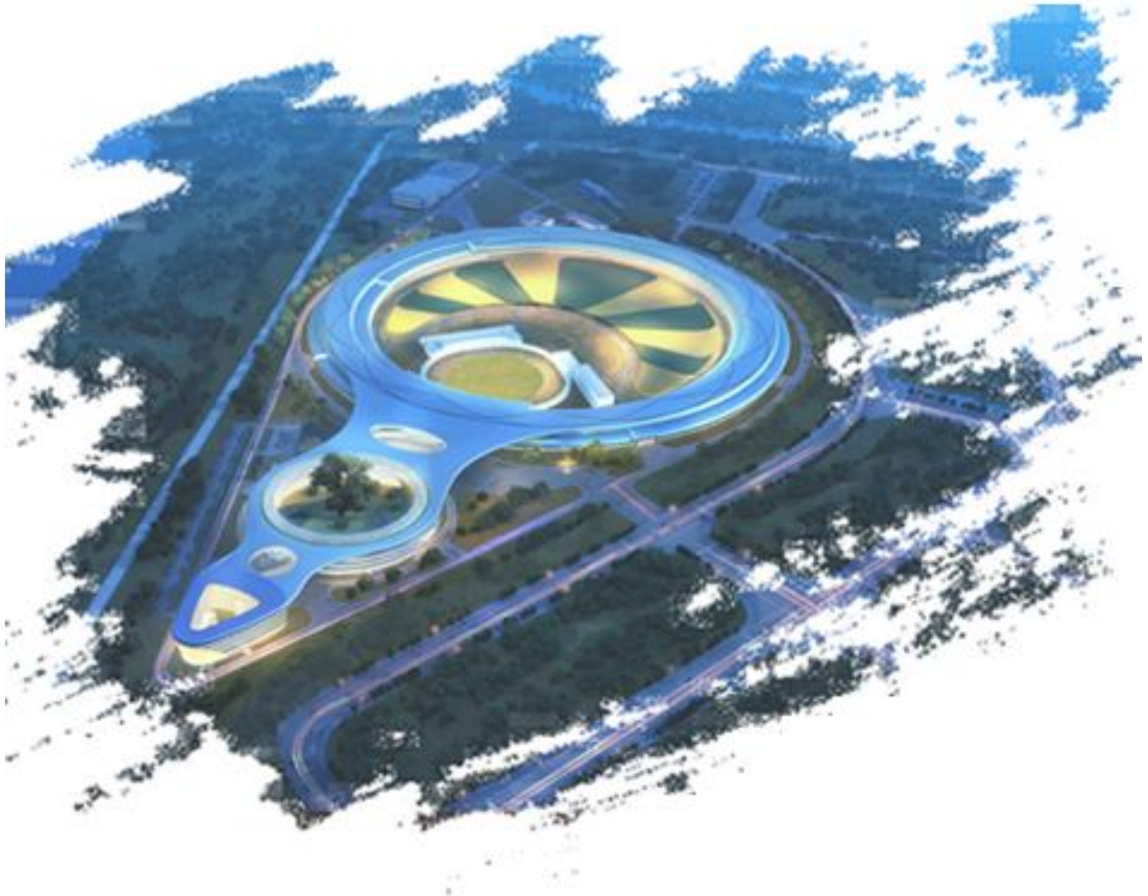
1st high energy synchrotron radiation facility in China

