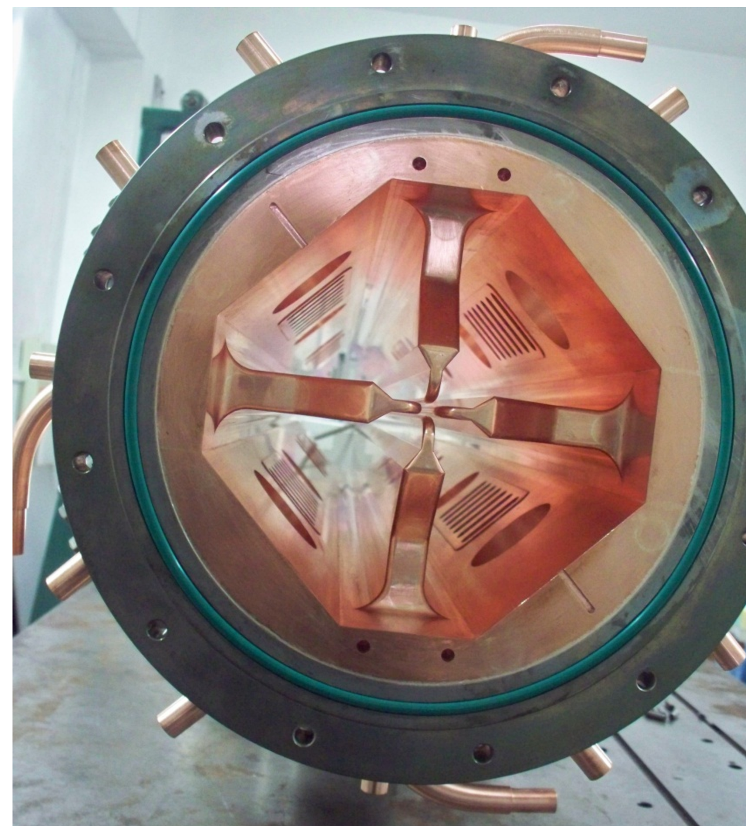
5-MeV/10-MeV test stand for Injector-I scheme at IHEP

A D S

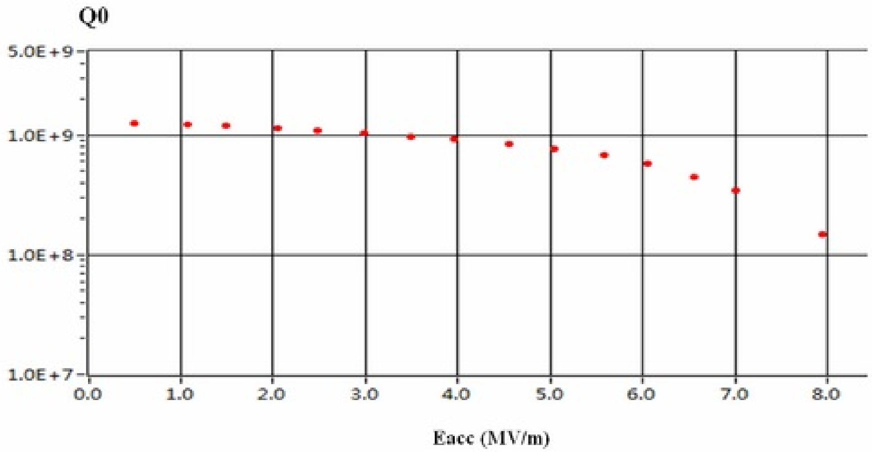
RFQ -- brazing for the first module

The end flanges, the tuner flanges, the vacuum bodies and water-cooling pipes are brazed together with the cavity.





