HEPS Accelerator Status

Ping HE

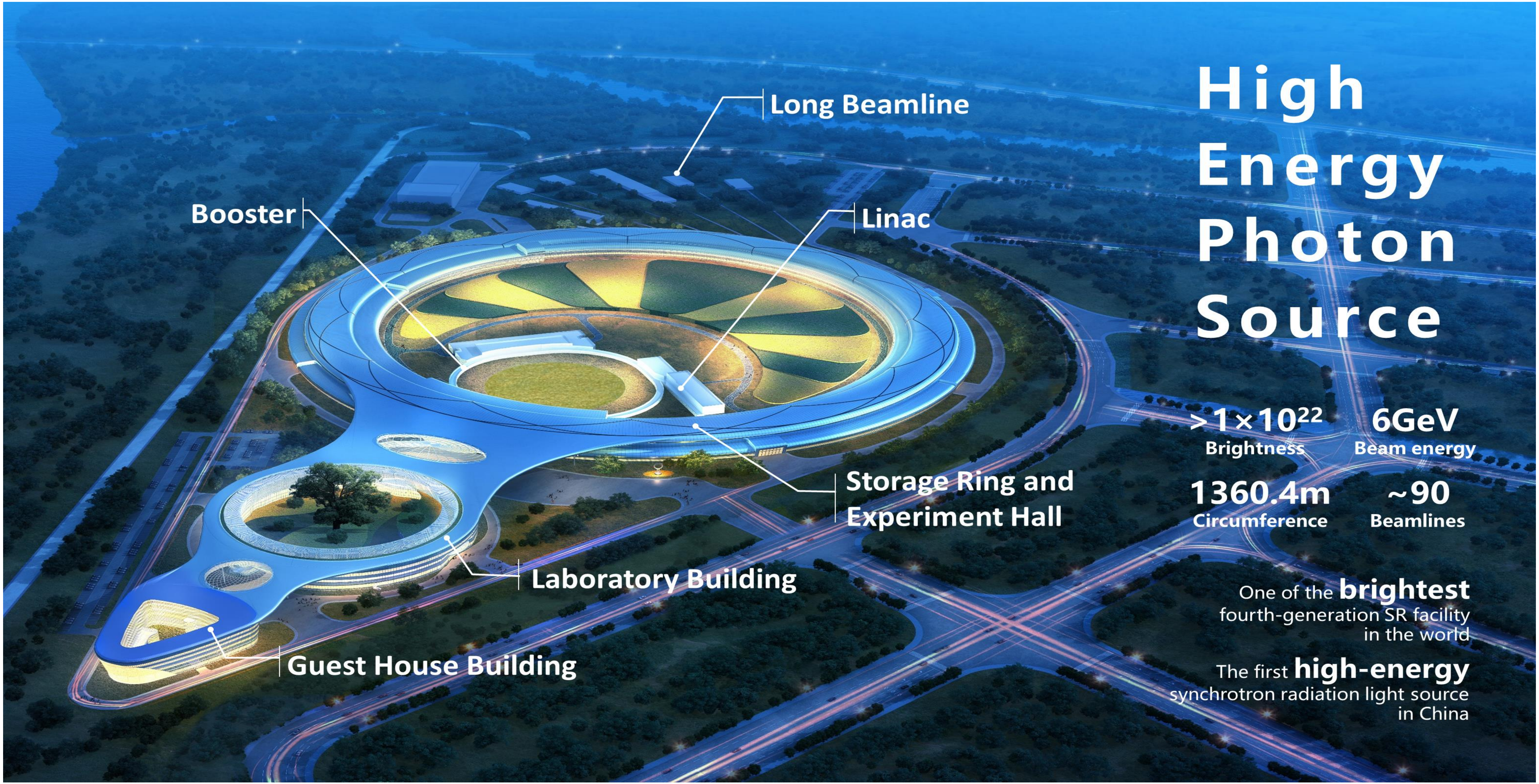
Accelerator Division

Sep. 21, 2023

Outline

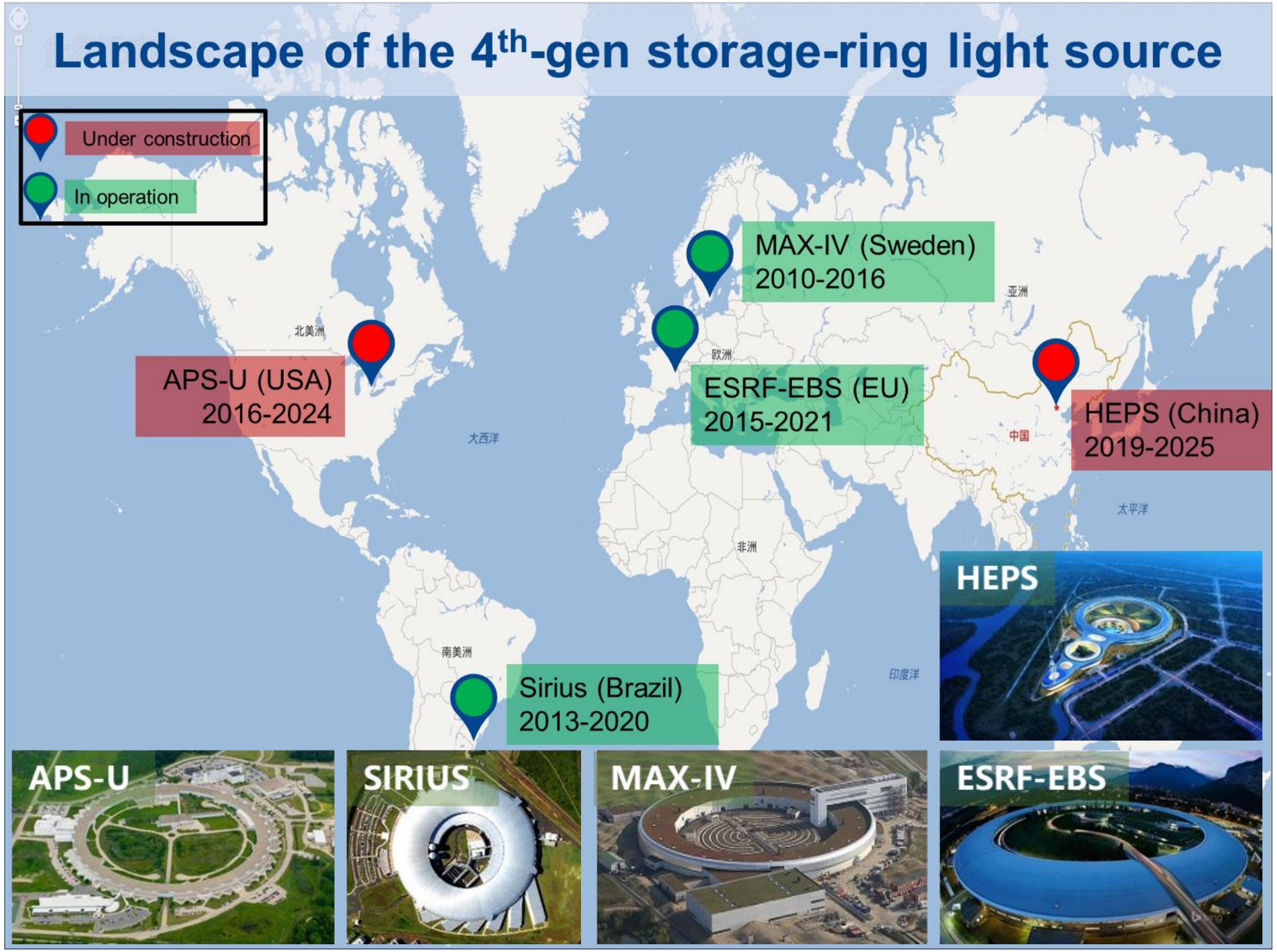
- Brief introduction on HEPS
- Schedule & Main milestones
- Accelerator progresses since Jan. 2020
- Summary

Overview of HEPS



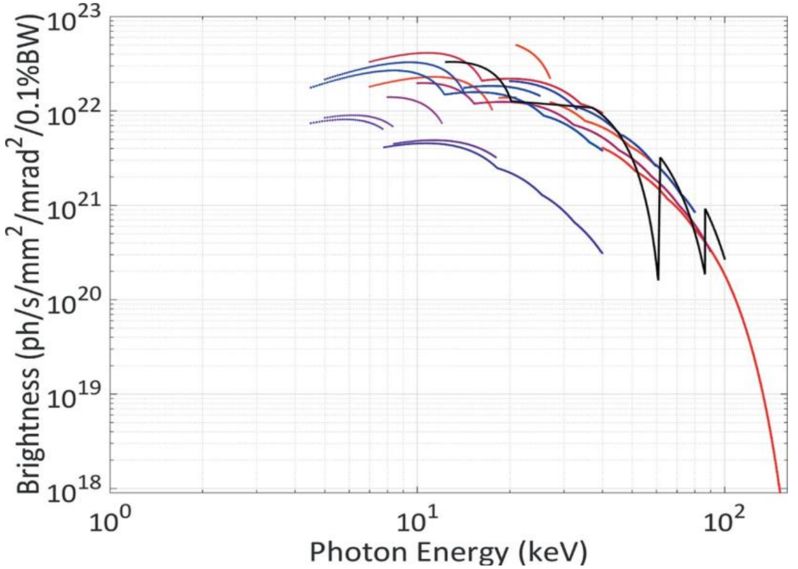
HEPS: a 4th-gen high-energy synchrotron LS

- One of the brightest fourth-generation synchrotron radiation facilities in the world



Main Parameters	Design goals	Unit
Beam energy	6	GeV
Circumference	1360.4	m
Hori. natural emittance	<60	pm·rad
Brightness	$>1\times10^{22}$	BU
Beam current	200	mA
Injection mode	Top-up	-

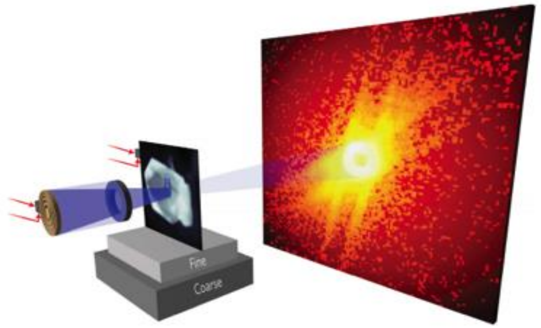
BU: phs/s/mm²/mrad²/0.1%BW

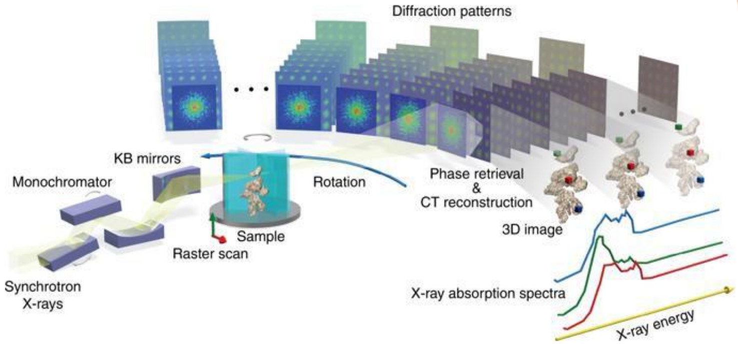


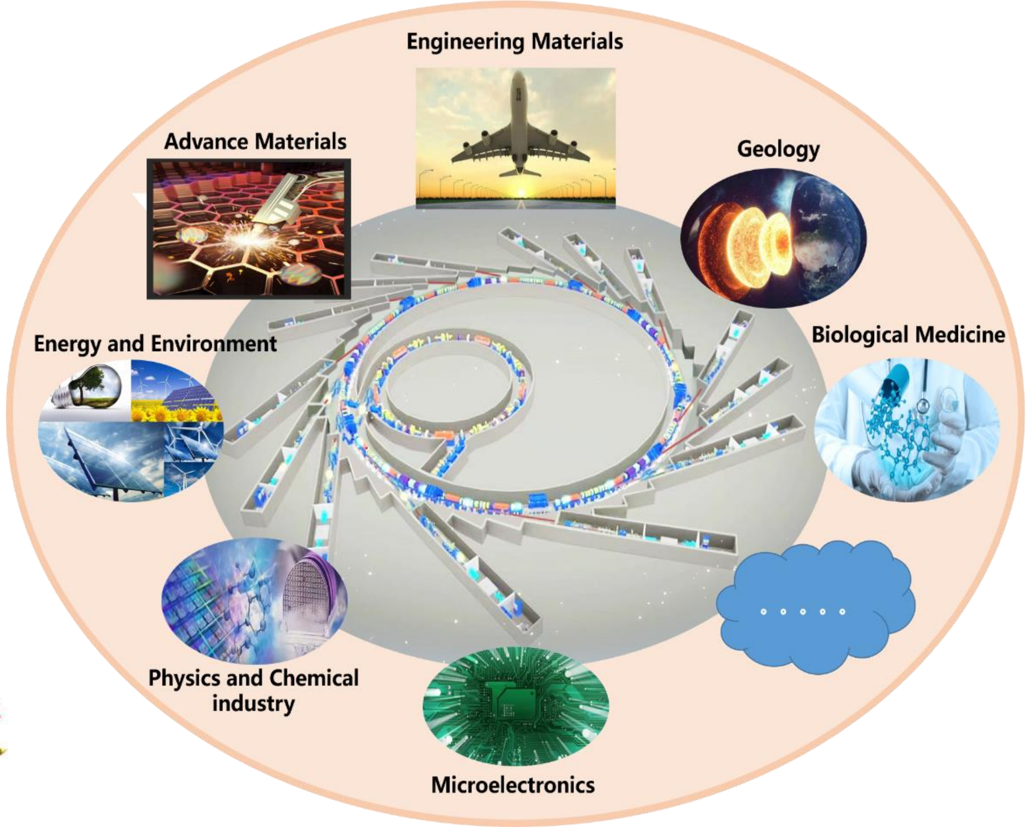
HEPS: a powerful light source

HEPS will provide **high-energy, high-brilliance, high-coherence** synchrotron **light with energies up to 300 keV and more**, with the capability for **nm spatial resolution**, **ps time resolution**, and **meV energy resolution**.