# The progress of HEPS project



**Ping He**

On the behalf of HEPS management

Oct. 26, 2020

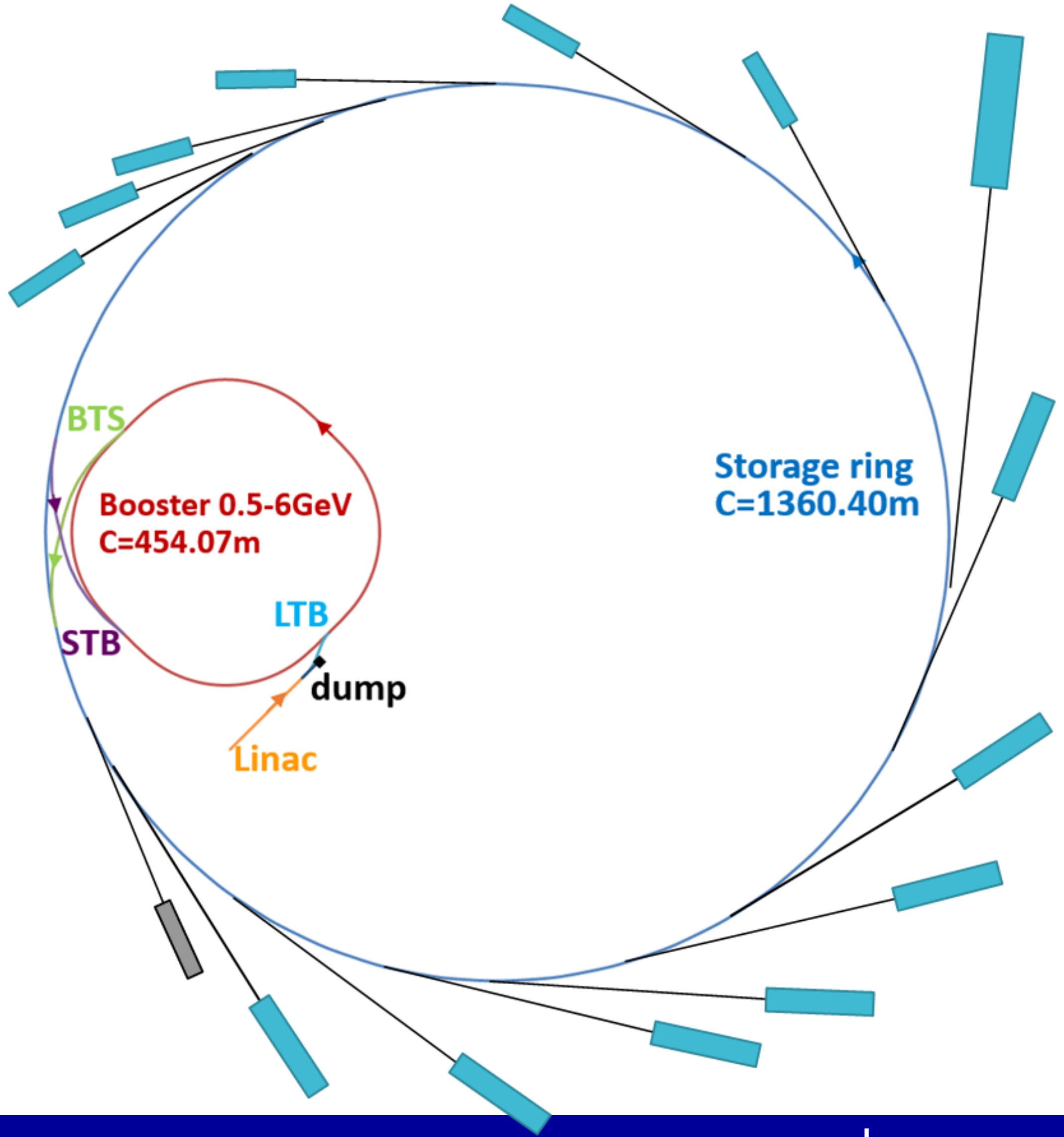
**Low Emittance Ring Workshop 2020（Oct. 26）**

# Outline

- Brief introduction on HEPS
- Schedule, cost & manpower
- Organization of the project
- Main progresses since Jan. 2020
- Risks and mitigation