Fabrication of two Spoke cavities (β=0.12) and vertical tested completed in 2012

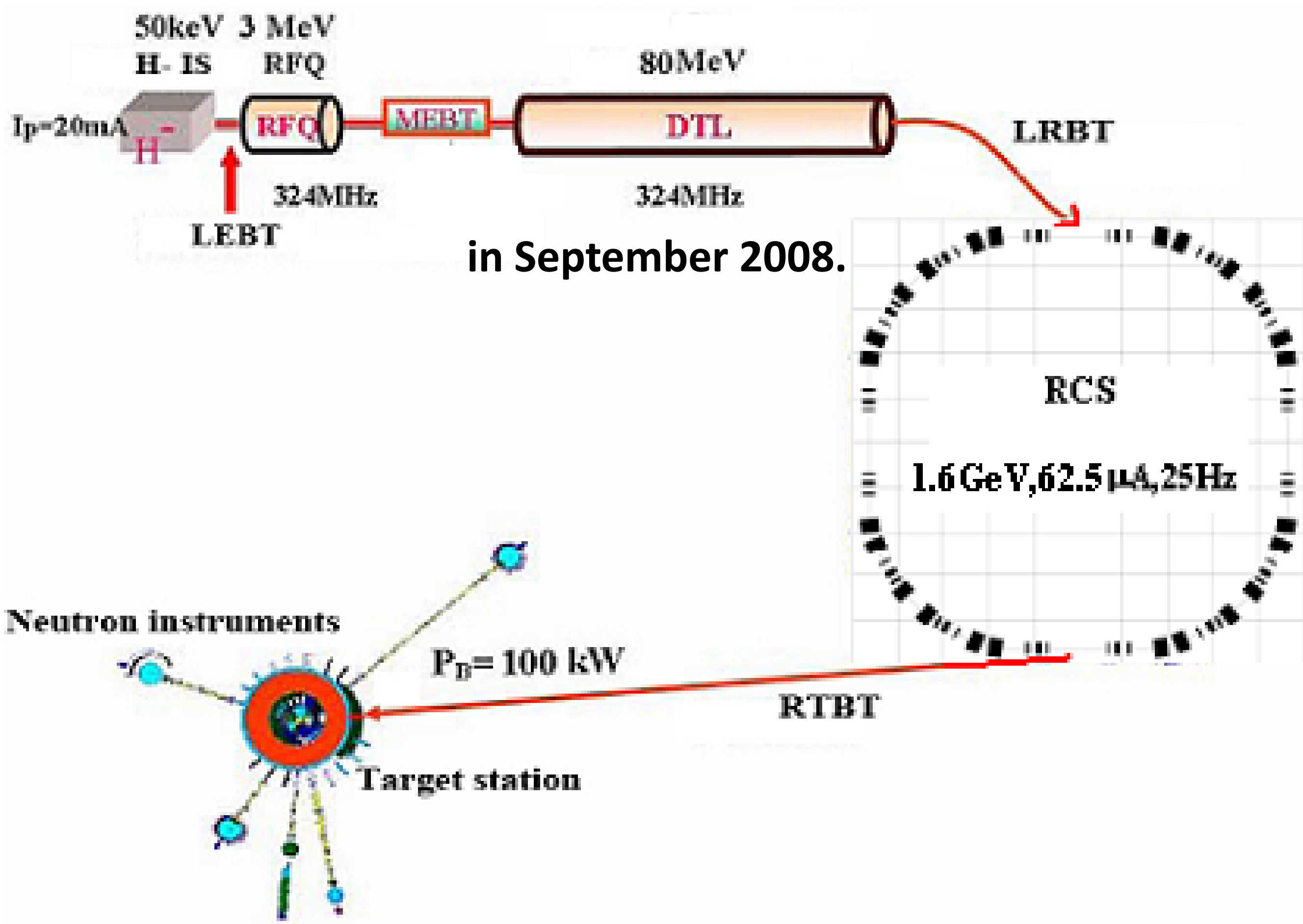


A D S

4.China Spallation Neutron Source(CSNS)

