Introduction to the accelerator division

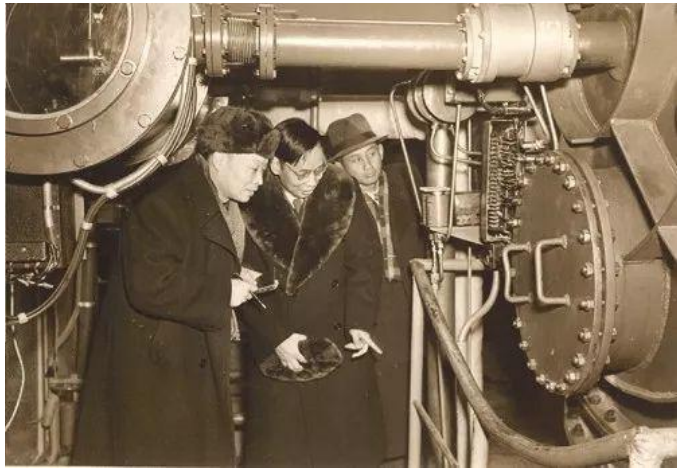
- History
- Team and research fields
- Large scale projects
- Abilities and vision
- International collaboration

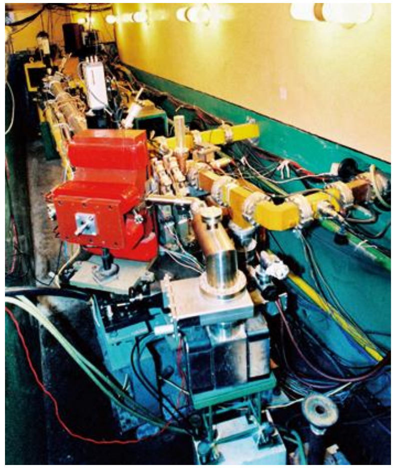
Ping He
Institute of High Energy Physics

2025-01-21

History of Accelerator Development

- **Chinese accelerator research was initiated by the patriotic scientists returning from oversea**
  - Prof. Zhongyao Zhao built 2.5MeV proton electrostatic accelerator in 1958, which played important roles in the nuclear physics;
  - In 1964, the research team led by Prof. Jialin Xie succeeded in developing a 30 MeV electron linear accelerator, knocking the door for the large-scale accelerator;
  - IHEP's history goes back to the early days of the People's Republic of China, when the Institute of Modern Physics was established in 1950. This was later renamed the Institute of Physics and then the Institute of Atomic Energy. IHEP itself began life as Division One of the Institute of Atomic Energy. After Premier Zhou Enlai highlighted high energy physics as a priority for the Chinese Academy of Sciences, IHEP was split off as a separate research institute, and officially established in February 1973. The first Director was Zhang Wenyu.
  - Since then, IHEP has grown from its humble beginnings to become one of China's biggest research institutes and a major player in the international particle physics community, as well as hosting experiments for fields from materials science to biology.





Research Groups and Staff

Accelerator Division

Group	Staff / Student
Acc. Physics	Staff: 31; student: 28
Linac	Staff: 19; student: 15
RF system	Staff: 21; student: 8
Superconducting Magnet	Staff: 11; student: 9
Magnet	Staff: 21; student: 2
Power Supply	Staff: 16; student: 1
Beam Diagnostics	Staff: 19; student: 9
Vacuum System	Staff: 14; student: 1
Control System	Staff: 17; student: 0
Mechanical System	Staff: 14; student: 1
Cryogenic System	Staff: 17; student: 5
Machine Operation	Staff: 21; student: 0
Alignment	Staff: 10; student: 0

Staff	Student
235	79

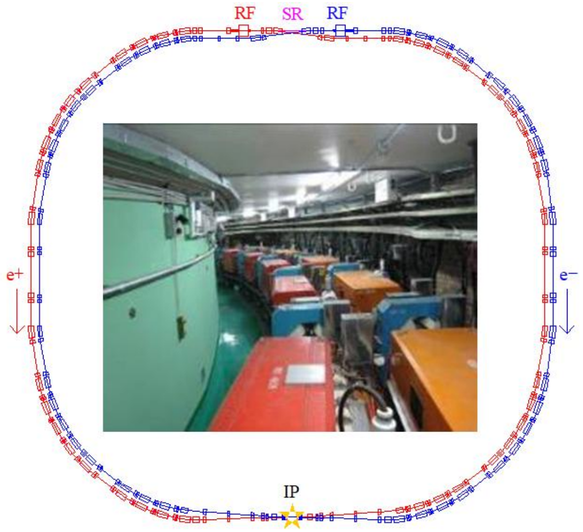
Guest Scientist/ Engineer	Post Doctor
4	11

One of the largest accelerator research centers in China and world wide

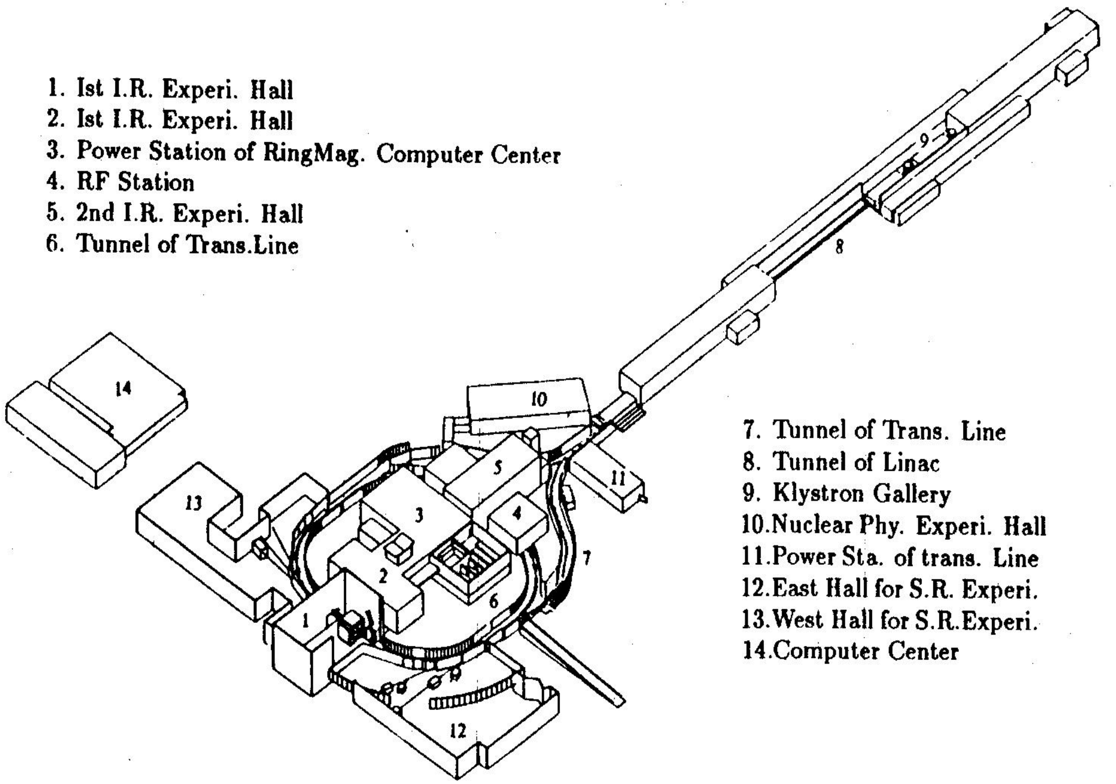
Switchable multi-operation modes in BEPC II

- **BEPCII**
  - Upgrade project of BEPC, operated since 2009
  - A double-ring factory-like collider
  - Collider & SR operation modes

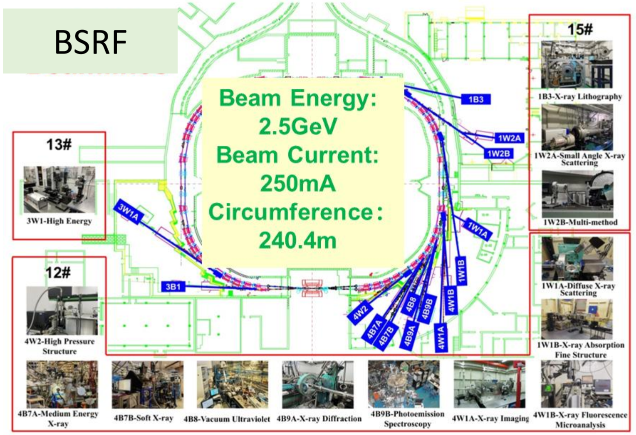
Main Parameters	Design
Energy (GeV)	1.89
Beam current (mA)	910
Bunch current (mA)	9.8
Bunch number	93
RF voltage	1.5
Beam-beam parameter	0.04
β_x^*/β_y^* (m)	1.0/0.015
Inj. Rate (mA/min)	$200\ e^- / 50\ e^+$
Lum. ($\times 10^{33} cm^{-2}s^{-1}$)	1.0