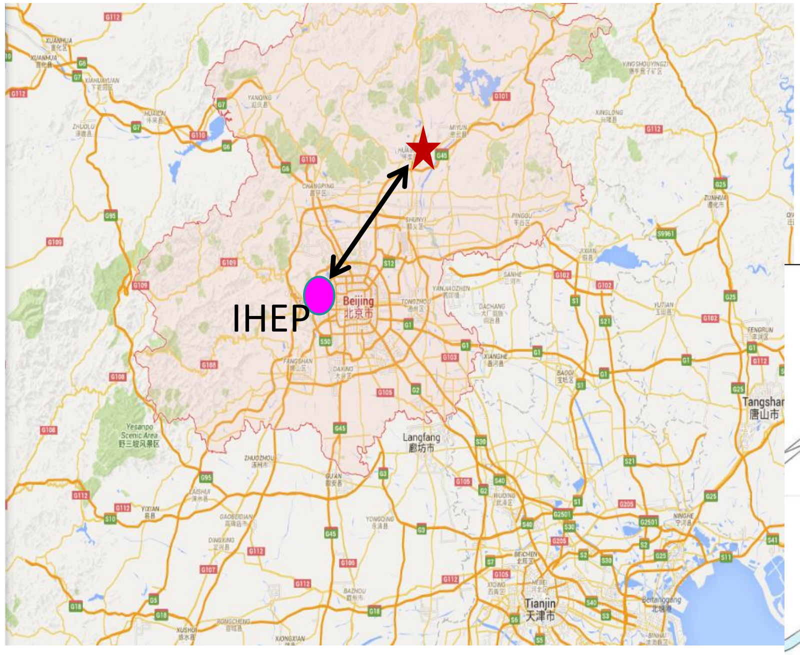
# Design goals of HEPS

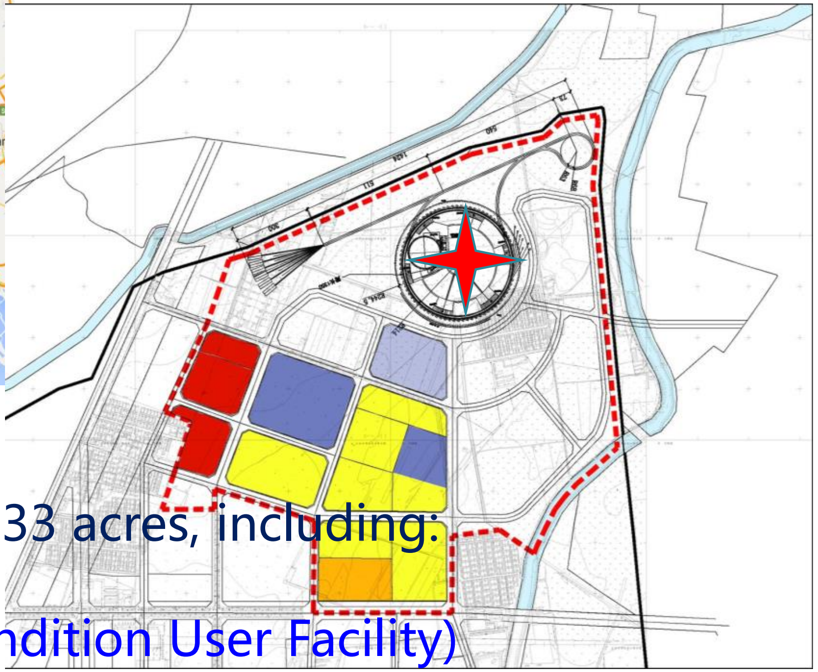
| Main parameters | Unit | Value |
|---|---|---|
| Beam energy | GeV | 6 |
| Circumference | m | 1360.4 |
| Emittance | pm·rad | < 60 |
| Brightness | $phs/s/mm^2/mrad^2/0.1\%BW$ | $>1x10^{22}$ |
| Beam current | mA | 200 |
| Injection | | Top-up |