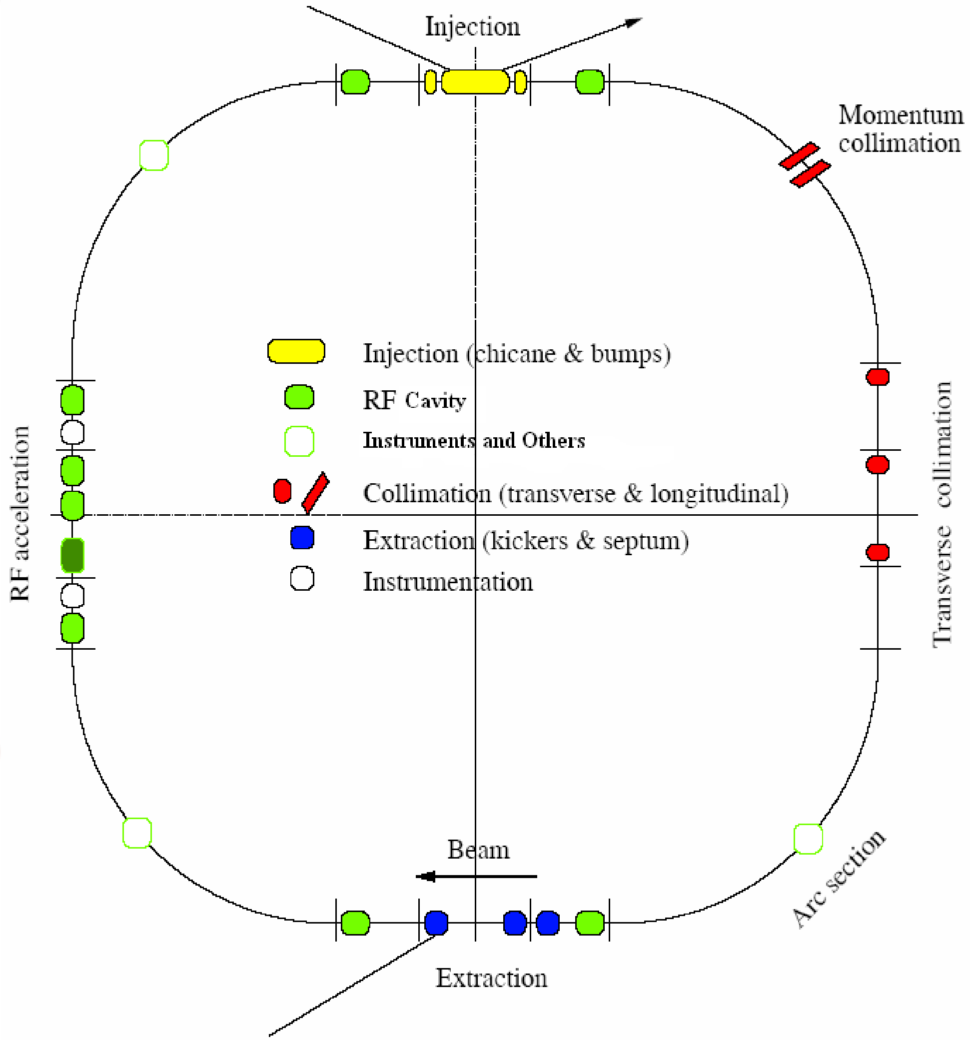
- **Starting from the late 2000, a series of discussions and symposiums were organized by me to clarify the necessity, possibility, and the design principle for the China's future spallation.**
  I. this machine be a world-class, but modest one within China's financial capability.
  II. beam power was chosen to be 100 kW in the first phase with a potential for further upgrades.
  III. the accelerators and target technologies of 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 80-MeV 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. It should be able to be upgraded to 500 kW beam power in its second phase. Its proposal was approved in September 2008.



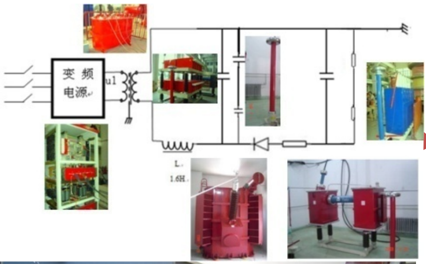
RCS Design

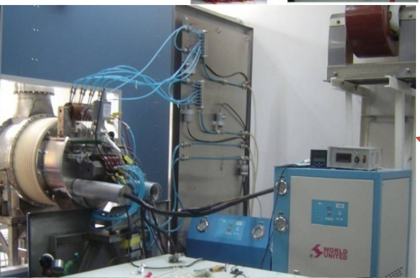
- Lattice of 4-fold symmetry, triplet
- 227.92m circumference
- 1.6GeV at 25Hz
- 80MeV injection energy for phase I
- four long straight sections for injection, acceleration, collimation and extraction
- Upgradeable with increased injection energy (beam current)



The most of key technology R&D started 2006, were completed now.