1. Ist I.R. Experi. Hall
2. Ist I.R. Experi. Hall
3. Power Station of RingMag. Computer Center
4. RF Station
5. 2nd I.R. Experi. Hall
6. Tunnel of Trans.Line



7. Tunnel of Trans. Line
8. Tunnel of Linac
9. Klystron Gallery
10. Nuclear Phy. Experi. Hall
11. Power Sta. of trans. Line
12. East Hall for S.R. Experi.
13. West Hall for S.R. Experi.
14. Computer Center



BEPCII performance enhancement

Major achievements in the past five years

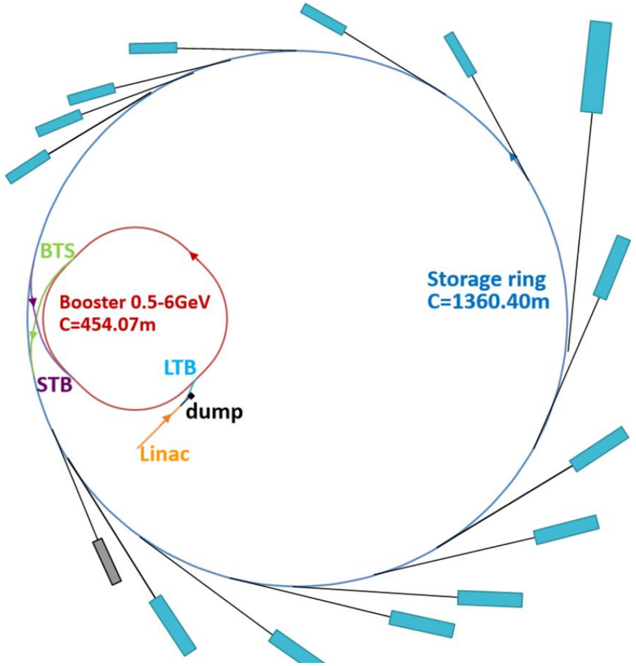
- Energy upgrade completed: Full energy injection and storage up to 2.472 GeV
- Top-up operation
- Stable high-luminosity operation: beam current exceeds 900mA with the instantaneous luminosity of $1.1\times10^{33}cm^{-2}s^{-1}$; In the last operation year, the accumulated luminosity reached as high as 5307 Pb^{-1}

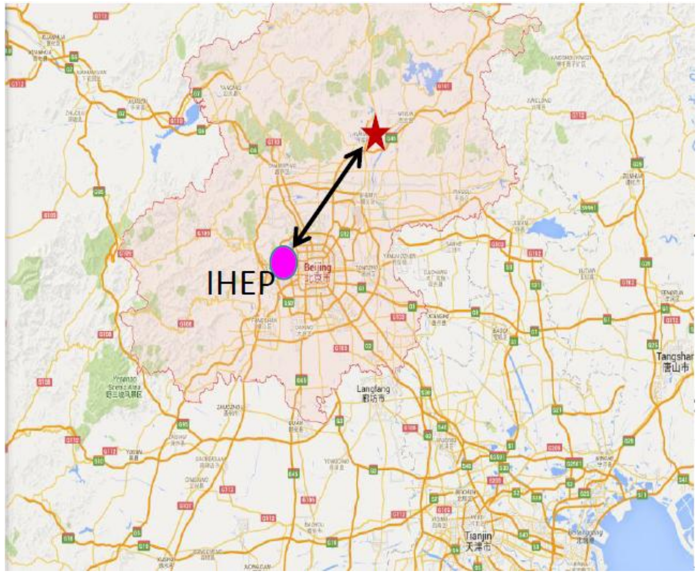
Significance

- Better knowledge on operating a high-current machine for high luminosity
- Better control over collective instabilities through feedback
- Invaluable experience for CEPC design and construction

HEPS: 4th generation light source

Main parameters	Unit	Value
Beam energy	GeV	6
Circumference	m	1360.4
Emittance	pm·rad	< 60
Brightness	phs/s/mm^2/mrad^2/0.1%BW	>1x10^{22}
Beam current	mA	200
Injection		Top-up





- Advanced 4th generation light source, promoting multi-disciplinary researches
- Accumulate conventional key technologies for CEPC

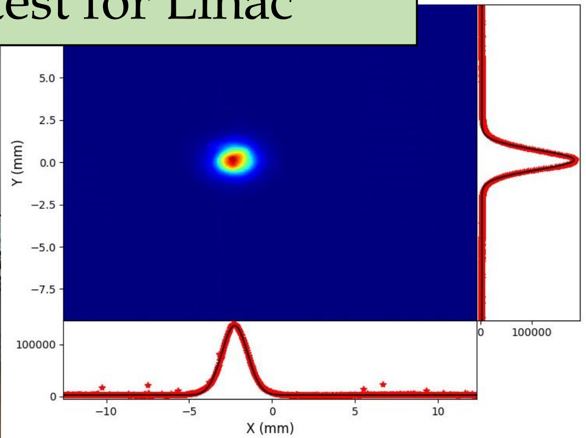
  – Magnet – Vacuum – Power supply – Beam instrumentation

  – Alignment – Control – Mechanical system – Linac complex

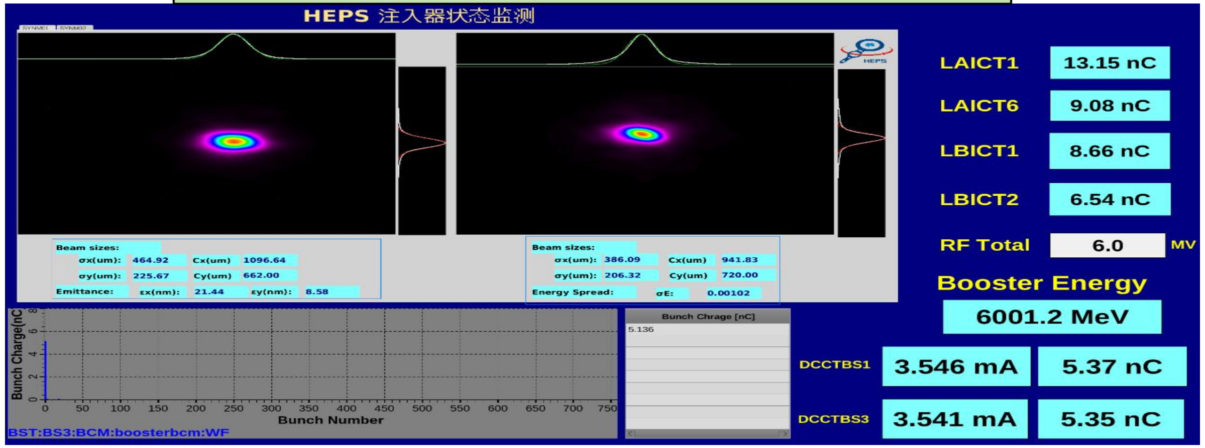
HEPS Progress

- Linac & Booster commissioning completed and passed the acceptation test
  - Boost alone is already the longest accelerator ring in main land China (circumference of 454m), with the highest electron-beam energy (6GeV), and the largest bunch charge
- Storage ring start commissioning on July 23 and got first SR light from ID on Oct.12.