# Project overview

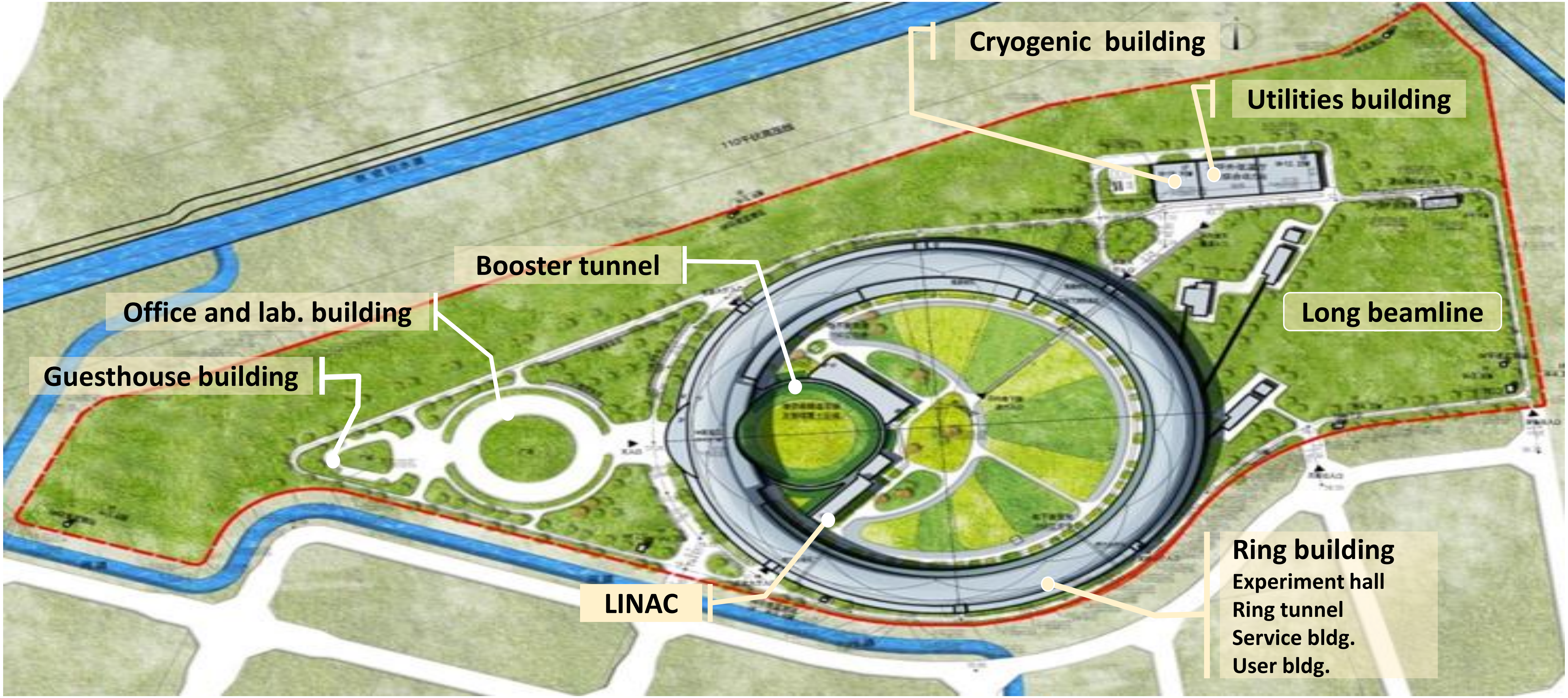
- Location:  Northeast of Beijing， In Huairou district, about 80km away from IHEP




Huairou Science City: An area of 233 acres, including:
- HEPS
- SECUF (Synergized Extreme Condition User Facility)
- Simulation Facility for the Earth
- Series research platforms in energy, environment, biology, materials, etc.