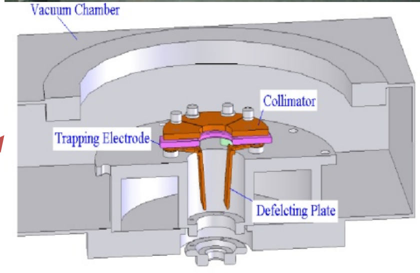
Date	Completed Items
2008.06.05	Linac RF pulsed power source
2009.12.04	RCS injection bump magnet PS
2010.05.27	H^- ion source test stand
2010.06.10	LEBT electrostatic pre-chopper
2010.06.21	RCS injection bump magnet
2010.07.12	RCS dipole field measurement system
2010.07.14	十
2010.07.26	RCS extraction kicker magnet
2010.10.21	RCS ceramic vacuum chamber
2010.11.12	RCS dipole power supply
2010.12.17	RCS ferrite loaded RF cavity
2010.12.31	Bandwidth limited chopper
2011.04.15	RCS quadrupole & field measurement









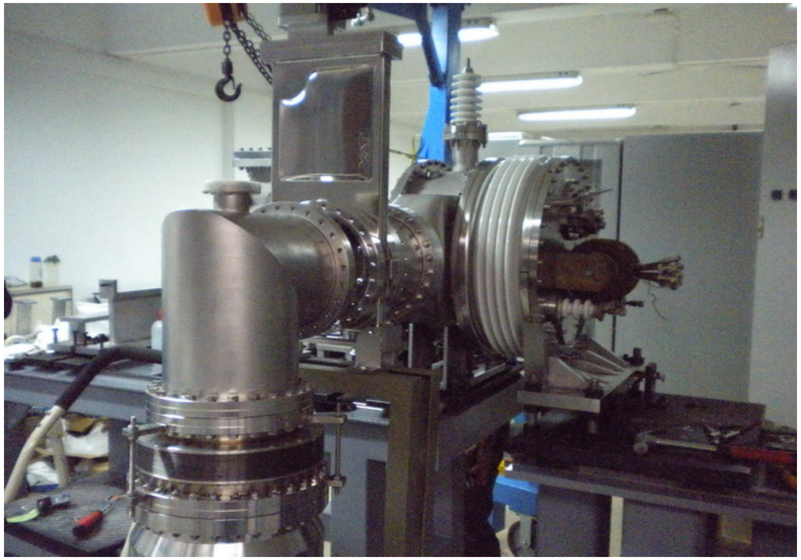





Component Production in Progress

- **H- Ion sour e and LEBT**

  Fabrication has been completed. It is under commissioning for beam test.



- **RCS Main Quadruple**

  Contracted with IHEP workshop and the first one has been manufactured. 72 hours test run has been conducted.

It locates at Dongguan city of Guangdong. The construction started in April 2010 and the groundbreaking ceremony was held on 20 Oct. 2011. Civil Engineering started in May 2012. It will be completed in the end of 2017.