While providing conventional technical support for the general users, HEPS will operate as a platform to analyze the structures, as well as the evolution of structures of engineering materials in the whole process, by in-situ, multi-dimensional and real-time observation.







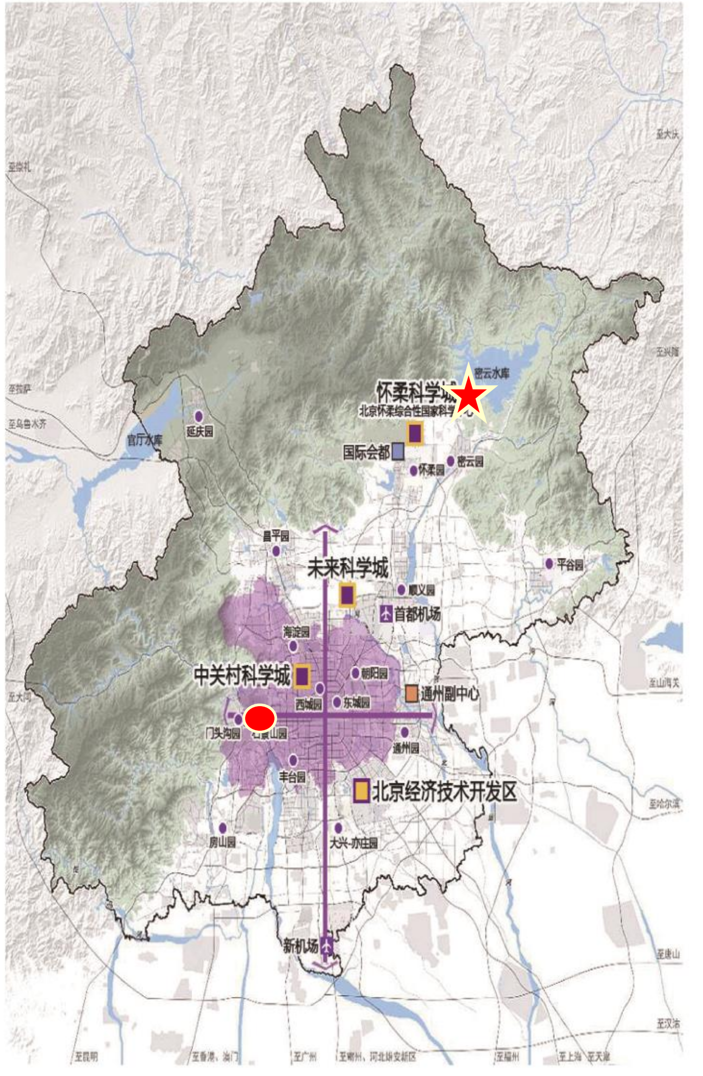
Location

~80km away from IHEP main campus

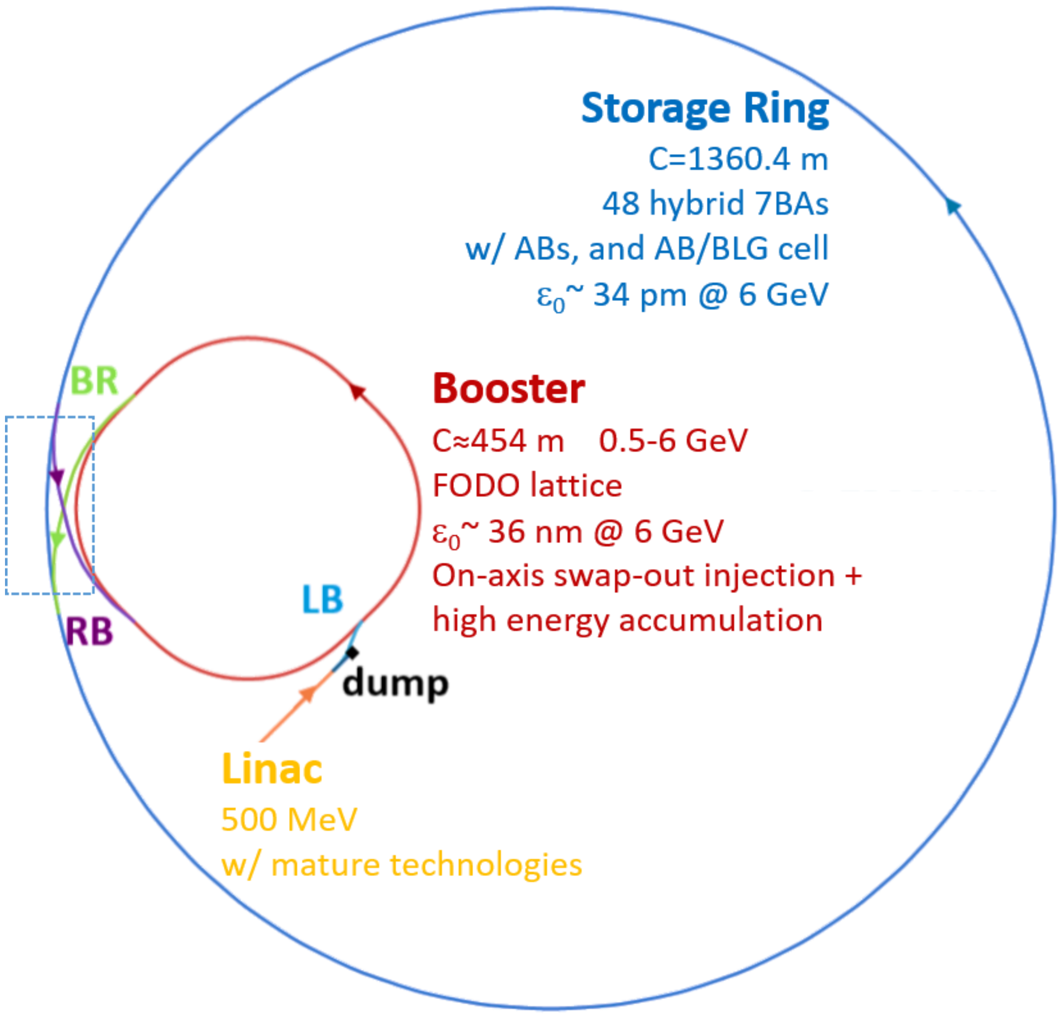
- **Huairou Science City** (an area of 233 acres)

  - **Five big science facilities**: **HEPS**, SECUF (Synergized Extreme Condition User Facility), CMP Phase II (Chinese Meridian Project Phase II), EarthLab (the Earth System Numerical Simulation Facility), Multi-mode, Multi-scale Biomedical Imaging Facility

  - **Series research platforms** in energy, environment, biology, materials, etc.



Design goals of HEPS



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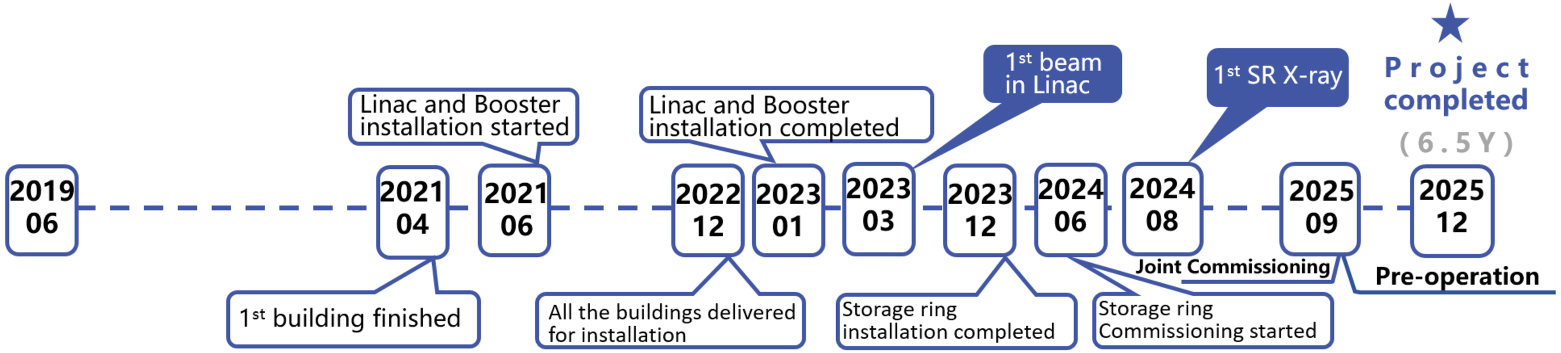
Schedule (2019-2025)

- **The construction period was estimated to be 6.5 years.**

  - Date of Groundbreaking ceremony: Jun. 29, 2019

  - Project is scheduled to be completed in 12.2025



Aug. 8, 2022, the installation in the booster tunnel began.

Jun. 28, 2021, HEPS Installs First Piece of Accelerator Equipment in Linac Tunnel.

Milestones

June 29, 2019
Groundbreaking ceremony

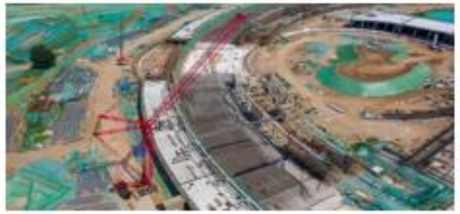
May 12, 2022
The Linac Vacuum-sealing in the tunnel completed

Jan. 13, 2023
The Booster Vacuum-sealing in the tunnel completed

Feb. 1,2023
The first girder was installed in the storage ring tunnel

Mar. 14, 2023
The first electron beam

July 1, 2020
The first steel beam was installed



Apr. 13, 2021
Utility installation in NO.2 Hall commenced

June 27, 2021
Roof-sealing work for the main ring building completed

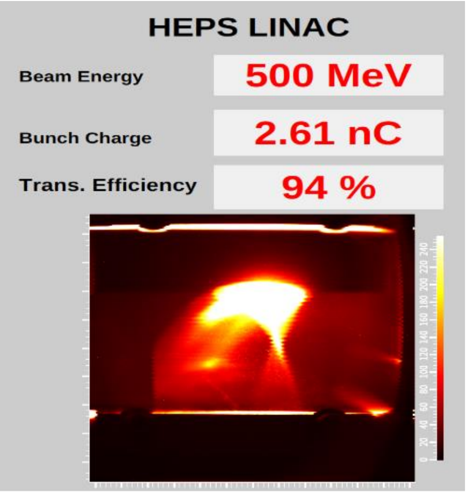
June 28, 2021
HEPS Installs First Piece of Accelerator Equipment in Linac Tunnel.

Nov. 18, 2021
Roof-sealing work for ancillary buildings completed

Progress of Linac

LINAC

Linac tunnel



The first electron beam of the HEPS was accelerated to 500 MeV with better than 2.5 nC of bunch charge by the Linac on March 14, which was a key milestone of the HEPS project—HEPS beam commissioning had begun.

Milestones of the HEPS Linac

29/06/2019: Design completed

28/06/2021: Electron gun, the first piece of accelerator equipment, was installed in the Linac tunnel.