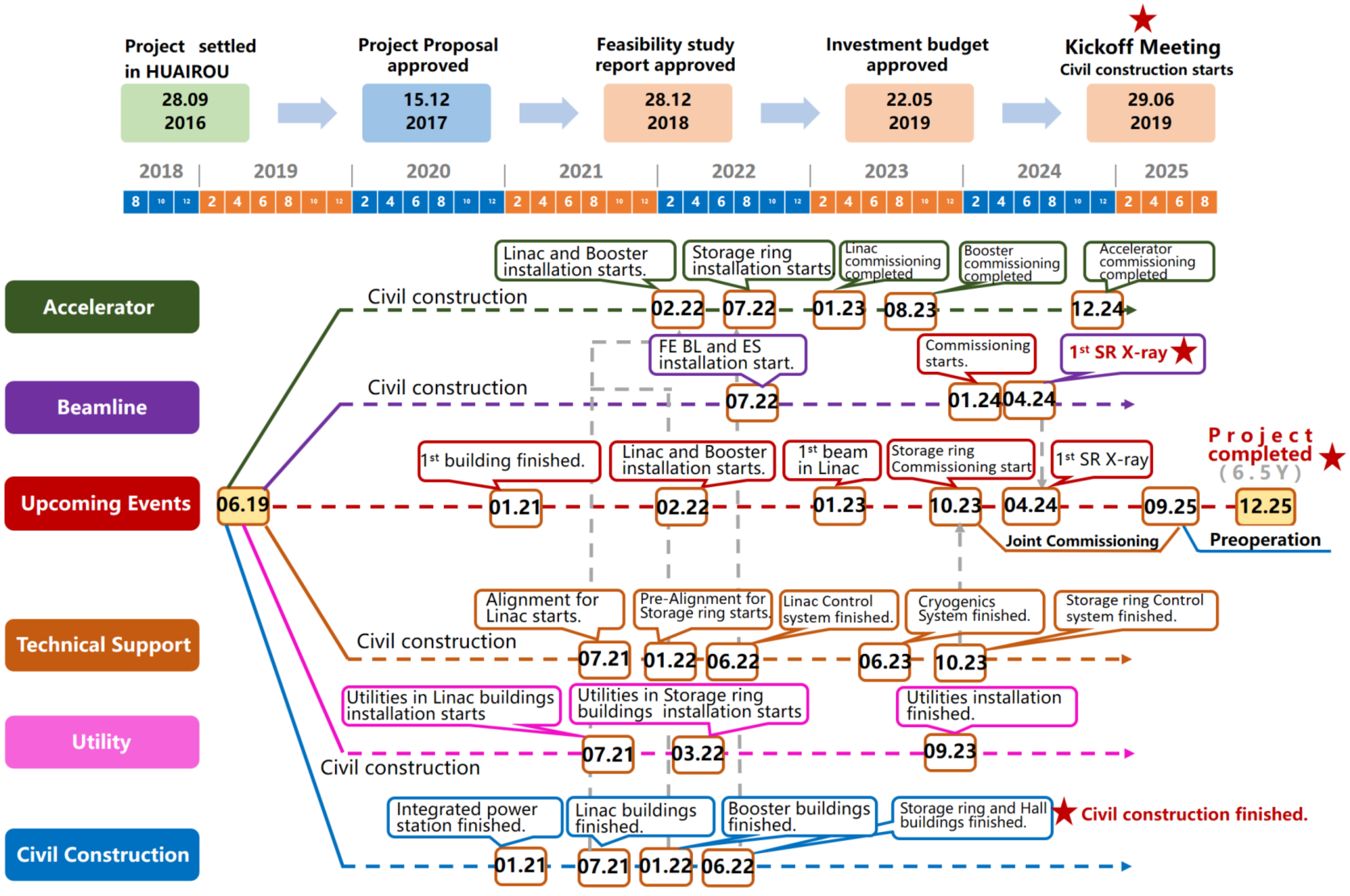
# Project overview



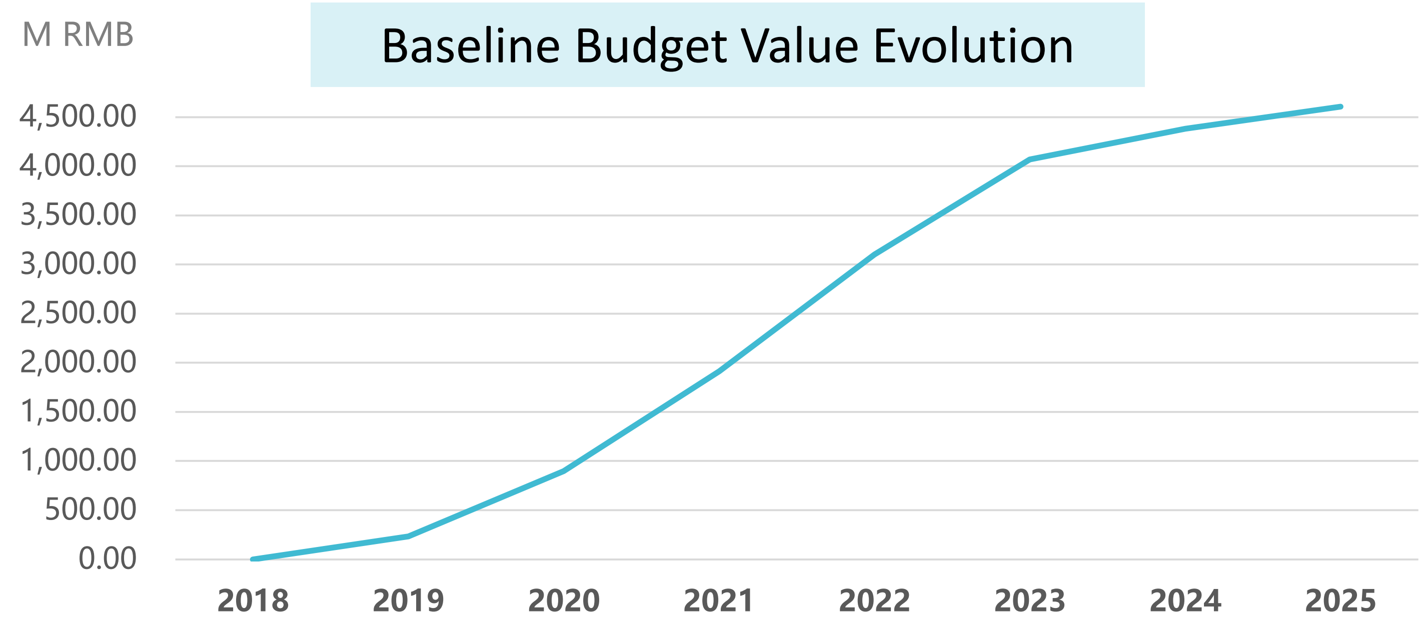