Linac tunnel construction

RCS base construction

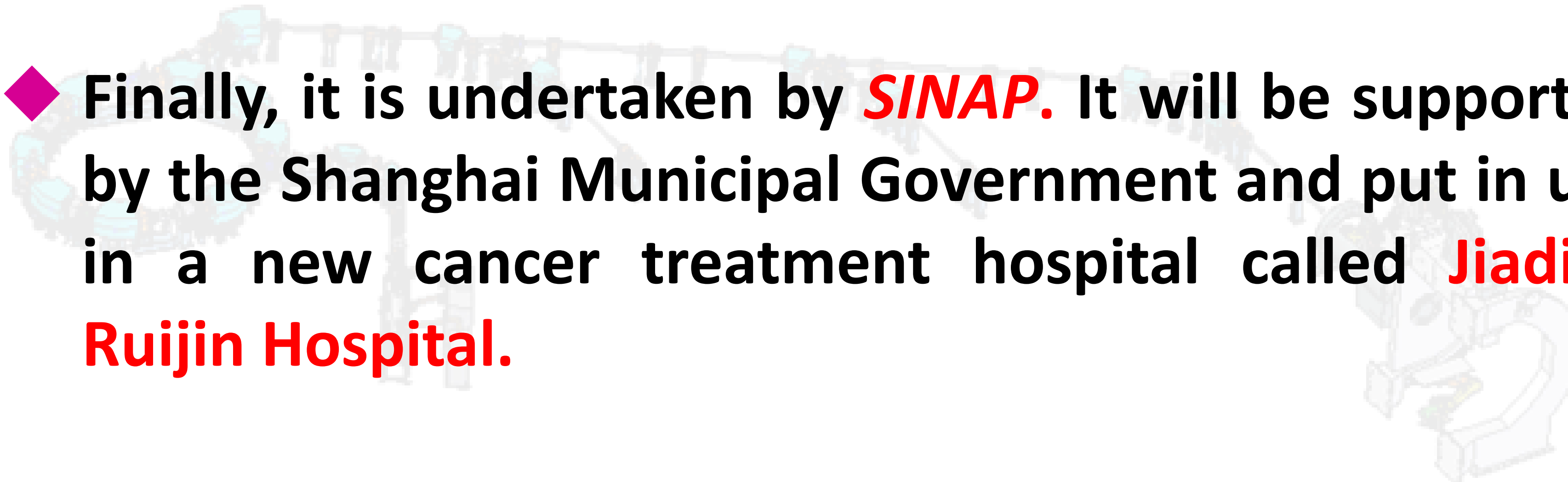
The total investment is about 250 M$, It will be completed in the end of 2017.

Details will be reported by Dr. S.N.Fu.

5. Proton Accelerator 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.
- Proton accelerator is one of the most advanced radiation therapy equipment for dealing with cancer efficiently. Technologically， it is similar to CSNS.
- So from 2007, I made great efforts in pushing and leading the designing and research of proton therapy machine.

Shanghai Advanced Therapy Facility (APTRON)



- 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.

- The preliminary design has been completed.

- The proton accelerator includes:
  - a synchrotron of 250 MeV in maximum energy
  - an injector of 7 MeV consisting of an RFQ
  - a DTL linac
- The repetition rate is 0.5 Hz.
- The slow extraction using the third-order resonance is adopted and together with the RFKO method is considered to obtain a beam spill being stable and more-or-less homogenous. 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. Adopts new technologies, new treatment methods.**