08/03/2022: Installation in the Linac tunnel begun

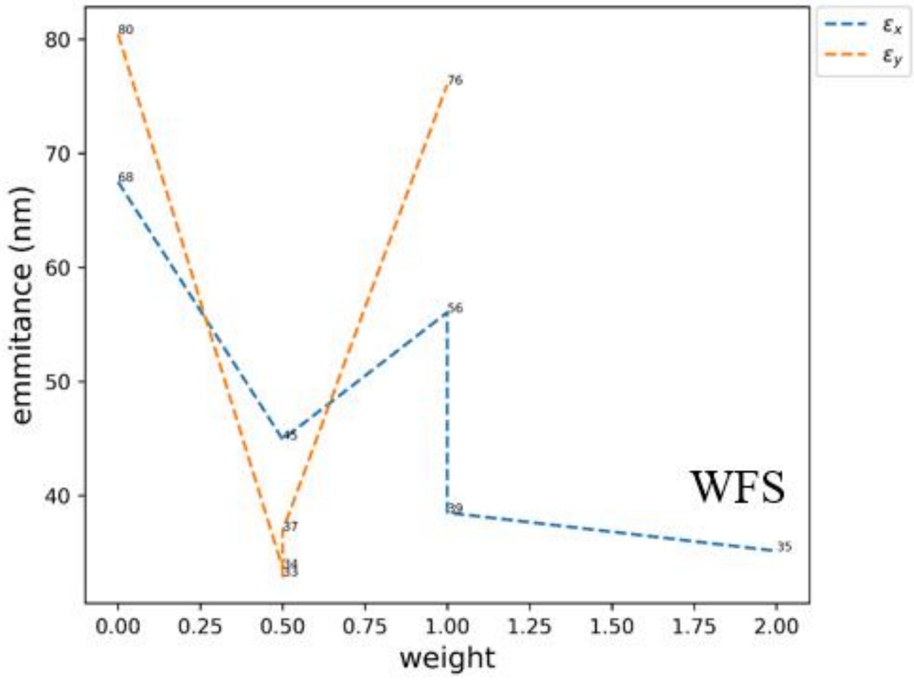
12/05/2022: Linac vacuum-sealing in the tunnel completed

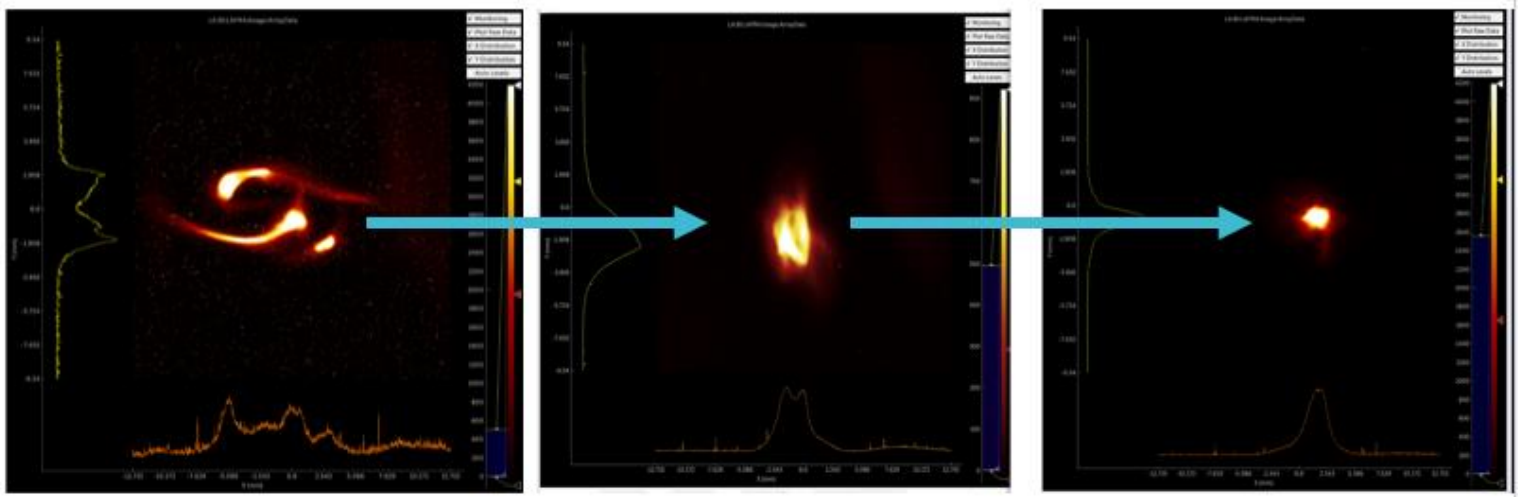
23/09/2022: Linac online RF conditioning completed

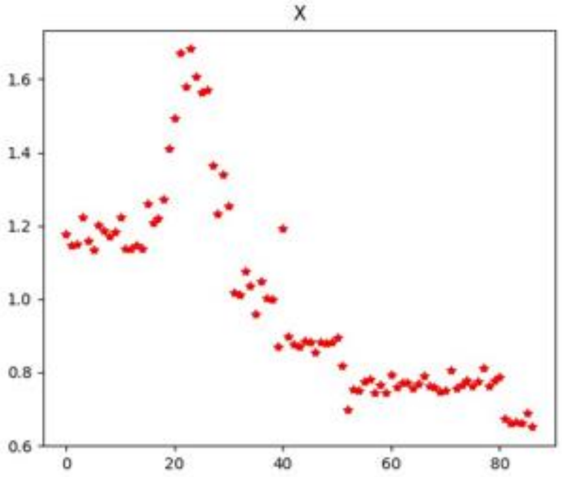
09/03/2023: Linac commissioning began

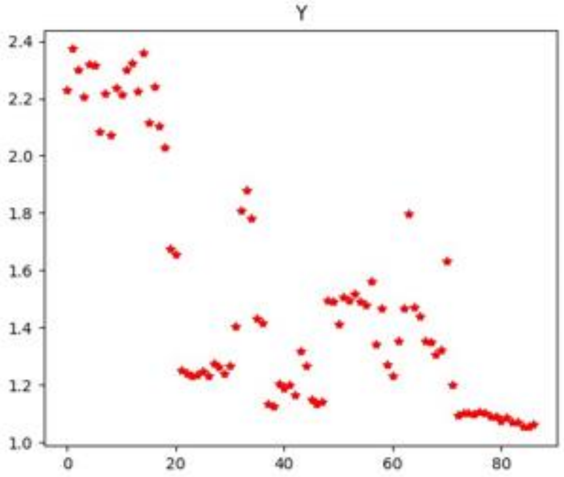
Emittance optimization: Wakefield

- Beam size optimization
- Wakefield-free steering（WFS）









Progress of booster

RF conditioning started on May 25, 2023 and beam commissioning began last month.

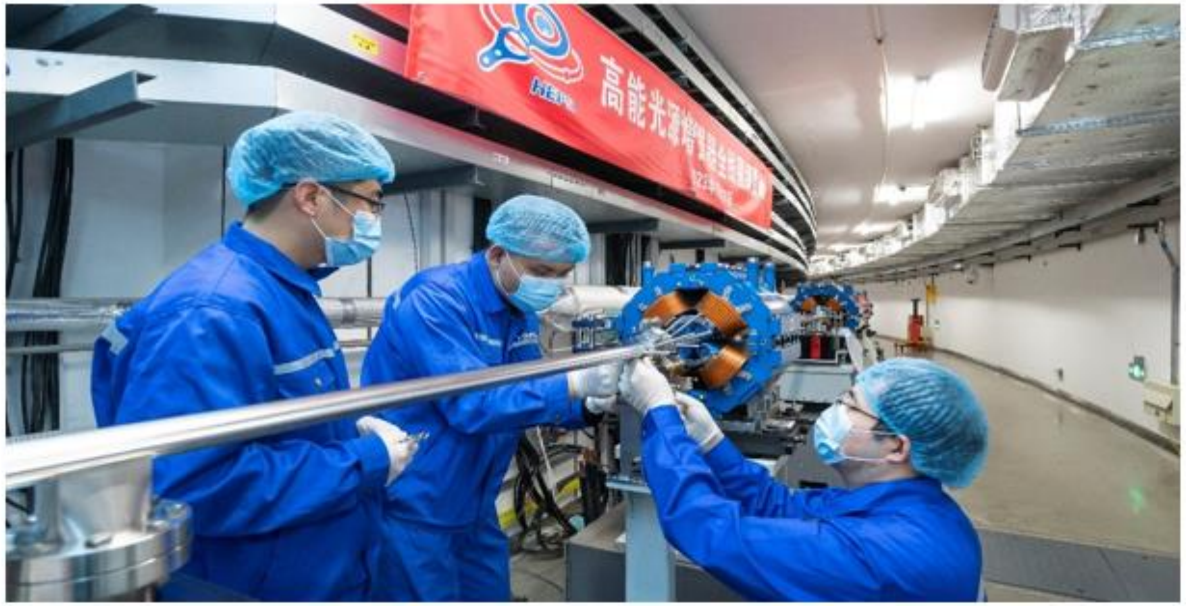
The Booster was vacuum-sealed on Jan. 13, 2023.

Sep. 30, 2022, The pre-alignment of the booster installation cells completed.

Aug. 8, 2022, The installation in the booster tunnel began.

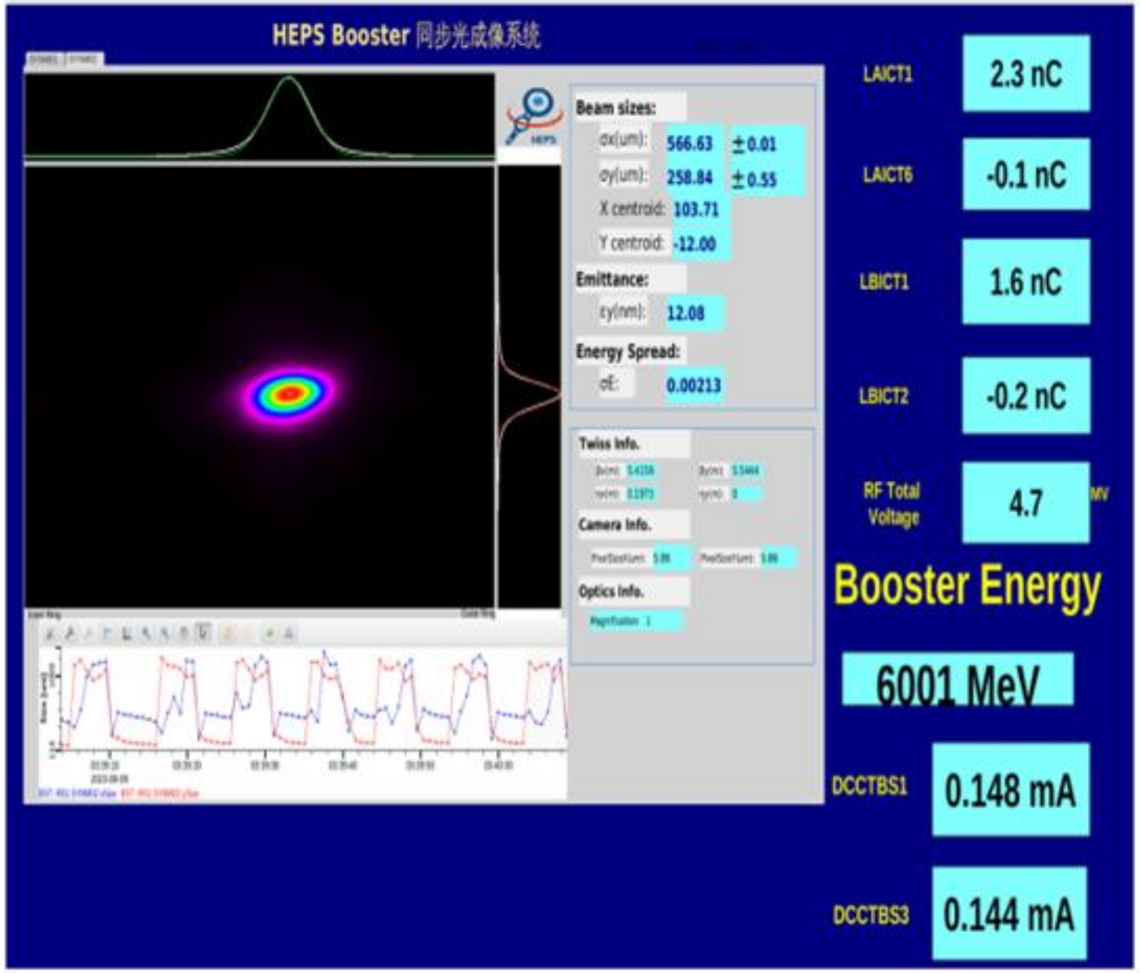
Dec. 14, 2021, Booster tunnel building moved to installation phase.