# SCHEDULE

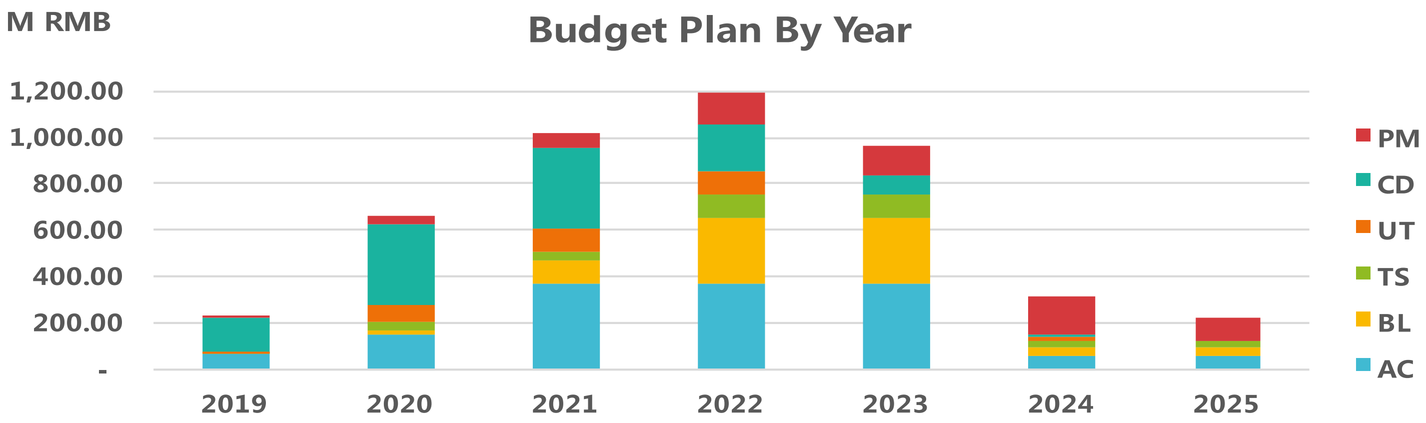
The construction period was estimated to be six and a half years.