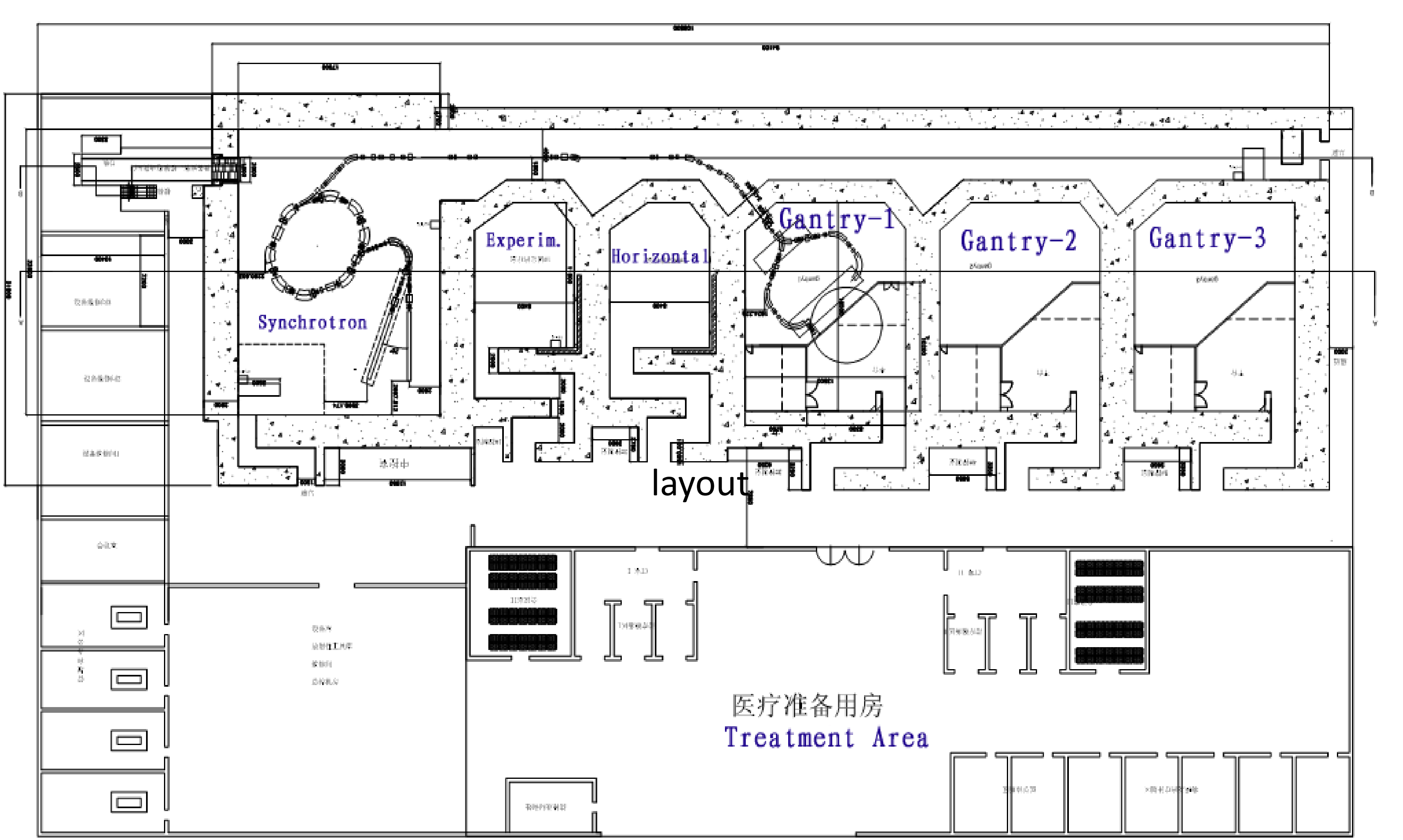
- **The design philosophy must emphasize the RAMI principle (Reliability, Availability, Maintainability, Inspect ability) and easy operating.**