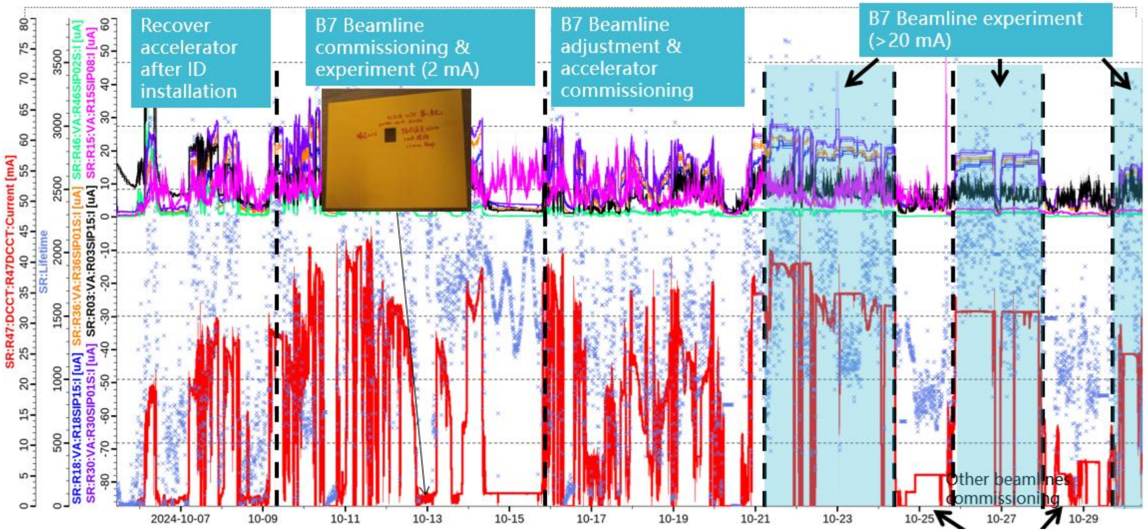
Acceptance test for Linac



Booster commissioning

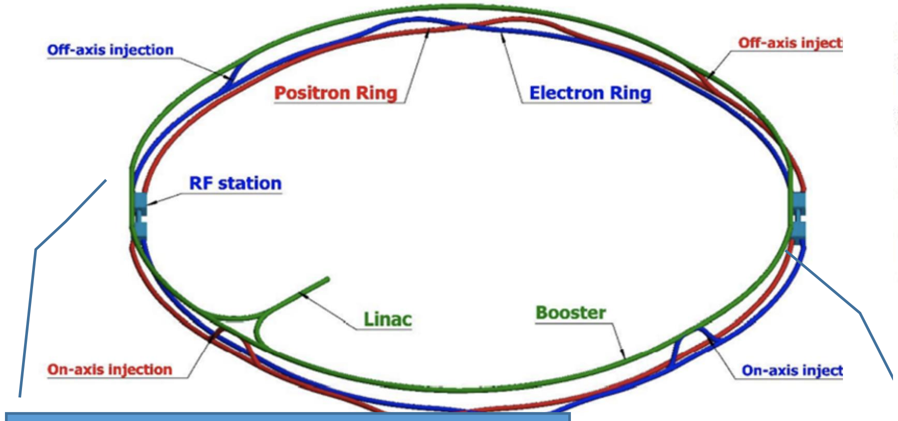


Storage ring commissioning

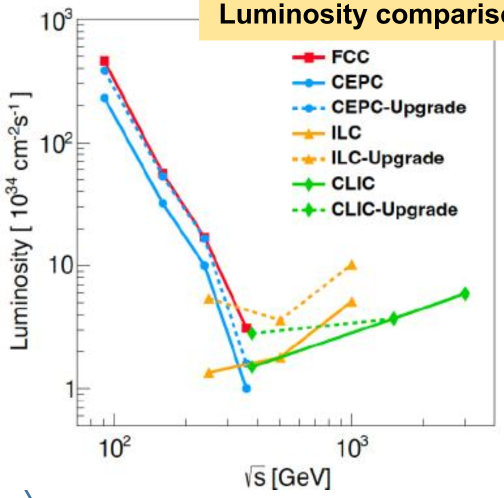


CEPC: Higgs factory

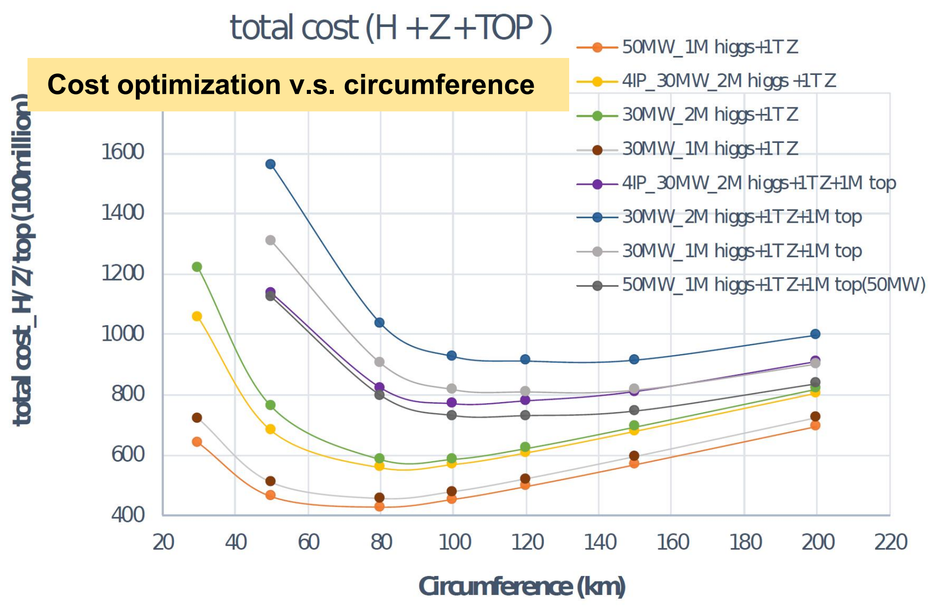
- **Circular collider**: Higher luminosity than a linear collider
- **100km circumference**: Optimum total cost
- **Shared tunnel**: Accommodate CEPC booster &collider and SppC
- **Switchable operation**: Higgs, W/Z, top



Luminosity comparison



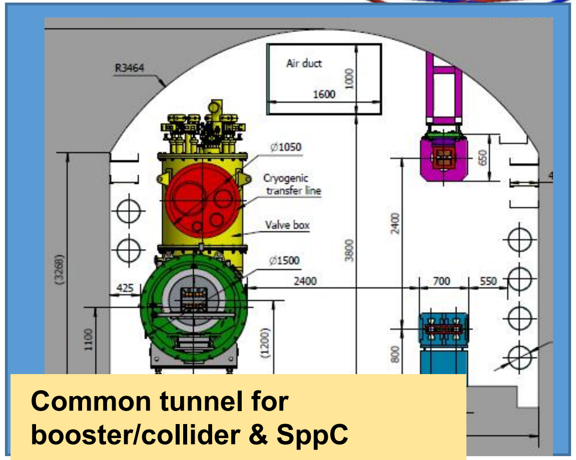
Cost optimization v.s. circumference



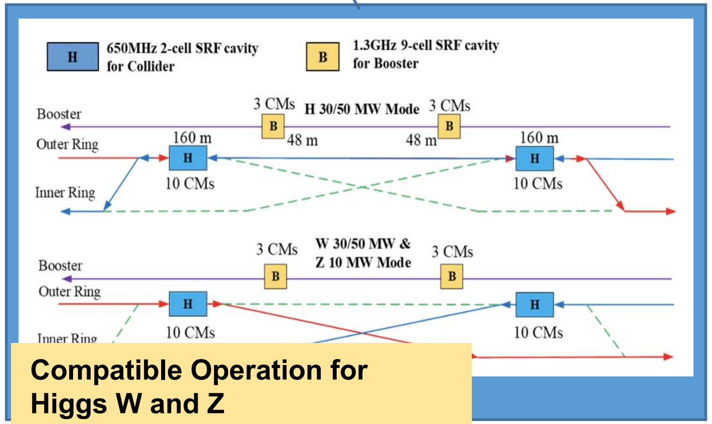
D. Wang *et al* 2022 *JINST* **17** P10018

Main Parameters: High luminosity as a Higgs Factory

	Higgs	W	Z	ttbar
Number of IPs	2			
Circumference [km]	100.0			
SR power per beam [MW]	**50**			
Energy [GeV]	**120**	**80**	**45.5**	**180**
Bunch number	415	2161	19918	59
Emittance ($\varepsilon x/\varepsilon y$) [nm/pm]	0.64/1.3	0.87/1.7	0.27/1.4	1.4/4.7
Beam size at IP ($\sigma x/\sigma y$) [um/nm]	15/36	13/42	6/35	39/113
Bunch length (SR/total) [mm]	2.3/3.9	2.5/4.9	2.5/8.7	2.2/2.9
Beam-beam parameters ($\xi x/\xi y$)	0.015/0.11	0.012/0.113	0.004/0.127	0.071/0.1
RF frequency [MHz]	650			
Luminosity per IP[10^{34}/cm²/s]	**8.3**	**27**	**192**	**0.83**



Common tunnel for booster/collider & SppC



Compatible Operation for Higgs W and Z

CEPC TDR international review and formal release

- **International TDR reviews**
  - ◆ 2023 June 12-16 : technical review; June 26: civil cost domestic review; September 11-15 : cost review
  - ◆ 2023 October: CEPC International Advisory Committee meeting

June 12-16, 2023, in HKUST-IAS, Hong Kong — Chaired by Frank Zimmermann

Phase 1 CEPC TDR Review Report

CEPC TDR Technical Review Committee

15 July 2023

The CEPC Study Group, hosted by the Institute of High Energy Physics (IHEP), has been working on the design and development of a forefront e^+e^- collider as a Higgs factory that can extend to energies corresponding to the Z, WW and the top-quark pairs, with the upgrade potential to a high-energy pp collider. The CEPC represents a "grand plan" proposed, studied, and to be constructed by Chinese scientists in close collaboration with international partners. Since the release of the CEPC Conceptual Design Report in 2018, the CEPC Study Group has devoted significant effort to the design optimisation, the R&D of key technologies and the study of the technical systems of the CEPC.

The CEPC Study Group has produced a draft Technical Design Report (TDR). The International Review Committee, chaired by Dr. Frank Zimmermann (CERN), was asked to conduct a first phase review of this TDR draft. This first phase review shall cover all but the cost and site aspects of the CEPC.

The Phase 1 CEPC TDR Review Committee meeting was held in person at HKUST from 12 to 16 June 2023.

Sept. 11-15, 2023, in HKUST-IAS, Hong Kong — Chaired by Loinid Rivkin

CEPC Accelerator TDR Cost Review

The CEPC Accelerator TDR Cost Review committee examined the cost estimate of the TDR of accelerator systems for the first stage of the CEPC project operated as a Higgs factory with synchrotron radiation power up to 30 MW per beam (including all infrastructure that is not easily upgradeable and is already designed to operate up to the ttbar energy and at 50 MW). The cost estimate under review does not include the civil engineering, the detectors at the IPs with their technical services, and the central computing services.