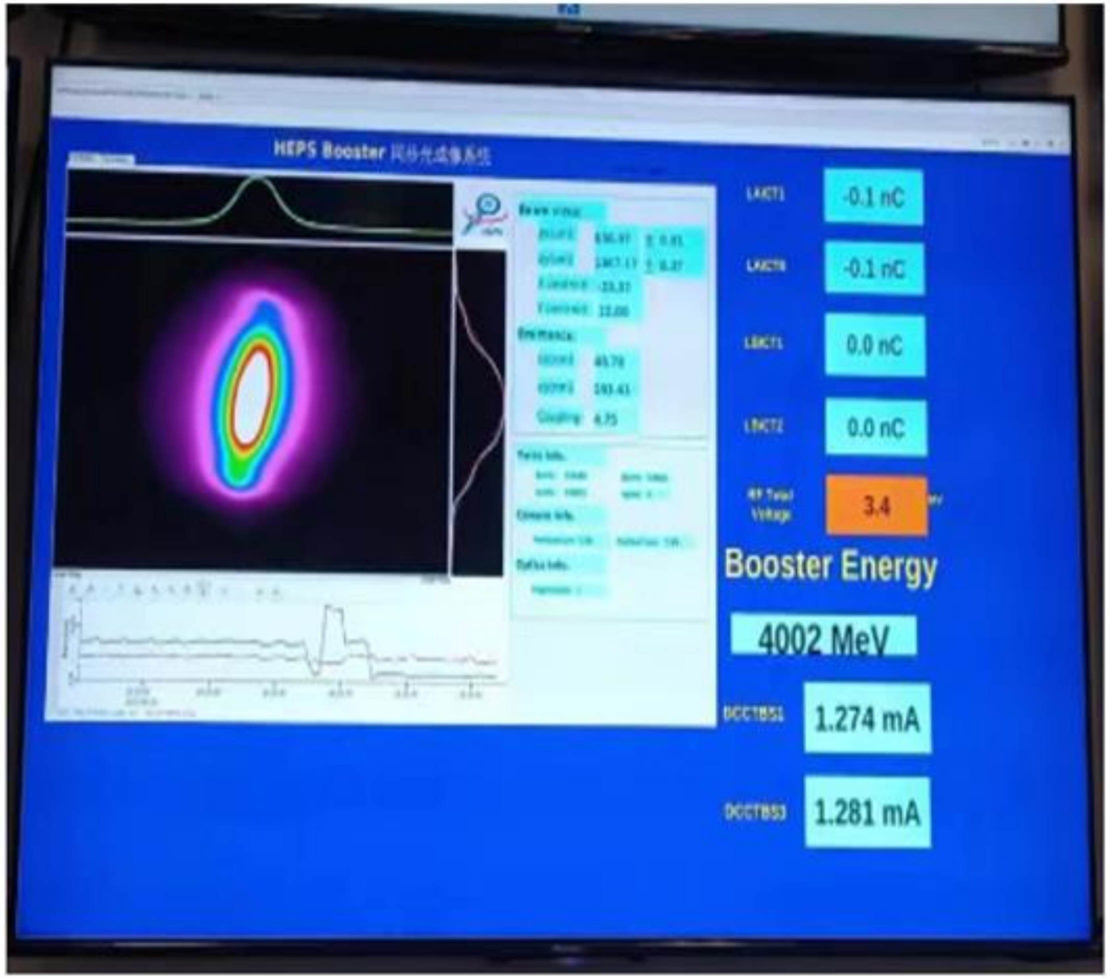
132 pre-alignment cells



Booster commissioning

Beam energy ramping to 6.0 GeV (with RF)





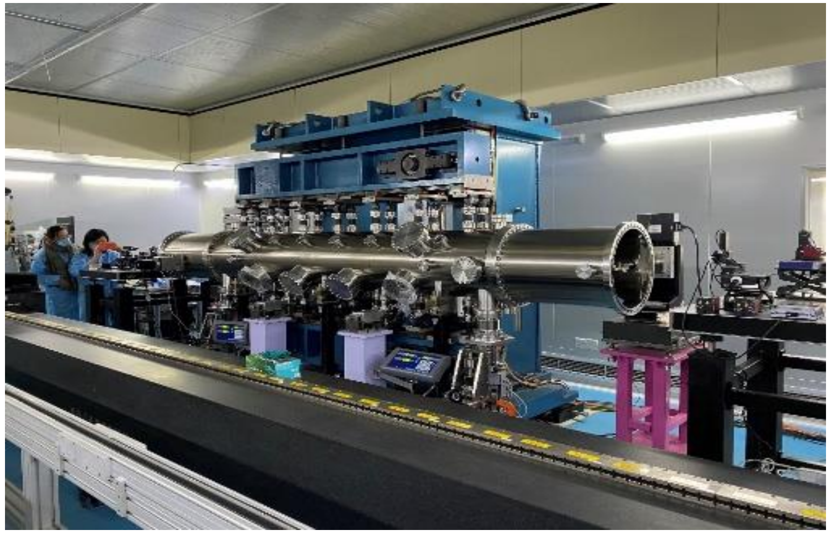
Progress of storage ring



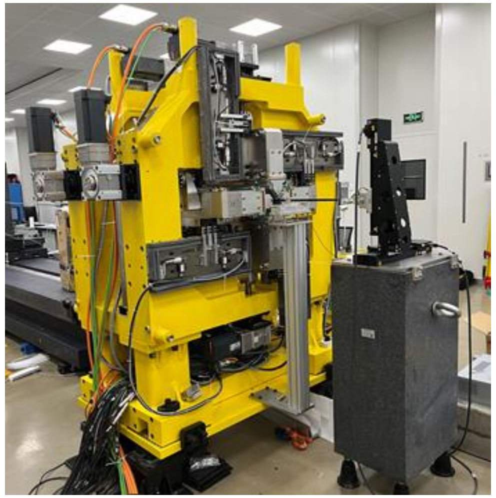
1776 magnets **288** girders

- The installation of a 7BA cell of the storage ring on the experiment bench was successfully finished to optimize process flow.
- The pre-alignment for the storage ring magnet girder began on July 13, 2022.
- The tunnel installation of the storage ring started on Feb. 1, 2023.
- Up to date, ~75% girders has been installed.

Progress of storage ring



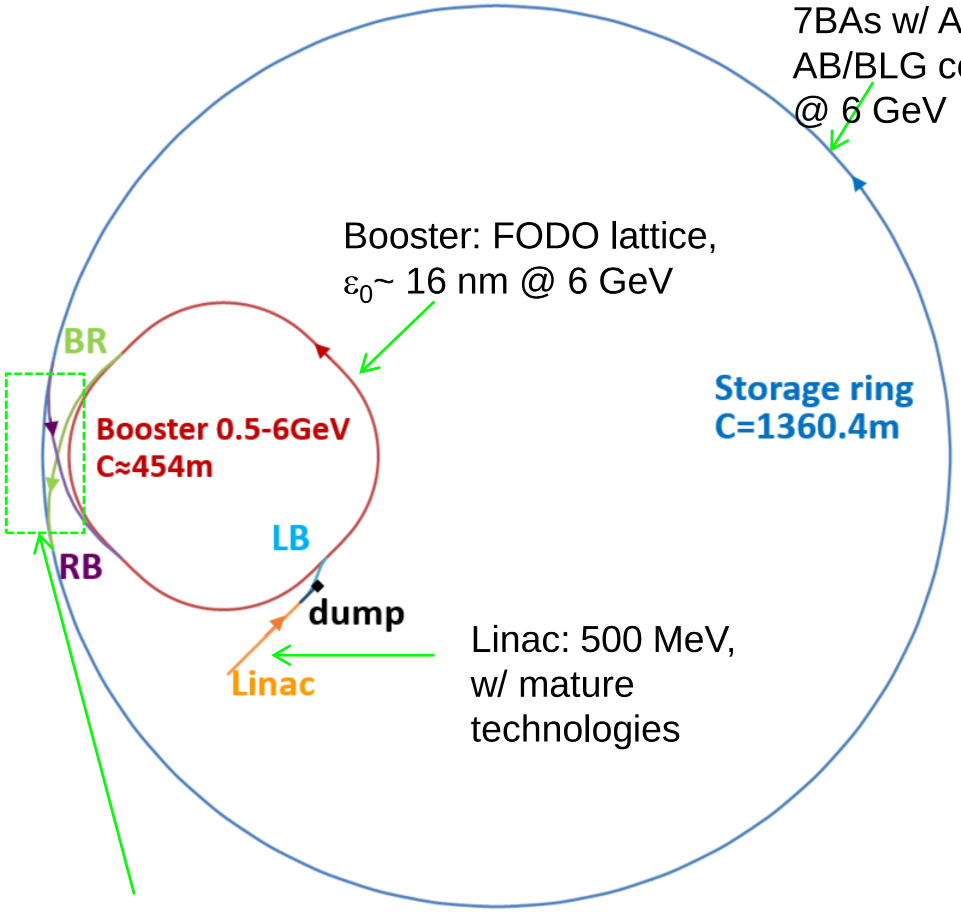
19 insertion devices (including IAU, IAW, CPMU and IVU AK Mango) were manufactured and received.



Accelerator Physics

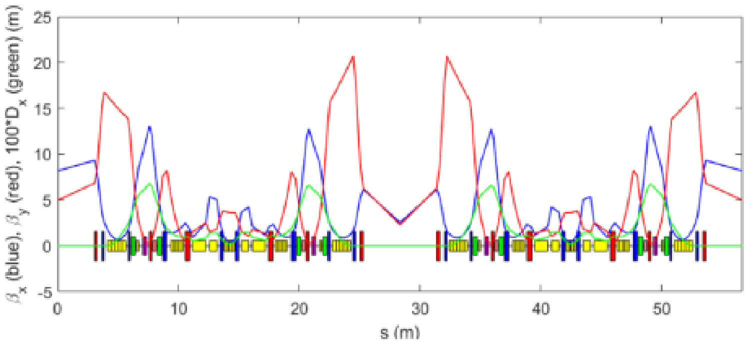
Storage ring: 48 hybrid 7BAs w/ ABs, and AB/BLG cell, ε_0~ 35 pm @ 6 GeV

Booster: FODO lattice, ε_0~ 16 nm @ 6 GeV



Linac: 500 MeV, w/ mature technologies

On-axis swap-out injection + high energy accumulation

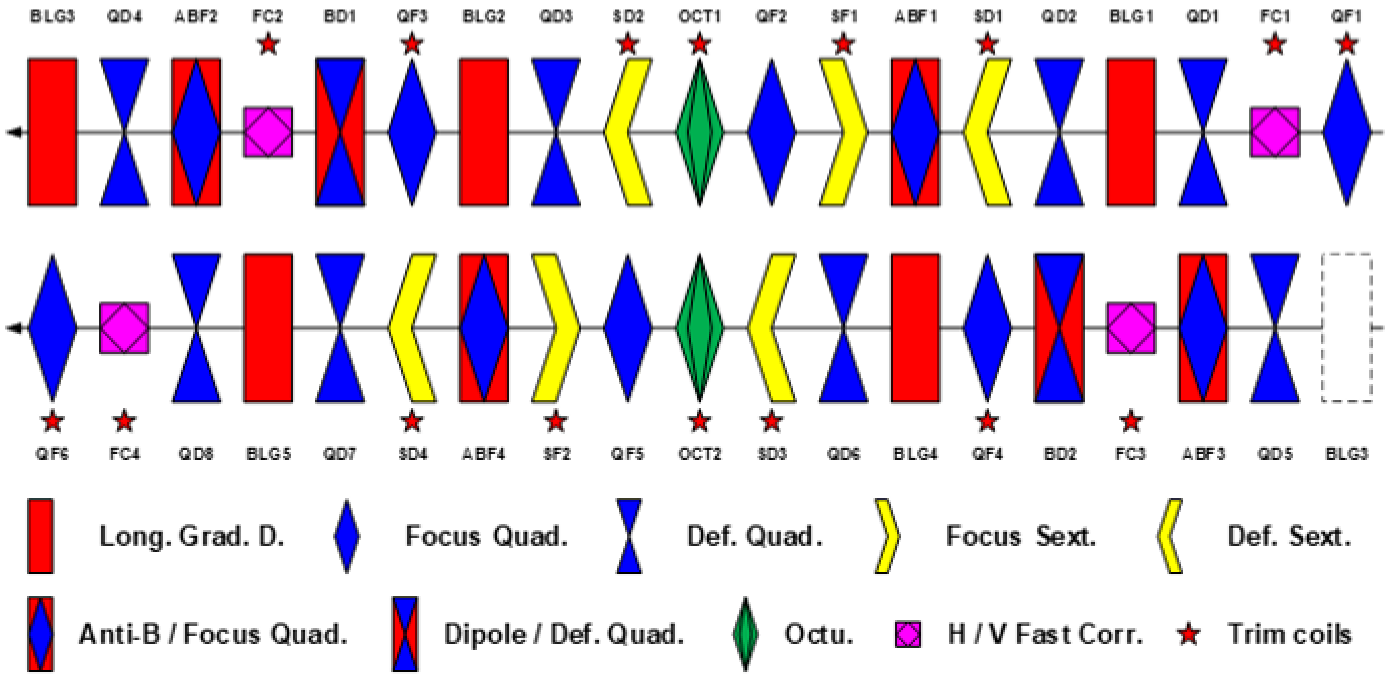


To deal with challenges from technical and engineering design, the accelerator physics design was updated

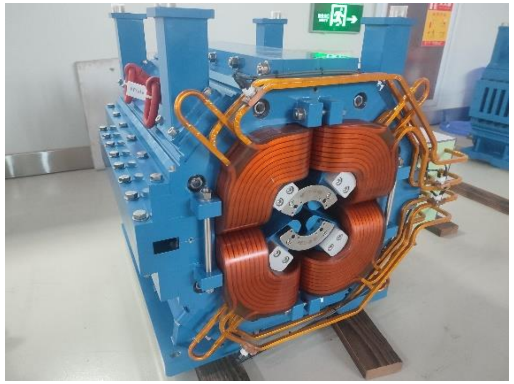
- Storage ring lattice: enlarged drift space in arc (1.1 m more space/7BA), slightly larger magnet aperture (25->26 mm), emittance preserved (34.2->34.8 pm) with however smaller dynamic acceptance
- Booster design: higher bunch charge (2->5 nC), and emittance reduced by more than 50% (35->16 nm)
- Linac design: higher bunch charge (5->7 nC) and optimized layout
- Transfer lines: updated accordingly