- **Its investment is $ 60million.**

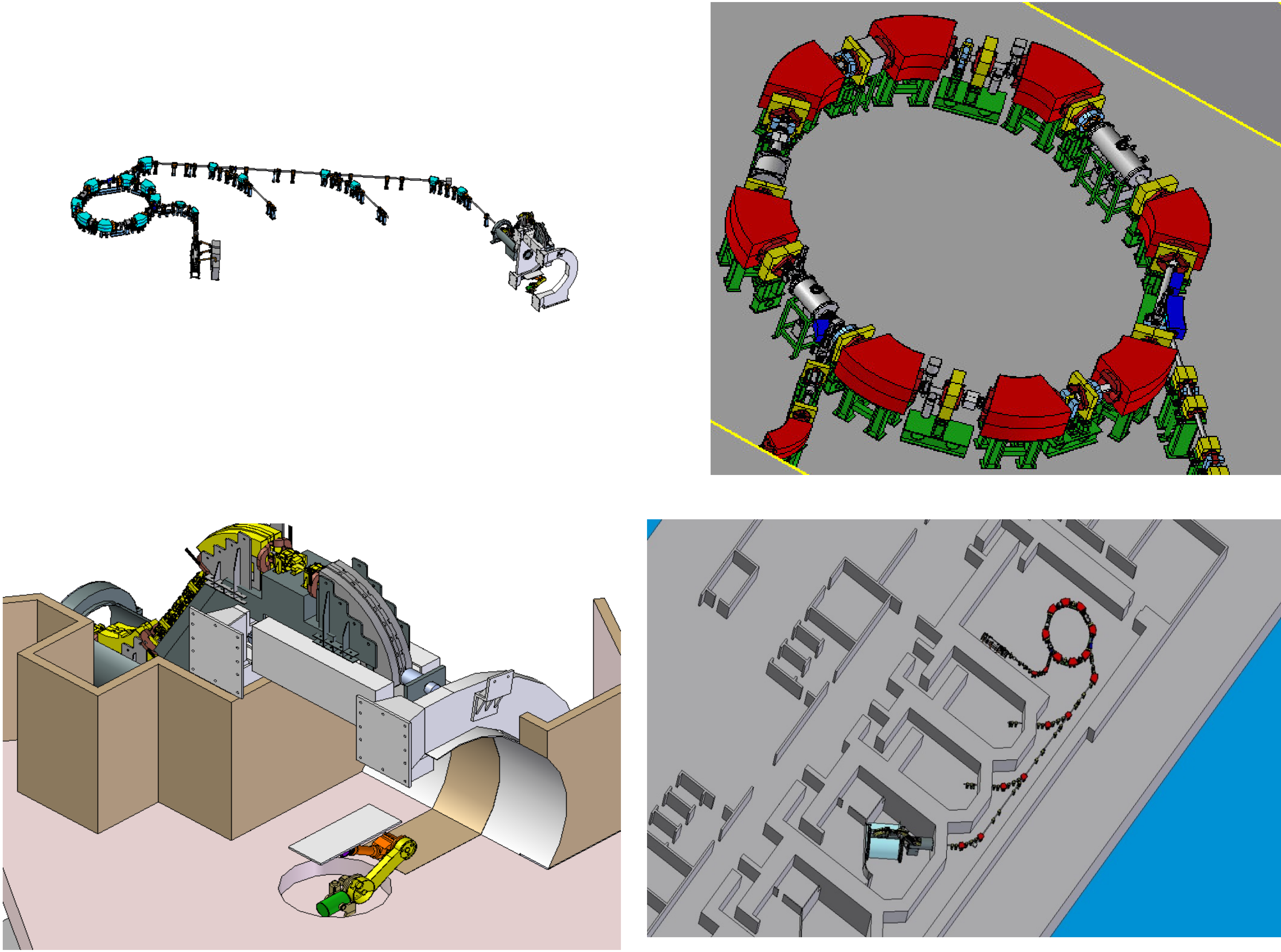
- **It will be completed in 2015.**

Specification of APTRON

- Particle accele.: Proton Synshroton
- Injection Energy: 7MeV RFQ+Linac
- Extraction energy: 70 MeV-250MeV
- Circuference: 24.6m
- Charge per pulse: $4\sim8\times10^{10}$
- Repetition: 0.1Hz - 0.67Hz
- Treatment Method: Spot Scanning
- Changed extraction energy： 100 steps in 60 MeV to 230 MeV.
- beam spill length: adjusted from 0.1 to ≥10 s.
- Treatment Field: 30cm x 30cm
- Nozzle: 1 Gantry + 1 Fixed + 1 Experimental.
- Isocentric 180^0 compact gantry coupled with robotic patient couch



Schematic Layout



Acknowledgement

Collaborations are very important for the successful completion of those projects . IHEP has received valuable supports from 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., without their help, it is impossible to made such great achievements. Here I would like to take this opportunity to express my sincere thanks to all our foreign friends who have helped us.

Summary

The achievement of China’s high energy accelerator described in the above 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 progresses.

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.

Let us join hands and work together to meet the new bright future of accelerator development in the next decades.

Thanks for your attention!