In the opinion of the committee the cost estimate presented is sufficiently complete to form a proper basis for the next iteration that will be done during the EDR stage.

Oct. 30-31, 2023, in IHEP — Chaired by Brian Foster

The Ninth Meeting of the CEPC-SppC International Advisory Committee

IAC Committee

M. E. Biagini, Y.-H. Chang, A. Cohen,
M. Davier, M. Demarteau, B. Foster (Chair),
B. Heinemann, K. Jakobs, L. Linssen,
L. Maiani, M.L. Mangano, T. Nakada, S. Stapnes,
G. N. Taylor, A. Yamamoto, H. Zhao

IHEP-CEPC-DR-2023-01
IHEP-AC-2023-01

CEPC

Technical Design Report

Accelerator

arXiv: 2312.14363

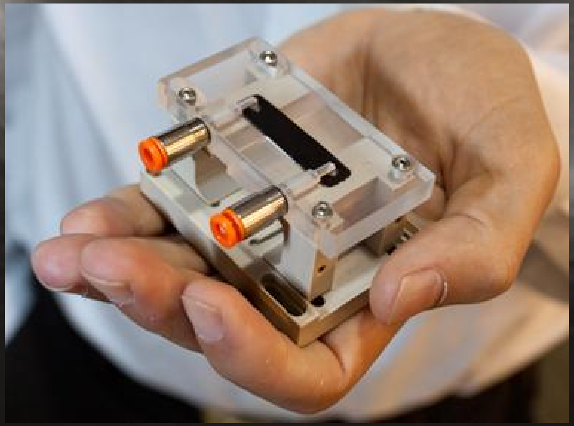
The CEPC Study Group
December 2023

CEPC TDR - Accelerator formally released on 25. Dec. 2023

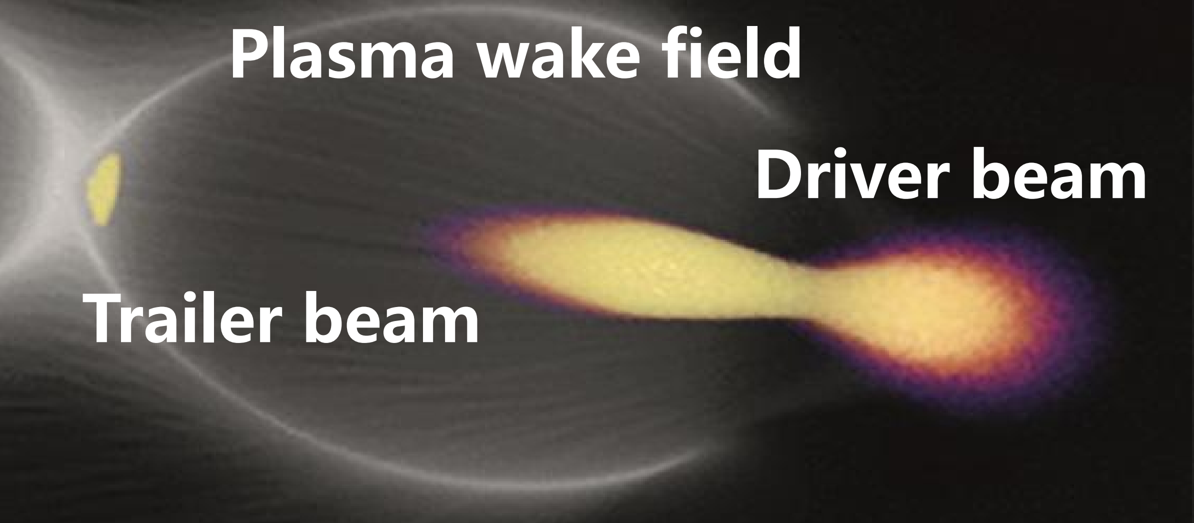
Significance of Plasma wake field acceleration

- **High gradient:** ~10-100GV/m, ~**1000times higher than conventional Acc.**
- **High energy conversion rate**
- **High repetition rate possibility**
- **Focus on PWFA acceleration**