Storage-ring magnets

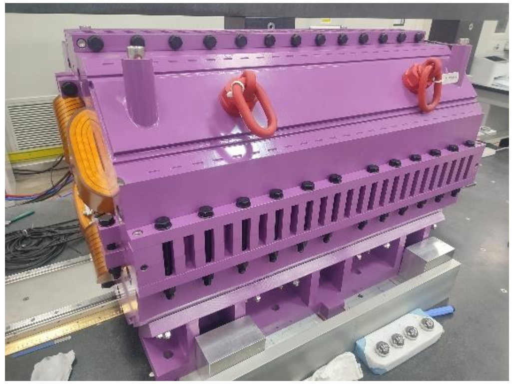
- Magnets
  - 37 magnets in one 7BA cell
  - BLG 0.11 – 1 T
  - Quad 82 T/m
  - BD 66 T/m
  - Sext 6082 T/m²
  - Oct 512600 T/m³
  - Fast Corr 0.08 T



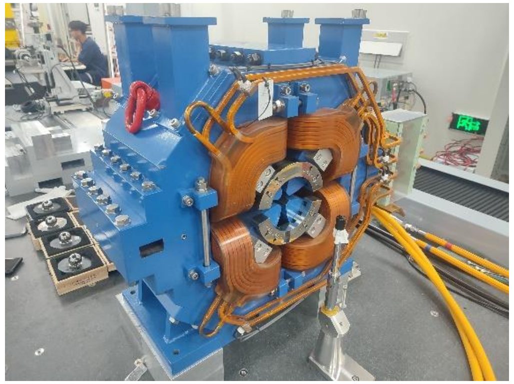
BLG2



ABF2/3



BD1/2



QD4

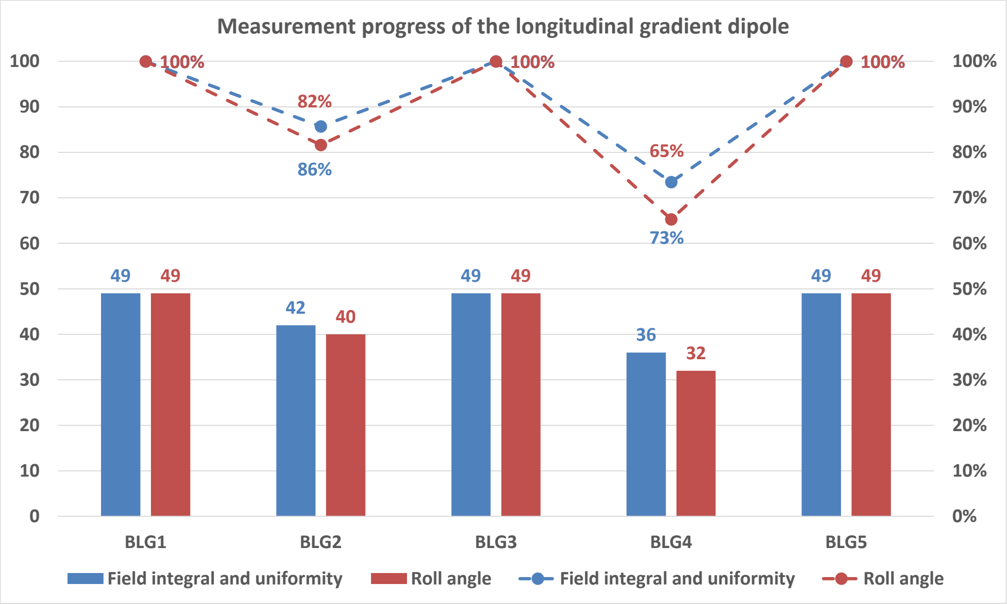
Magnetic field measurement

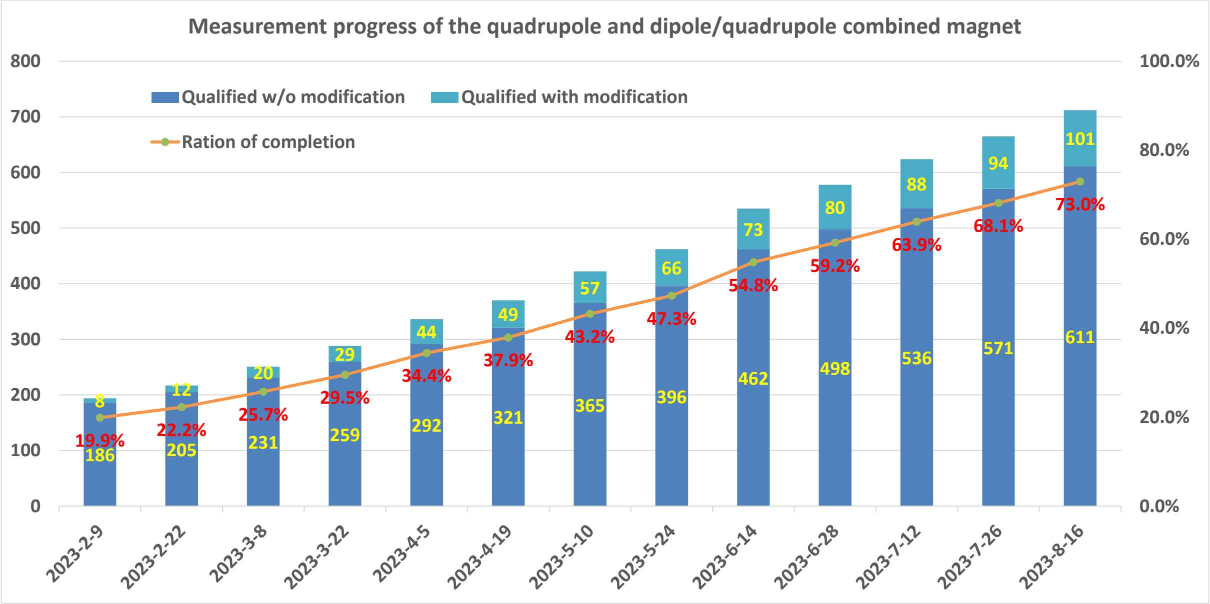
- **Measurement and pre-alignment move on schedule**

  - Measurement of the dipoles, quadrupoles and dipole/quadrupole combined function magnet will be finished by the end of November

  - All sextupoles, octupoles and fast correctors have been measured

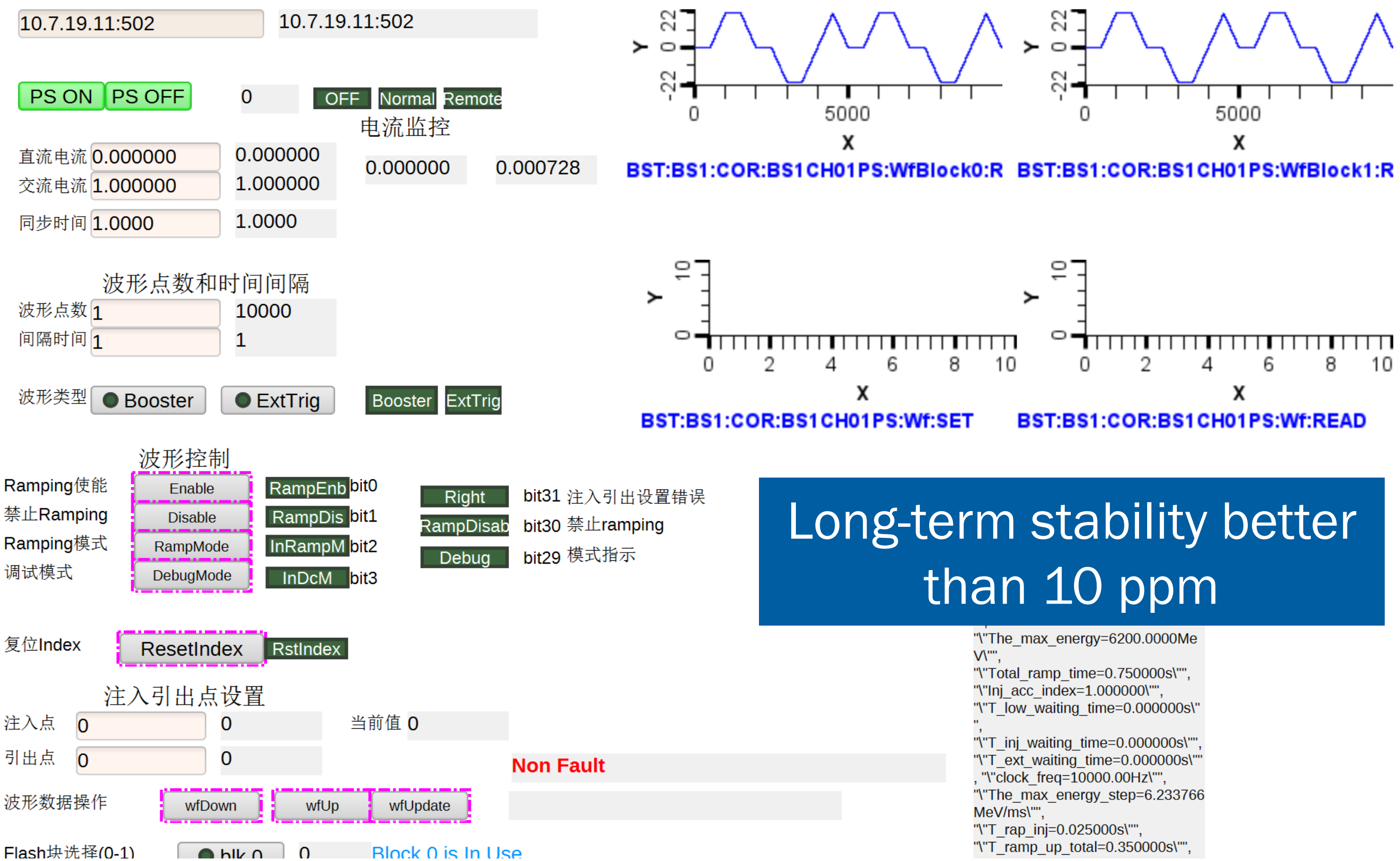
  - Fine tuning of the BLGs field integrals is performed by using adjustable screw. All the BLGs are within 5×10^{-5} after tuning





Magnet power supply

- All power supplies installed（total number 2804）at 10 PS Halls and M01-48
- PS for Linac, Low energy transport and Booster started commissioning

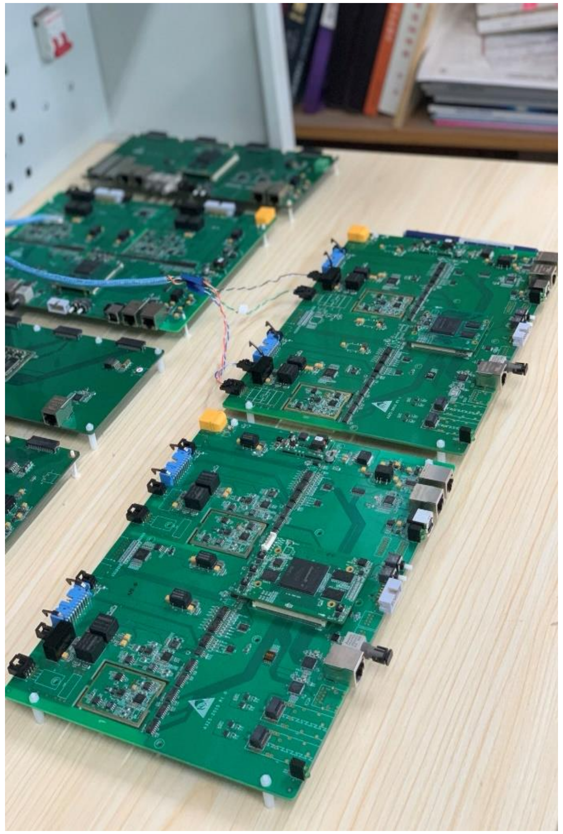


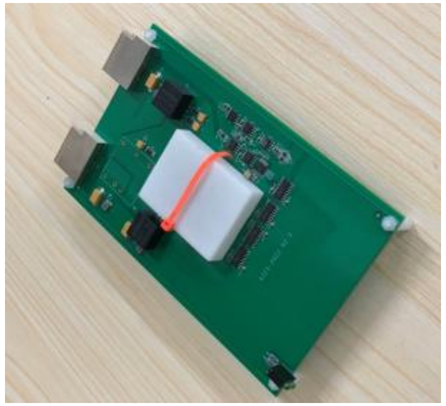
Long-term stability better than 10 ppm

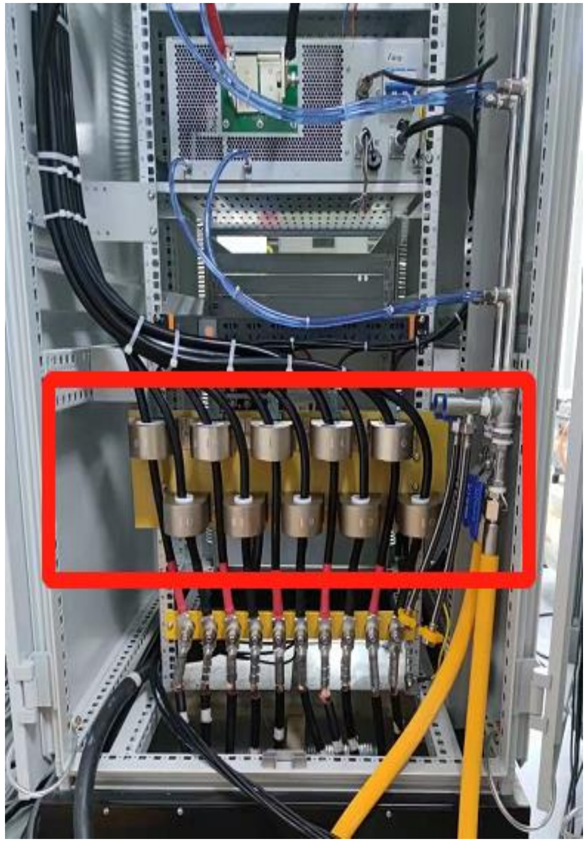
Magnet power supply

- All power supplies are digital-controlled with self-designed DPSCM(Digital Power Supply Control Module) and DCCT(two scales with 20A and 300A).