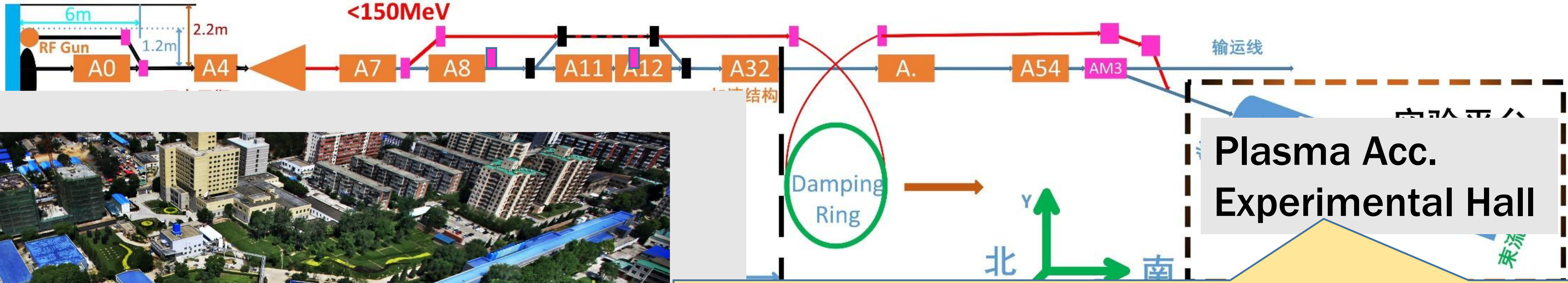
Conventional linac

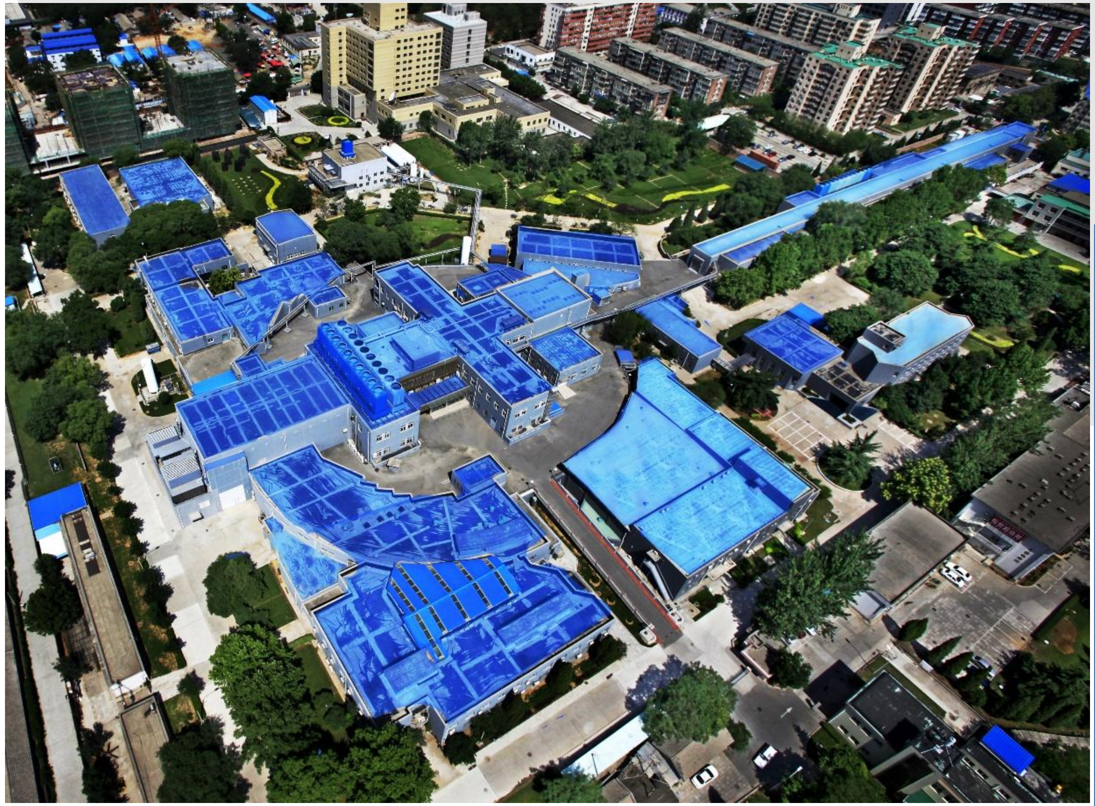


1GeV accelerator in hand



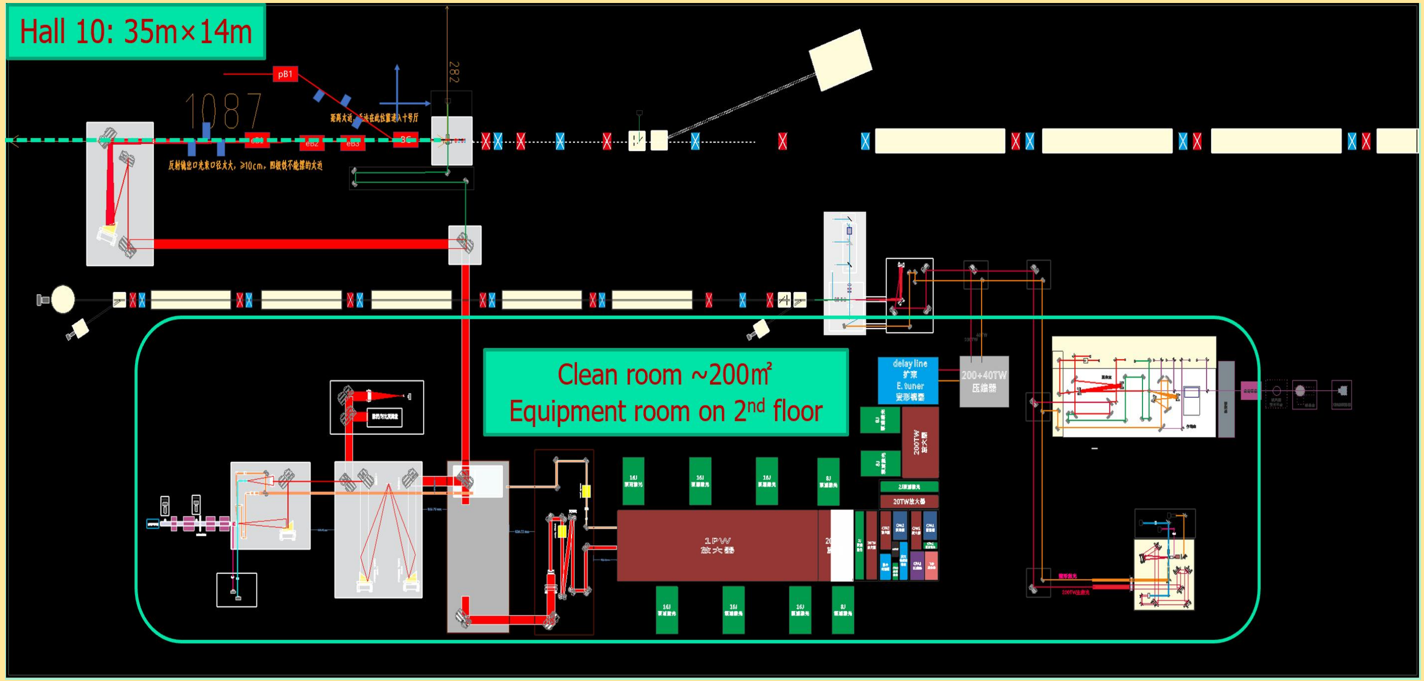
Test facility to be built at BEPCII





2.5 GeV e-/e+ beamline + PW-level high performance laser system

Plasma Acc. Experimental Hall



Accelerator Physics

Research Field	Collider	SR
Lattice Design & Optimization	✓	✓
Optics measurement & error correction	✓	✓
Collective Instability	✓	✓
Injection/Extraction schemes	✓	✓
AI application (design, commissioning, error mitigation, …)	✓	✓
Machine protection	✓	✓
Beam-beam effect	✓	
MDI research: final focus, background radiation, …	✓	
Polarization	✓	
Insertion device impact and mitigation		✓

- **Special emphasis on Plasma acceleration**
  - laser/beam driven plasma acceleration;
  - positron acceleration, cascaded acceleration for >10 GeV, high bunch charge, …
  - simulations as well as experiment study

Accelerator Physics

Research on COLLIDER	Future planning
Advanced collider performance improvement	Participate the collaboration with SuperKEKB, BEPCII Study
Lattice design for future collider	Novel concept (strong nonlinear effect & SR) & machine learning
Error correction and luminosity tuning	Explore new methods
Collider Modeling and software development	A team is funded +PIFI collaborations
New phenomenon under multi-dynamics impact	Joint research, simulations & analysis, wide collaborations

Research on Light Source	Future planning
HEPS Commissioning and operation	Software package R&D for beam tuning, feedback tuning, experiment of current dependent effects, injection/extraction efficiency, optical beam based alignment, insertion device impact and mitigation
Beam dynamics frontier	Numerical study for nonlinear effect, novel injection scheme, beam dynamics with multi-RF frequency, Measurement & correction based on TBT data
Machine learning and cross-discipline research	Fast problem identification, error mitigation, feedback, …
Phase space manipulation with electro-optical tuning	Use reference of Laser or FEL tuning methods, enhanced SR
Novel insertion device	SCU, ultra-short period UND,…

Magnet and insertion device

- **High performance Magnet**

  - High gradient QUAD: >= 104T/m

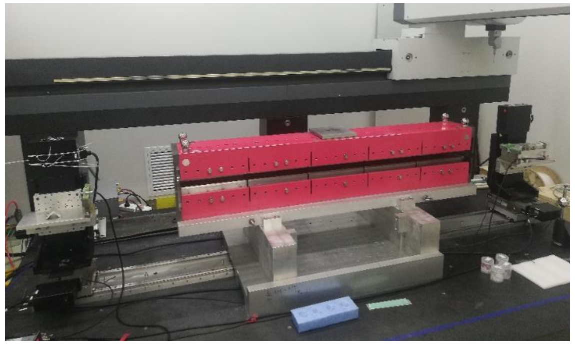
  - Longitudinal gradient variable permanent magnet Dipole, field accuracy better than 5×10^{-5}

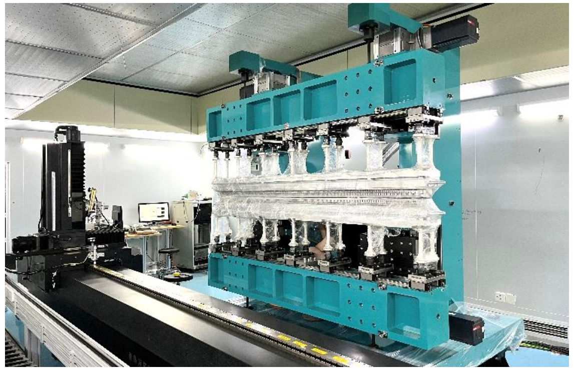
- **Magnet measurement**

  - Alignment system based on Coordinate Measurement Machine, offset error smaller than 10μm, angular error smaller than 0.03mrad

- **Insertion device**

  - Cryogenic Permanent Magnet Undulator, CPMU
  - In-vaccum Undulator with 4-m length
  - Apple-Knot undulator with variable polarizations
  - Mango wiggler, innovative device
  - Superconducting Wiggler and Undulators

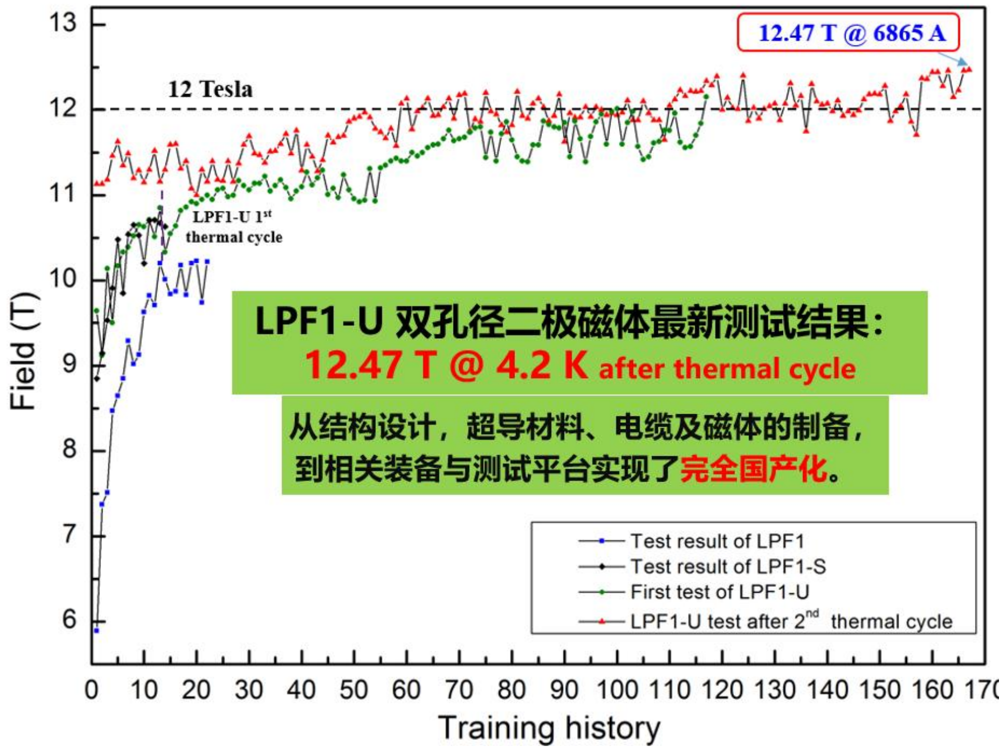


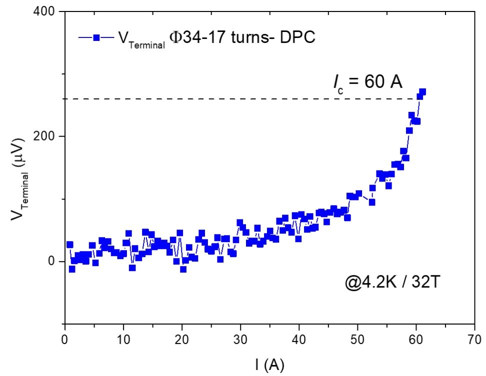


Superconducting Magnet

- Superconducting dipole reaches the field of 12.47T@4.2K, NbTi&Nb3Sn combined coils
- Aiming at 16T dipole
- Novel SC magnets

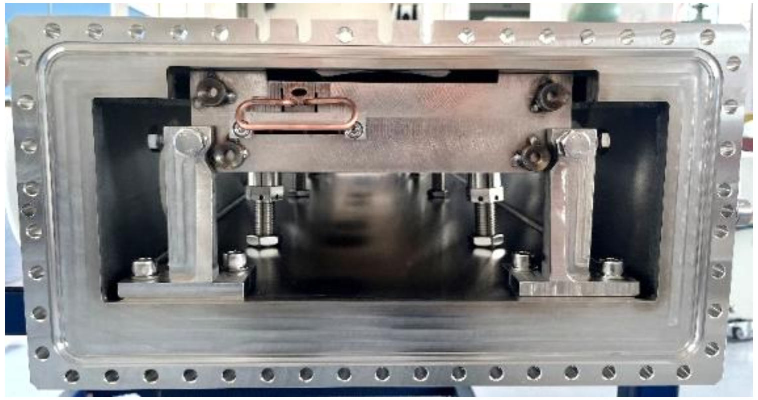
  - Iron Based HTS and applications； - CCT magnet (Dipole, Quadrupole,…)； - HTS cables
- Al- stabilized HTS cables and large size solenoid





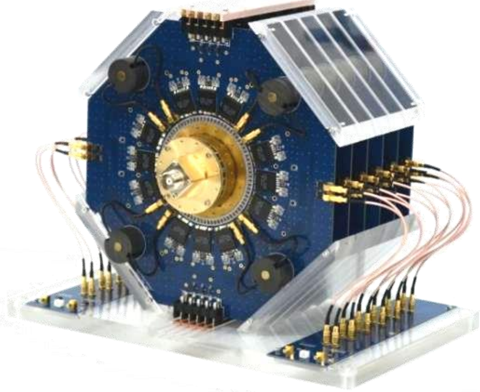
Magnet power supply

- High stable & accurate power supply
  - Sensor - Digital signal and feedback
- topological structure of power electronic circuits
- Maturity for mass production and application to large scale Acc. facilities
- Lambertson septum and various fast-kicks
  - invacuum/half invacuum LSM, slotted-pipe kicker, strip line kicker, delay-line kicker, ferrite kicker, …
- Short pulse generator: 1μs-10ns; different pulse shapes



2mm Lambertson

5cell-Strip-line kicker

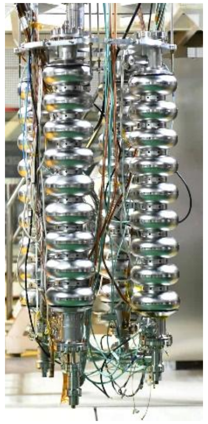


10ns DSRD pulser

Magnet power supply

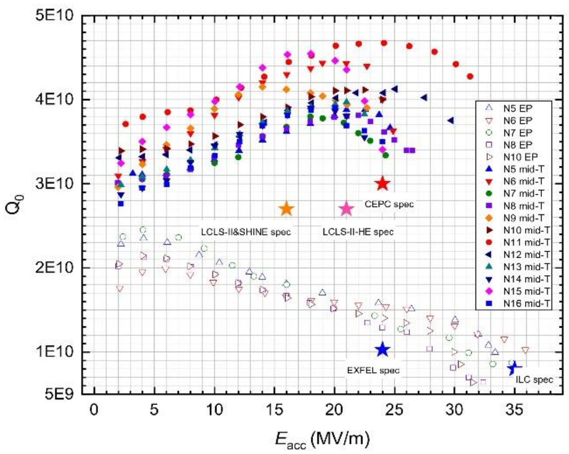
Superconducting RF system

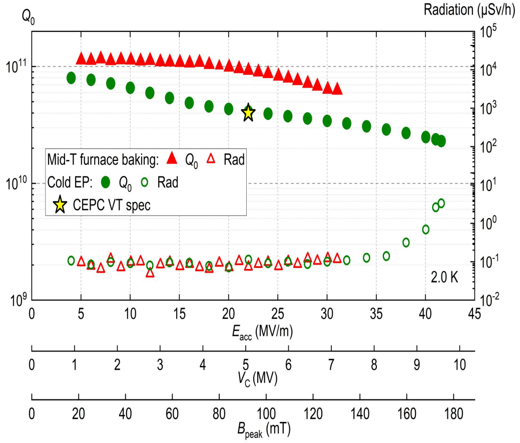
Cavity Category	Status	Leading performance world wide
1.3 GHz 9-cell	4.7E10@24 MV/m (max Q@mid-Eacc) 4.3E10@31 MV/m (max Q@high-Eacc) 1.0E10@36 MV/m (max Eacc)	4.2E10@24 MV/m (max Q@mid-Eacc, FNAL&JLAB) 3.0E10@31 MV/m (max Q@high-Eacc, JLAB) 1.1E10@45 MV/m (max Eacc, DESY)
650 MHz 1-cell	8E10@25 MV/m (max Q@mid-Eacc) 6.3E10@31 MV/m (max Q@high-Eacc) 2.5E10@41.6 MV/m (max Eacc)	6.0E10@25 MV/m (max Q@mid-Eacc, FNAL) 4.5E10@30 MV/m (max Q@high-Eacc, FNAL) 1.0E10@35 MV/m (max Eacc, FNAL)



1.3GHz 9-cell, spoke, 166MHz QWR, 500MHz

Vertical test reach the state of the art level





Vertical test results of 1.3GHz 9-cell and 650MHz 1-cell

SRF cryo-module horizontal test results

- 650 MHz test cryomodules including cavities, couplers, HOM absorbers, tuners..., was built and tested OK
- A full eight 1.3 GHz 9-cell cavities with input couplers, tuners, SC magnet, BPM, cryostat, module cart, feed/end-cap, volve-box … was built and tested OK

Parameters	Horizontal test results	CEPC Booster Higgs	LCLS-II, SHINE	LCLS-II-HE
Average Q_0 @ 21.8 MV/m	3.6×10^{10}	3.0×10^{10} @ 21.8 MV/m	2.7×10^{10} @ 16 MV/m	2.7×10^{10} @ 20.8 MV/m
Average CW E_{acc} (MV/m)	23.1			

650MHz 2-cell

1.3GHz 9-cell

1.3GHz 9-cell

166MHz QW

Superconducting RF system

Reseach Goal: Provide advanced schemes and technologies for future accelerators

Aiming at SRF cutting-edge technologies , focusing on the applications in Collider, SR, FEL, Proton Linac, emphasizing on high-performance cavity and complete module R&D, seeking new material and concept breakthroughs.

1. SC physics Frontier: RF critical magnet field, flux dynamics, field emission, secondary electron multiplication, surface resistance, nano-tech., HTS
2. Material frontier: Nb thermal treatment, Nb coating, Nb_3Sn, IBS, travel-wave cavity, dual-aperture cavity
3. Gradient frontier: EP Nb 45MV/m (ILC&CEPC) → Novel structure 70MV/m →Nb_3Sn 100MV/m →IBS 200MV/m
4. High Q frontier: 1.3G Nb cavity 3E10@45MV/m@2K,Nb_3Sn 1.3G 2E10@25MV/m@4.2K→2E10@100MV/m
5. System frontier: High power coupler, HOM, fast detune, LLRF → complex design, assembly, stable operation
6. Cross disciplinary frontier: Dark matter axion detector, Helium free accelerator (Nb_3Sn)

Cryogenic System

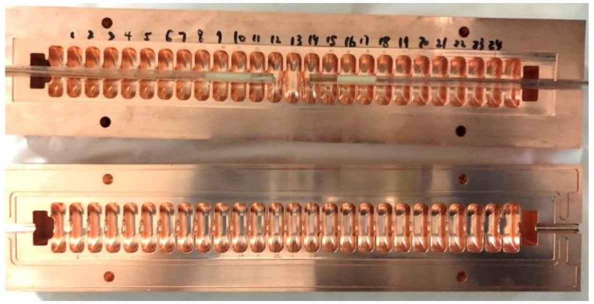
Orientation: Provide advanced cryogenic system for SRF and SC magnet