DCCT: DC Current Transformer (Accuracy < 2 ppm)





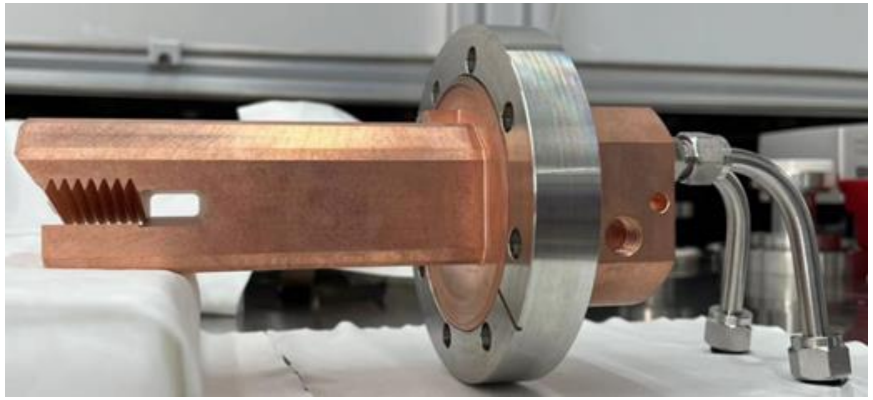


Storage-ring vacuum

- The vacuum components in the storage ring are being mass-produced, and the vacuum equipment of a standard arc cell have been installed and verified

Stainless steel chamber with pumps, photon absorbers and end mask, and copper is coated inside.

Extruded Cu-Cr-Zr (C18150) antechamber



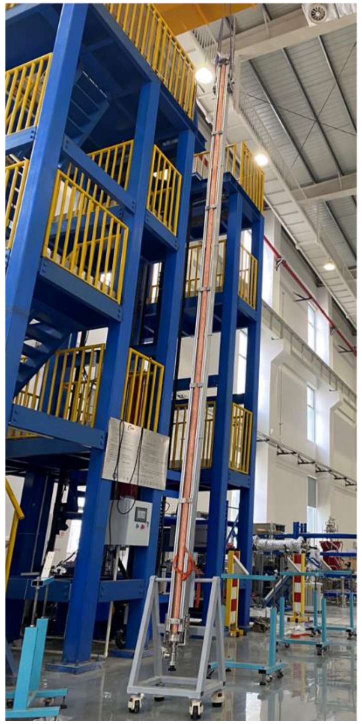
Cu-Cr-Zr /dispersion-Cu crotch photon absorber

RF shielding bellows with double-fingers type, and BPM module is integrated.

NEG coating facilities

- 3 sets of NEG coating equipment have been built
  - 1 for coating small aperture circle vacuum chambers, and 6*3.5m vacuum chambers can be coated simultaneously
  - 1 for antechambers paralleled with 4 groups in a length of 1.5m, and the NEG coating have been verified in a slit height of 6mm with a length of 1.2m
  - A 6m long vacuum chamber can be coated in the 3rd setup by moving solenoid vertically.

NEG coating pumping speed ~ 0.72 L/(s·cm^2)(H2)



Girder & Magnet support

SR magnet support system

- Prototypes developed and engineering design scheme finalized
- Contradiction between the precise motion and stability compromised effectively

- Eigen frequency： ≥71Hz
- Motion resolution : 1μm

- Concrete plinths grouting finished in tunnel and passed the final test acceptance.
- Girder mass production finished and installation is in progress, 70% completed.

LA & BS mechanical support

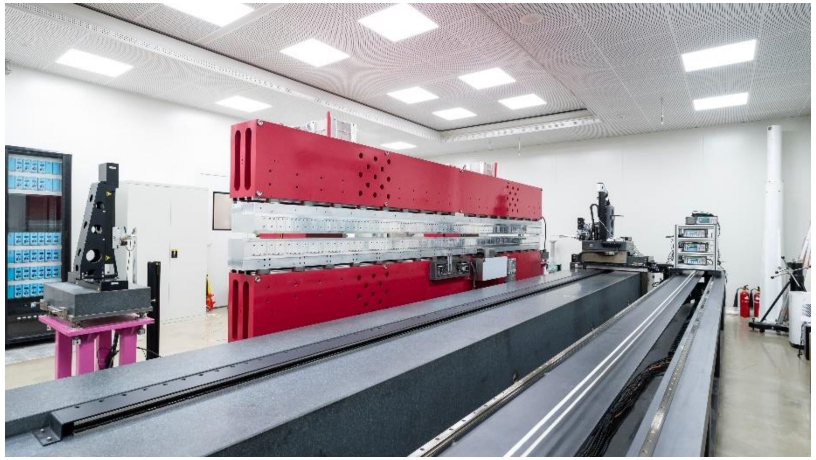
- All the mass production and tunnel installation have been completed

Insertion Device

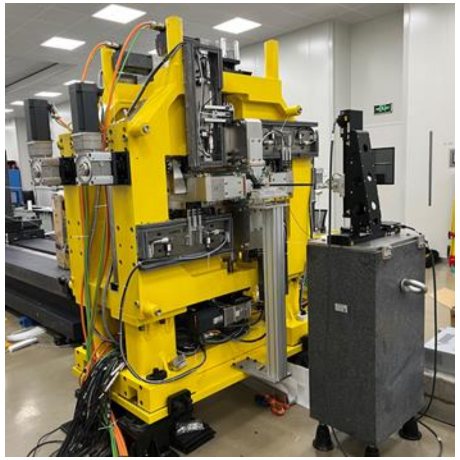
- The **APPLE-Knot undulator** is an innovative device which can achieve both circular polarization and low on-axis heat load. The "**Mango**" wiggler is designed to offer a big radiation spot size for Large - field X-ray diagnosis and flaw detection. They are both successfully realized and through expert review.
- The development of 6 in-air IDs (4 **IAU**s+ 2 **IAW**s) is finished, ready for tunnel installation.

Merged APPLE-Knot: 1st 4 Array AK

Mango: Scan range 0.6mrad*0.6mrad



AK



MANGO

IAU

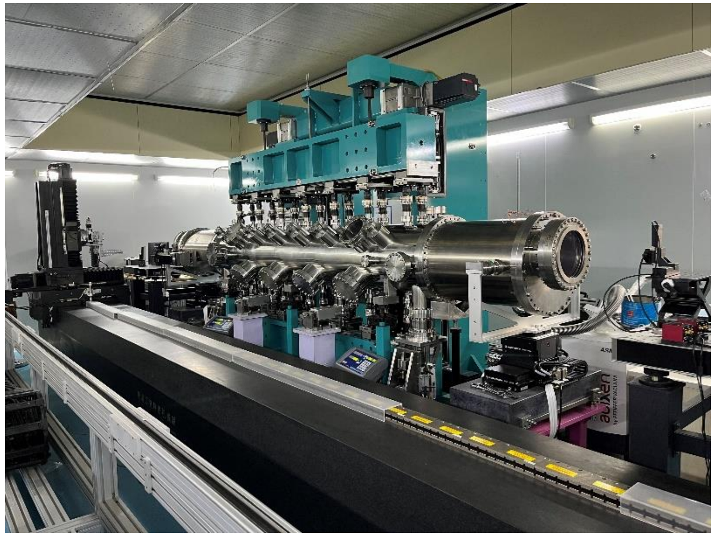
IAW

Insertion Device

In-vacuum IDs

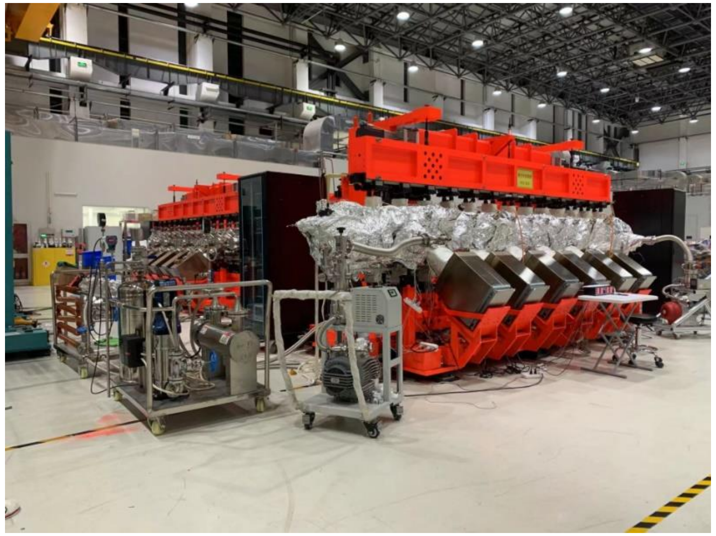
- The mass production of 11 in-vacuum IDs (6 CPMUs + 5 IVUs) completed
- The batch tuning is underway

Short period 12mm



CPMU in Tuning

IVU in Tuning

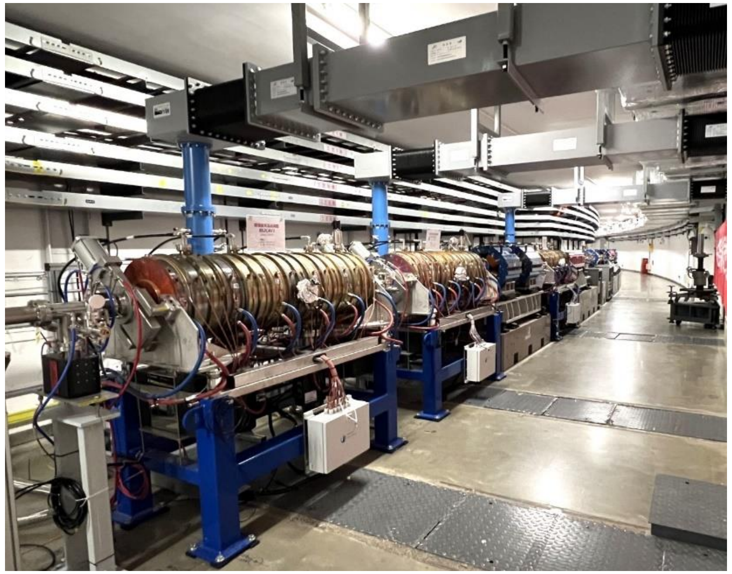


IVU in Baking

RF cavities

- 2022.12, all six 500MHz 5-cell copper cavities passed SAT at PAPS (c.w. 120kW)
- 2023.07, three 500MHz 5-cell **copper cavities installed in the Booster tunnel and commissioned**
- 2021.11, first 166MHz bare SRF cavity passed vertical acceptance tests
- 2022.06, first **166MHz jacketed SRF cavity passed vertical acceptance tests**
- 2023.06, first **166MHz cryomodule assembled** and moved into the horizontal test stand
- 2022.12, four **500MHz bare SRF cavities** produced and **passed vertical acceptance tests**

500MHz 5-cell copper cavities

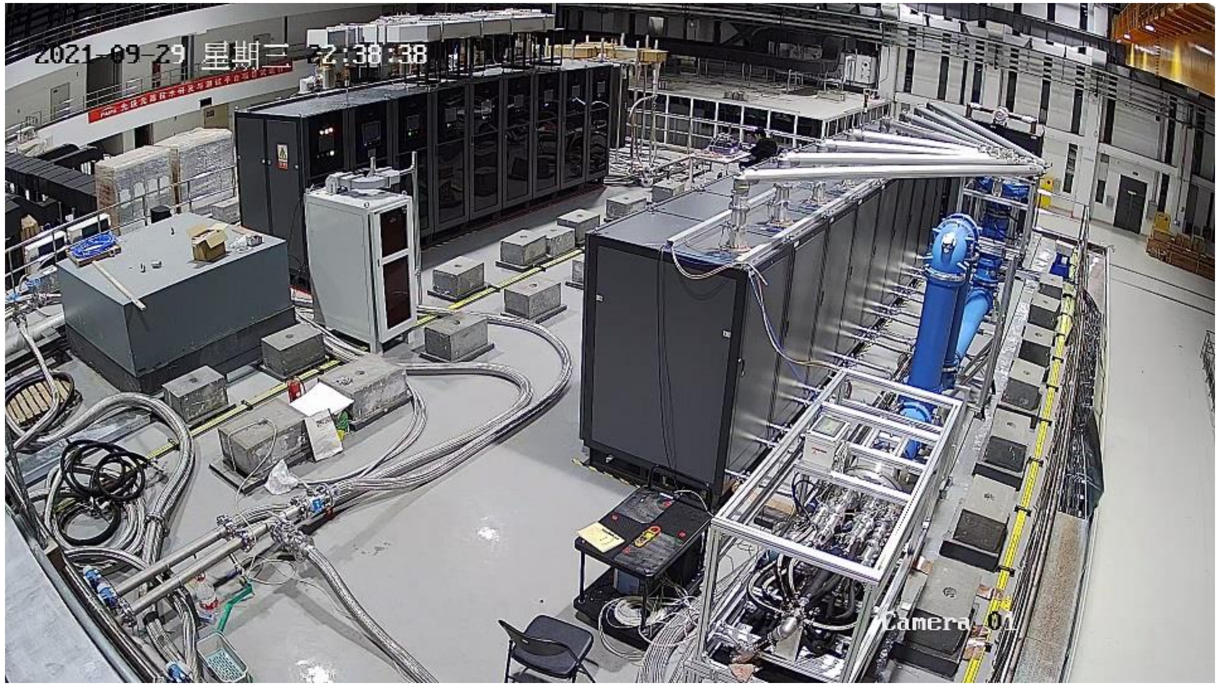


166MHz SRF cryomodule

500MHz SRF cavity string

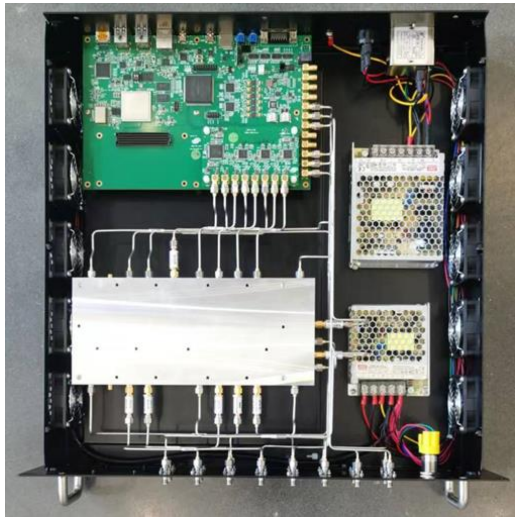
High-power RF system

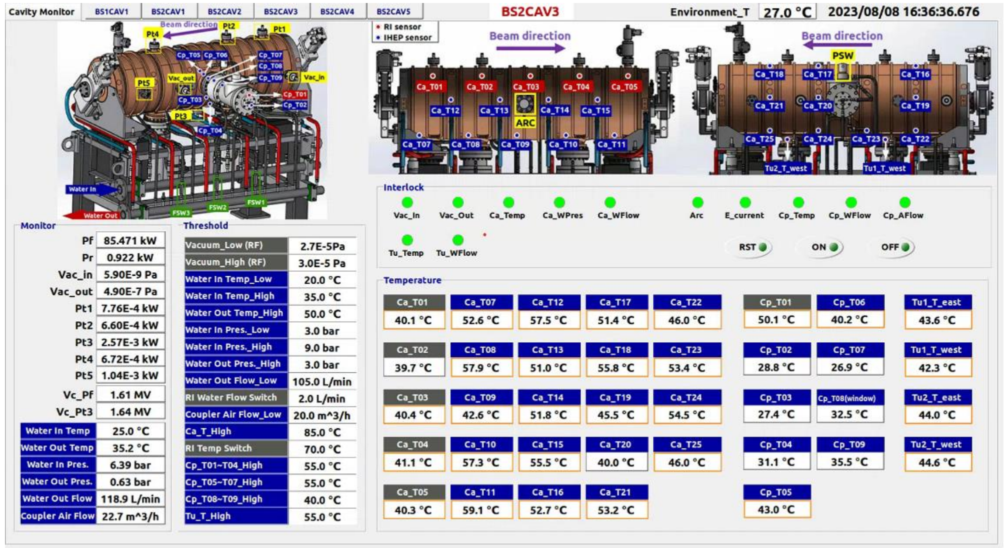
- 2021.10, 166MHz-260kW and 500MHz-150kW prototype SSAs passed essential tests at PAPS
- 2023.04, 166MHz-260kW and 500MHz-260kW **series SSAs production complete and passed FAT**
- 2023.07, **500MHz-100kW series SSAs complete and passed SAT** at Booster RF hall
- 2023.06, first 500MHz-150kW circulator installed at Booster and passed SAT



Low-level RF system

- 2022.12, XILINX-based LLRF in-house developed
- 2023.05, integration of cavity, SSA and LLRF at Booster complete
- 2023.07, **commissioning of booster RF complete**
- 2023.04, RF EPICS database start archiving data
- 2023.04, Booster RF control OPI developed





Cryogenics system

- Layout of the cryogenics system finished and met the technical requirements of HEPS micro-vibration requirement
- All cryogenic equipment of cryogenic hall, tank area and HEPS zone installed

Transport line from cryogenic hall to HEPS

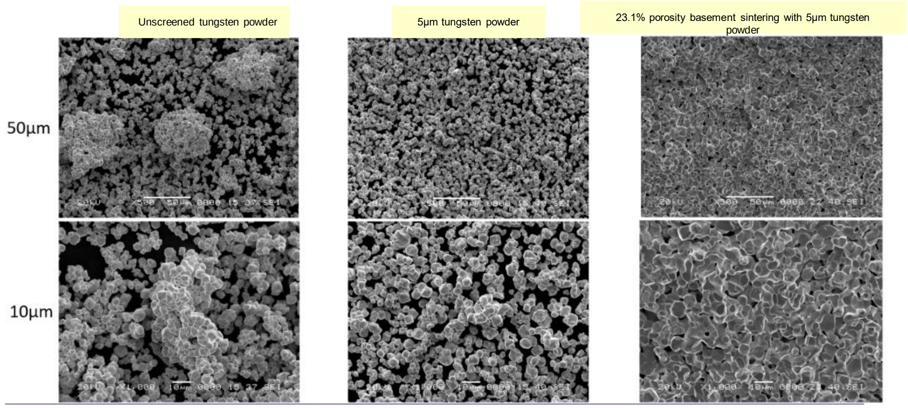
Tank area and cryogenic hall

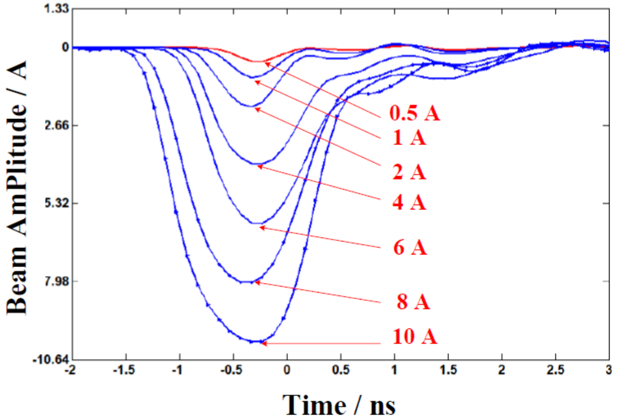
Linac microwave and power source

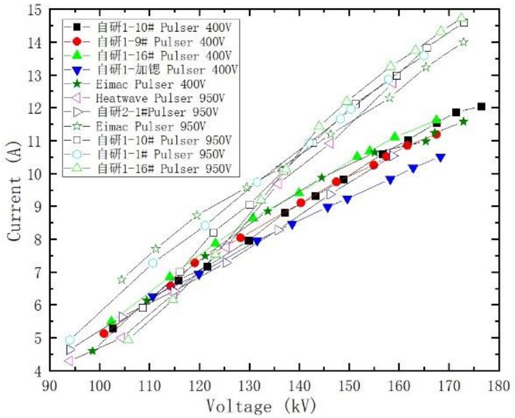
- **Cathode-grid Assembly R&D**

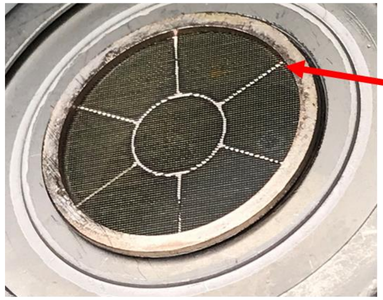
  - Assembly emission current satisfied E-gun of HEPS linac

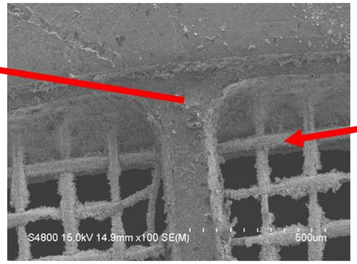
  - Reliability and lifetime of assembly are under tests

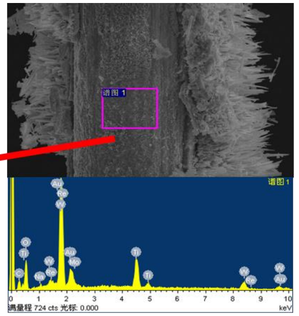


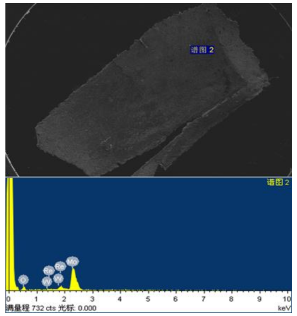












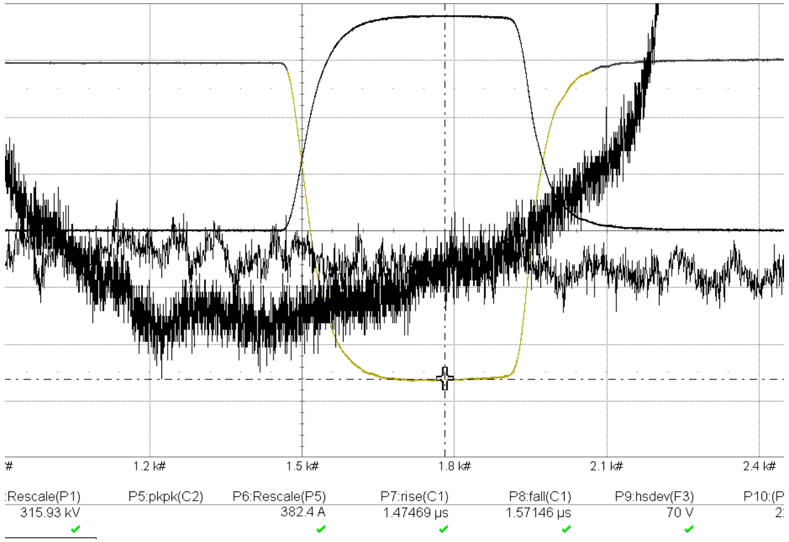
Linac microwave and power source

- **Solid-state modulator**

 - Completely eliminate instability and limited lifetime of thyratron

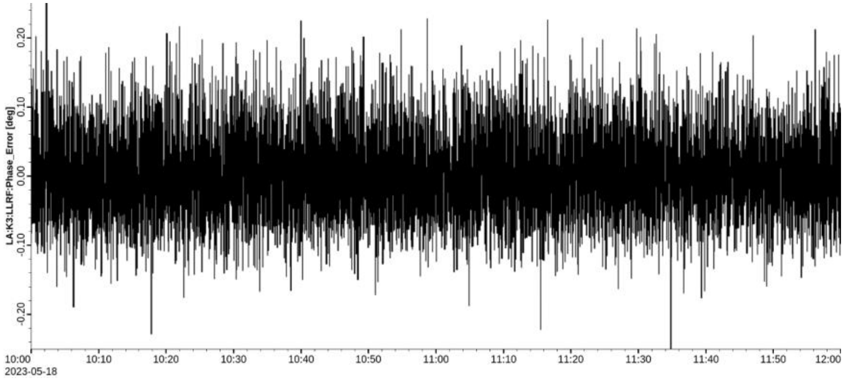
 - Solid-state modulator technology in-housed developed

Modulators in HEPS Linac Gallery



Pulse Repeat stability 0.018%
305kV/354.2A/30min

Microwave phase stability of Linac K3
2 hours p-p stability: 0.4°
2 hours RMS stability: 0.07°