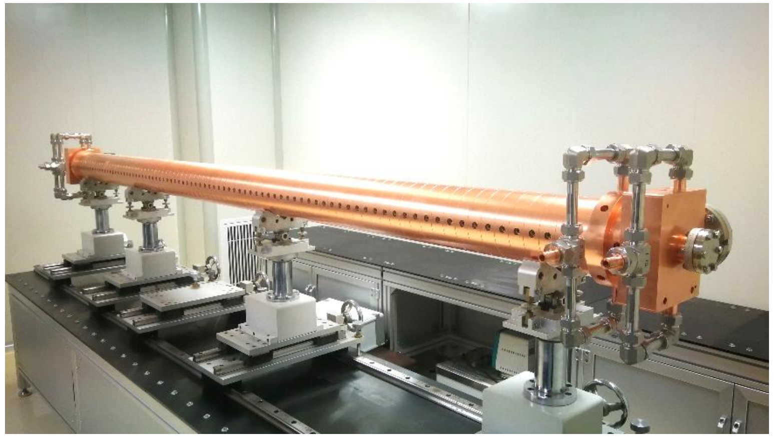
- SRF cavity and SR magnet cooling technology
  - Design and build 4K & 2K super-fluid liquid helium system
- Key technology for large-scale cryogenic system
  - Cryostat design & assembly, system key components, fluid distribution
- Cryogenic system Control
  - error diagnostics, stable running,
- Helium recycling & purification, 2K thermal exchanger




Advance accelerator key technologies

- **High efficiency klystron**
  - 650 MHz CW klystron, MBK, aiming at 75-80% transfer efficiency
  - S band high power klystron
- **Solid State Modulator and PSM high voltage power supply**
  - 320kV/50MW pulsed transformer, applied in HEPS linac
  - 130kV/16A PSM high voltage power supply
- **Advanced copper accelerator structure**
  - S band travel accelerator, C-band, X-band accelerator
  - Cool copper accelerator
- **Electron / Positron source**
  - Thermal cathode gun, photon cathode DC gun 5.2mA current
  - Positron source, magnetic concentrator

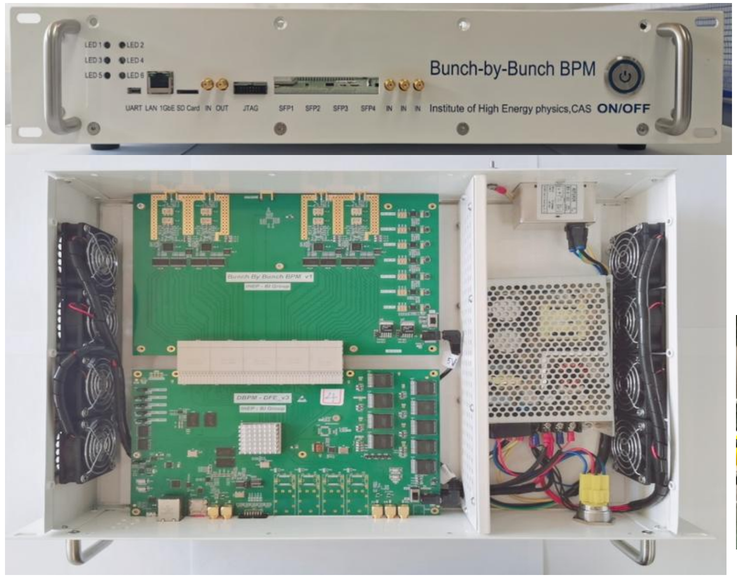




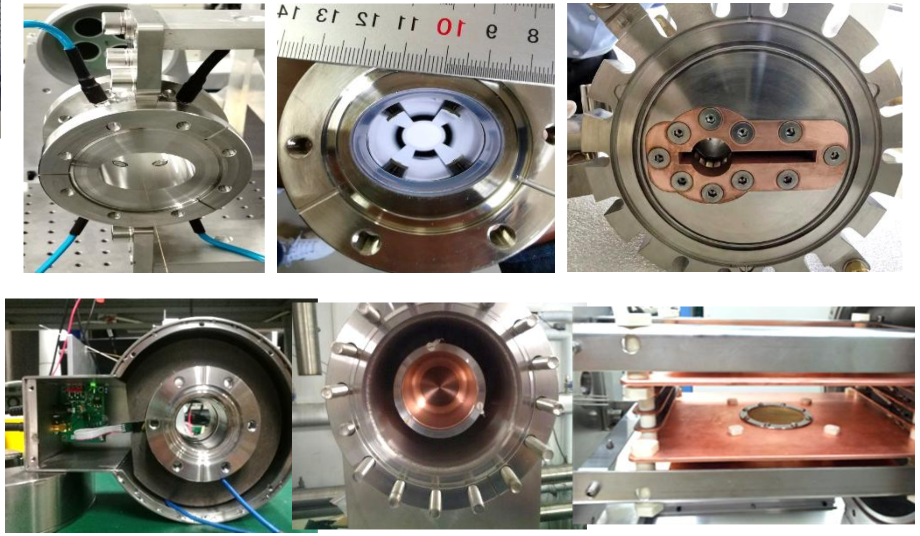
Beam diagnostics

- Rich experience for electron and proton beams diagnostics
- Comprehensive researches towards: detector, data acquisition, FB control, data analysis,
- Advanced BPM applies to BEPCII, HEPS,…
- One of the best research teams in China

BPM mass production and application



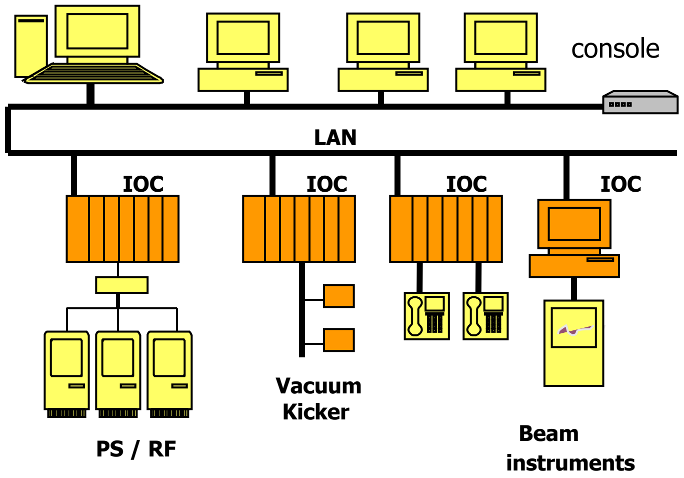
Bunch by bunch measurement and processor

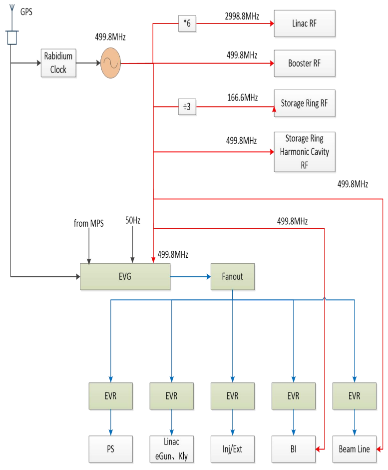


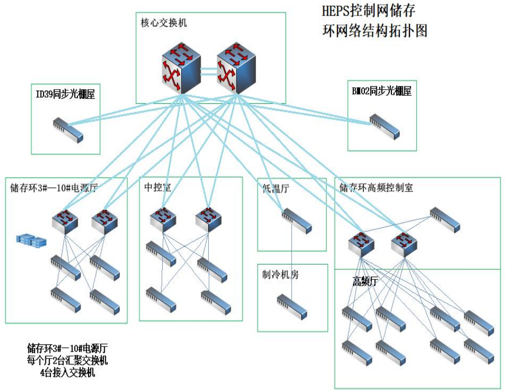
In-house study for beam current monitor

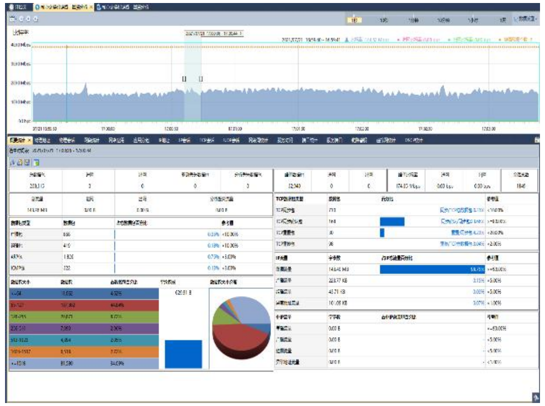
Control System

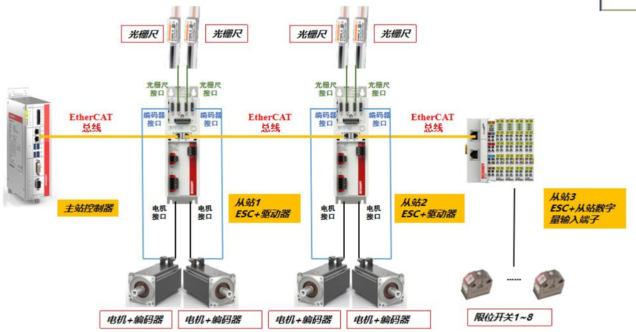
- **Control system for large-scale accelerators**
  - EPICS based system
- **Timing system & synchronization**
  - success in Event Receiver R&D
- **Data collection & Control in front-end equipment**
  - FPGA and SoC based controller and applications in BEPCII power supply, HEPS MPS
- **High precision motion control**
  - sub micron movement stage
- **Large volume data storage and fast search**
  - database by EPICS, support web, client search
- **Fast internet networks and security**
  - topologic for accelerator, low time delay, high speed, fireworks
- **Machine protection system and interlock**
  - personnel safety protection, machine protection











Vacuum System

- **Extreme vacuum level in large-scale accelerator complex, sophistic structures**

  - leakage detection, operation failure,
- **Coating technologies for multi-applications**

  - TiN, NEG;
- **Key components design/fabrication for complexed system**

  - special shaped chamber, shielding bellow, photon absorber
- **Simulations for the complexed system design (SYNRad, Molflow)**

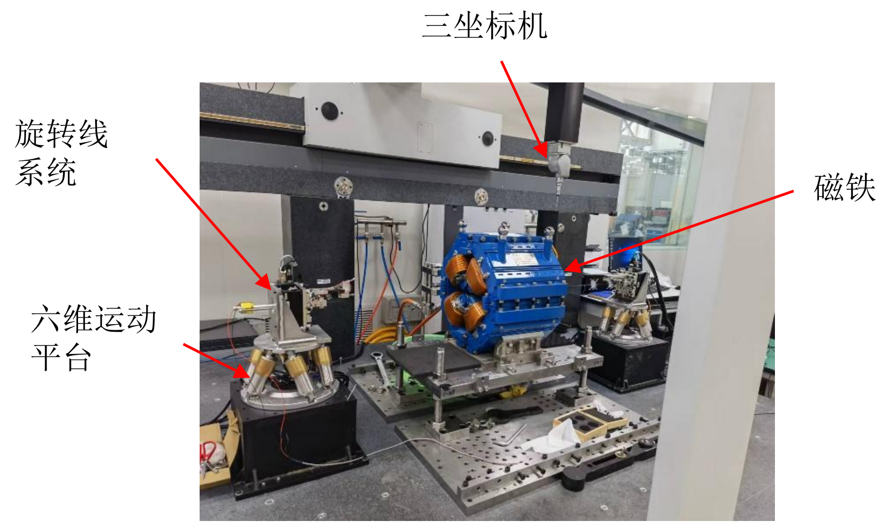
BEPC-II

NEG coating

HEPS_VA Chamber

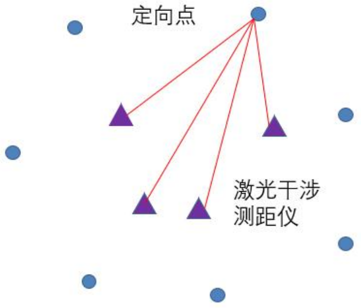
Alignment group

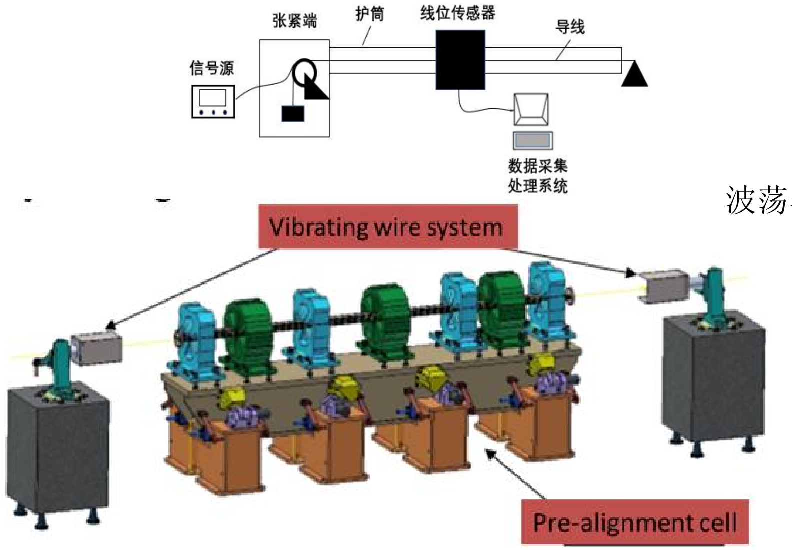
- **Magnet center measurement and calibration**
  - rotary coil alignment: measurement accuracy better than 8 microns, calibration better than 15 μm
  - laser fiducial alignment: for undulator magnet center calibration
- **Pre-alignment system**
  - vibration string alignment, accuracy better than 8 microns
  - relative alignment better than 20 microns
- **Wide space alignment**
  - Setup alignment network

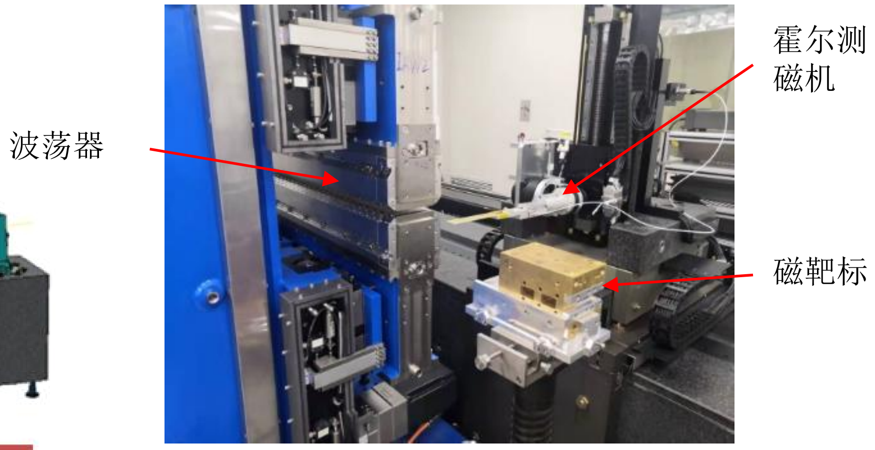


$$(S_{ij}+\Delta S_{ij})^2=(x_j-x_i)^2+(y_j-y_i)^2+(z_j-z_i)^2$$

$$V=A\delta X-l$$







Efforts on green accelerator

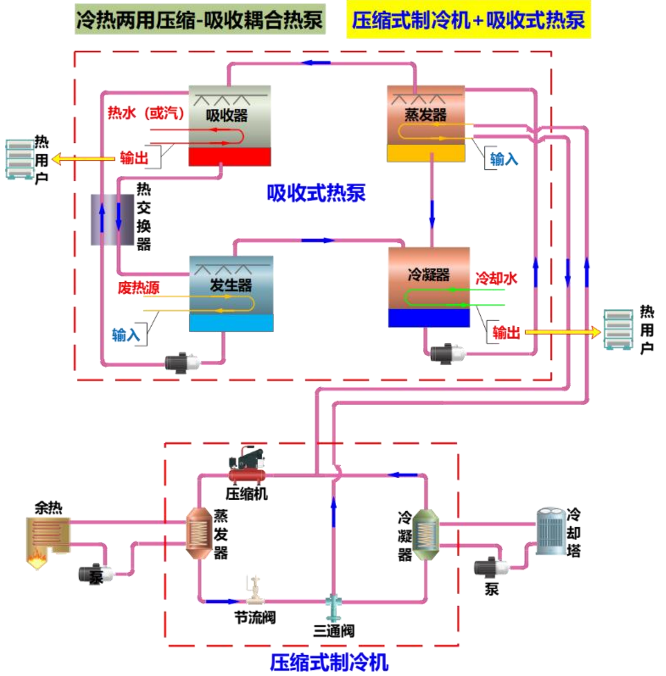
● Measures at HEPS

- Solar panel on roof: 10 MW ➔ 10% saving
- Permanent-magnet dipole @ storage ring: 5.6M kWh saving/yr
- Energy recovery from cooling water (13 MW@42oC) : Exceeds HEPS heating requirement

Solar panel on the roof of HEPS

● R&D for CEPC

- High Q SRF cavity: reduce 10MW operation power in a comprehensive evaluation, saving electricity consumption ~60M kWh per-year
- R&D effort for High efficiency & Energy recovery klystron: improve the efficiency from the conventional value (55%) the high efficiency of 80%, CEPC will save 160M kWh electricity per-year
- Proposal and R&D for "heating-cooling" switchable waste energy recovery system, and increasing the re-use of energy in the cooling water
- R&D and prototypes for dual-aperture magnets with a common coil



International Collaborations

1st C

- Collaboration with the world leading accelerator facilities
  - International advisory and review
  - Synergy on accelerator design, key technology R&D, mass production
  - beam commissioning and machine operation

CEPC TDR review meeting, 2023


CEPC CDR released, 2018

Let’s work together for

Higher

- Energy
- Luminosity / brightness
- Current