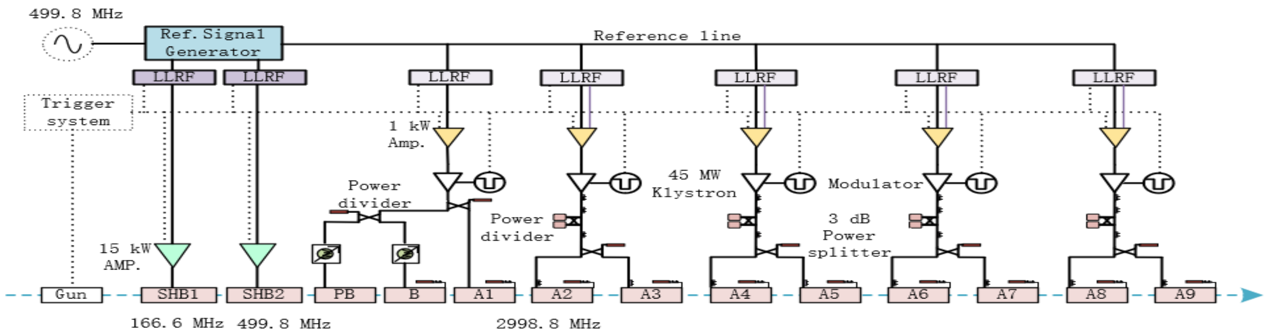
Linac RF system

- **Features**

  - The accelerating structure adopts an round-shaped cavity, an elliptical cross-section iris design, and the coupler design is a single port doubly fed structure
  - The pulse compressor design is a dual cavity structure with dual hole coupling, and internal water cooling
  - The directivity of DC: 40dB, LLRF is fully digital

- **Milestone**

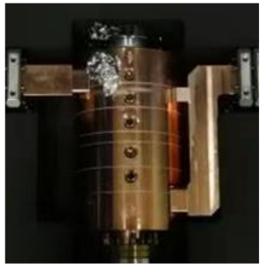
  - 2019.6, microwave system design completed and begin to manufacture the component
  - 2021.3, complete the acceptance of the first accelerating structure
  - 2022.4, complete the installation of the accelerating structure and pass the final acceptance
  - 2022.5, complete the installation and test of the microwave system and begin online high-power practice
  - 2022.9, the energy reaches 500MeV at linac exit



The layout of the linac RF system

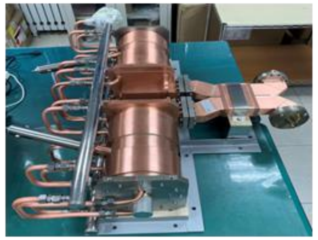
SHB

Prebuncher (S-band)



Buncher (S-band)

S-band Accelerating structure



Pulse compressor

Directional coupler

3dB hybrid directional coupler

LLRF system

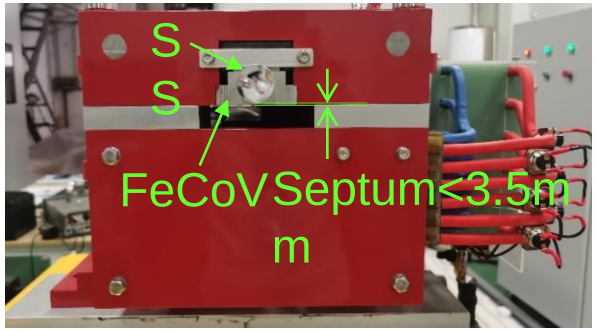
SiC load

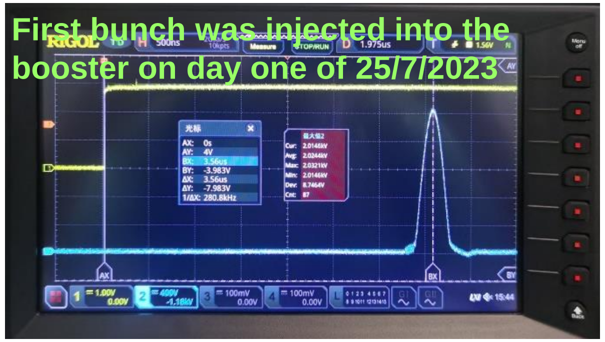
Phase shift & attenuation

Main components

Injection & extraction system

- **Booster**
  - All hardware including Lambertson magnets, kicker magnets and pulsers were delivered for installation in May 2023
  - The low-energy injection system has been put into operation for beam commissioning

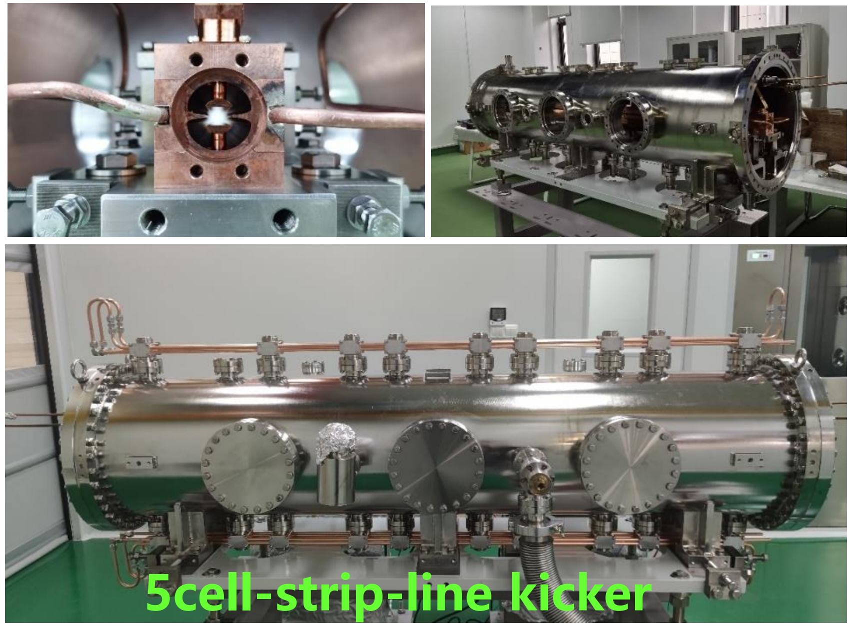


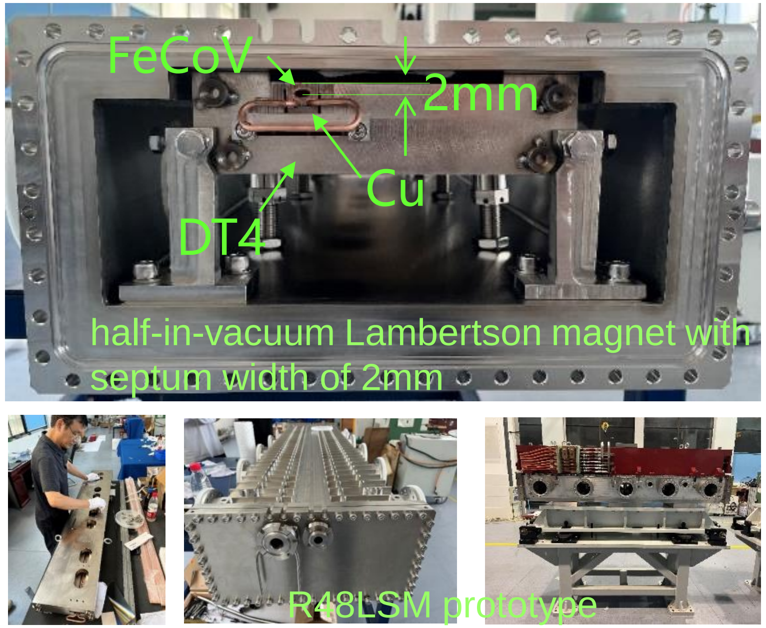


Injection & extraction system

- **Storage ring**
  - Kicker: All strip-line kickers delivered on 24/7/2023
  - Septum: the full-size prototype was completed in Jan. 2023 and 2 sets of final magnets are still under processing.

Fast kicker and pulser: pulse bottom width (3%-3%) < 10ns, pulse peak = ±15kV



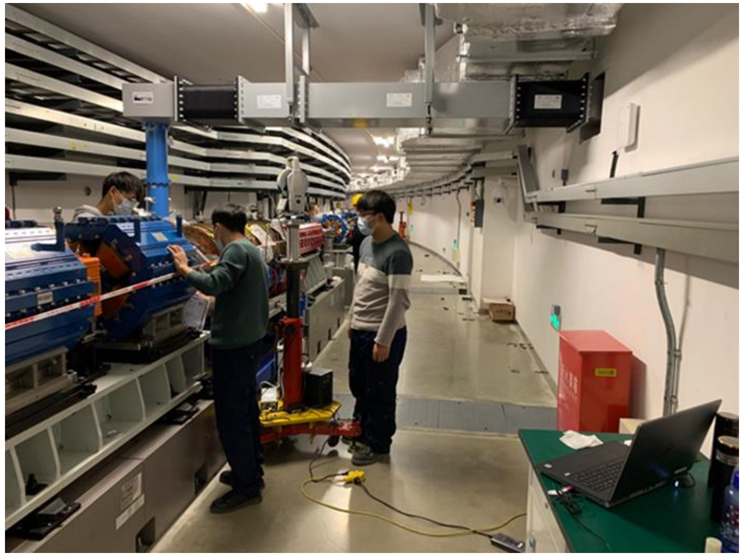


Alignment: Linac and Booster

- The initial alignment and smooth precise alignment of the 50-meter linear accelerator were completed from March to August 2022, with an alignment accuracy of **0.1mm**.
- From October to December 2022, the initial alignment of the 454-meter circumference booster was completed. From February to May 2023, two rounds of smooth precise alignment of the booster 's orbit were conducted with an alignment accuracy of **0.065mm**.
- All these alignment works have effectively improved the efficiency of beam commissioning and ensured stable beam operation. Currently, the linear tunnel is operating successfully, and the booster tunnel has completed beam commissioning. This demonstrates the correctness and practicality of the principle and procedure for achieving smooth precise alignment of the orbit.

Smooth precise alignment of linear accelerator

Smooth precise alignment of booster



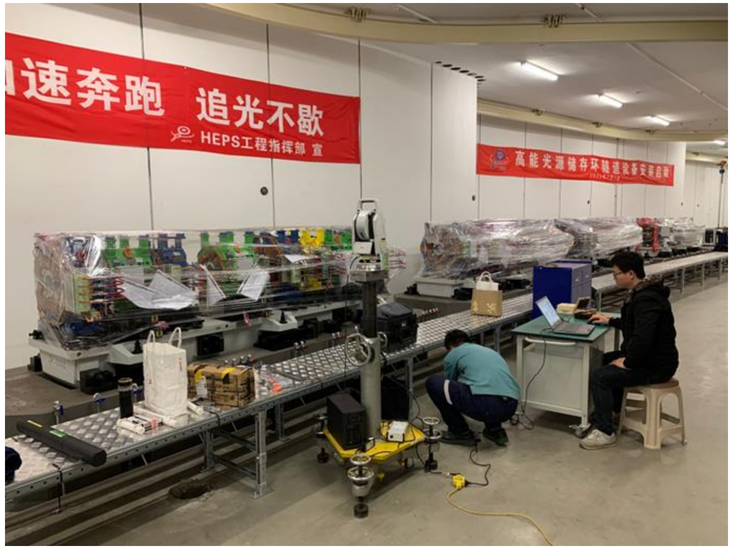
Initial alignment of booster

Alignment: storage ring

- For the first time in China, the laser multilateration measurement method is adopted to the pre-alignment of storage ring magnets of HEPS. **The spatial coordinate measurement precision of 6μm within a 6.5-meter control range have been achieved.** The system has reached a world-leading level in terms of stability and measurement efficiency. By August 2023, 217 out of 288 girders have been pre-aligned.
- The initial alignment of the storage ring is currently underway. It is being carried out using a conventional single tracker control network fitting positioning method. The deviations have been adjusted to 0.05mm, the instrument control network fitting positioning error is 0.4mm, and the magnet position error is 0.5mm, meeting the requirements for initial alignment. By August 2023, 156 out of 288 girders has been completed.


Pre-alignment of storage ring magnets


Pre-alignment of storage ring magnets



Initial alignment of the storage ring

Mock-up of storage-ring standard cell

- The operation space and interfaces have been checked, and pre-alignment scheme, transport scheme and other critical problems have been thoroughly tested

Aim to verify the feasibility of the magnet, vacuum chamber, BPM, etc. installation procedure

Summary

- **HEPS Accelerator execution progression**
  - Engineering Design completed
  - Procurement completed
  - Delivery of main components almost completed (excepted storage-ring vacuum chamber)
  - Mock-up storage ring standard cell completed
  - Storage ring magnet girder nearly 75% installed
  - Linac and Booster commissioning well progressed
  - COVID-19 caused the project 3~4 months delay and we try to catch up
  - No show stoppers to start storage-ring commissioning next year

Photo taken in July 2023