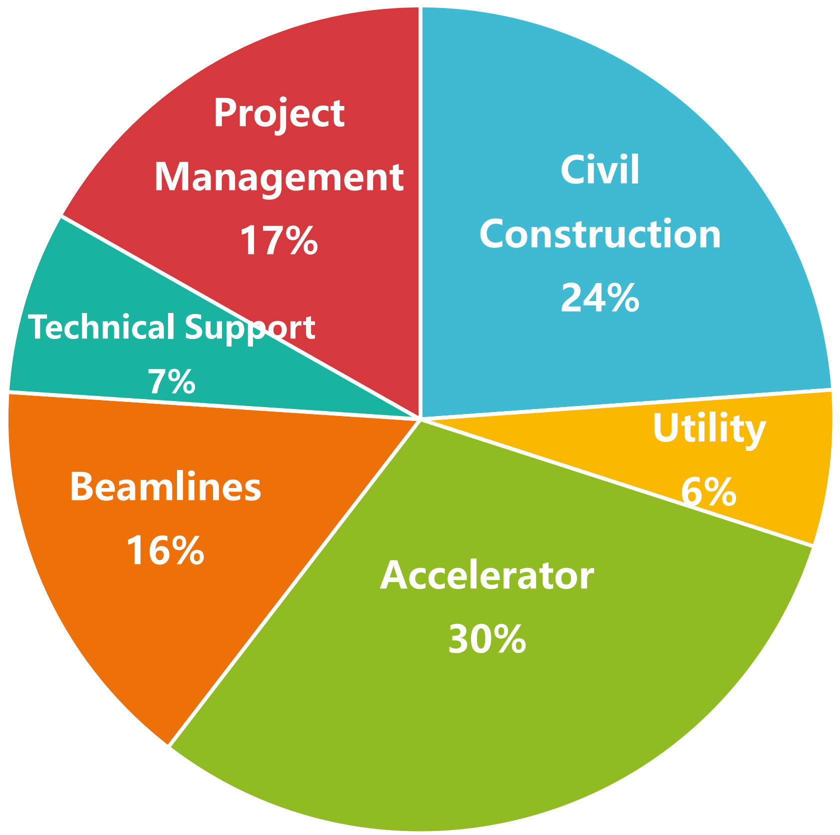
- Date of Groundbreaking ceremony: **Jun. 29, 2019**

# Proposed HEPS Funding Profile

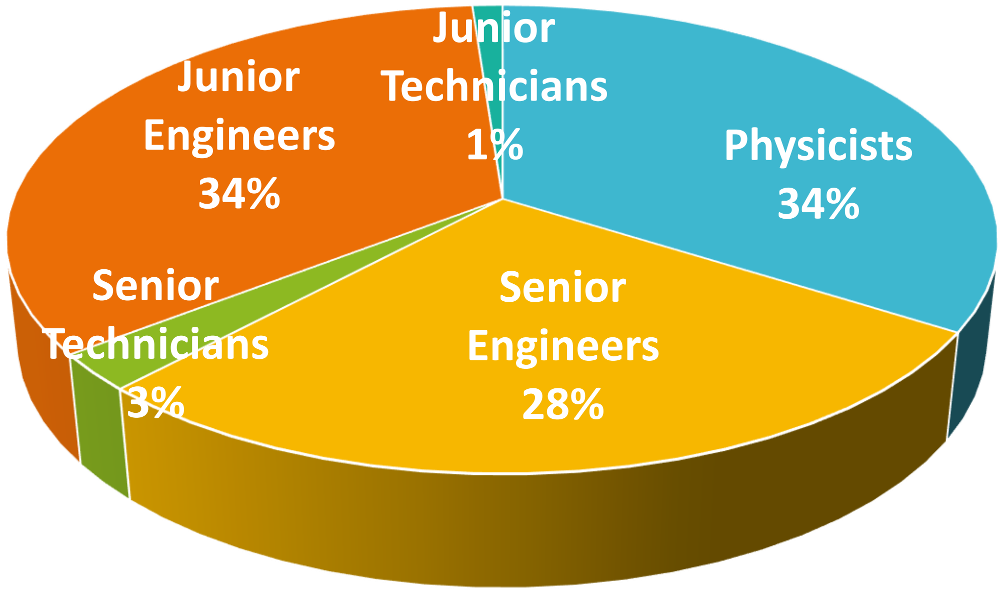


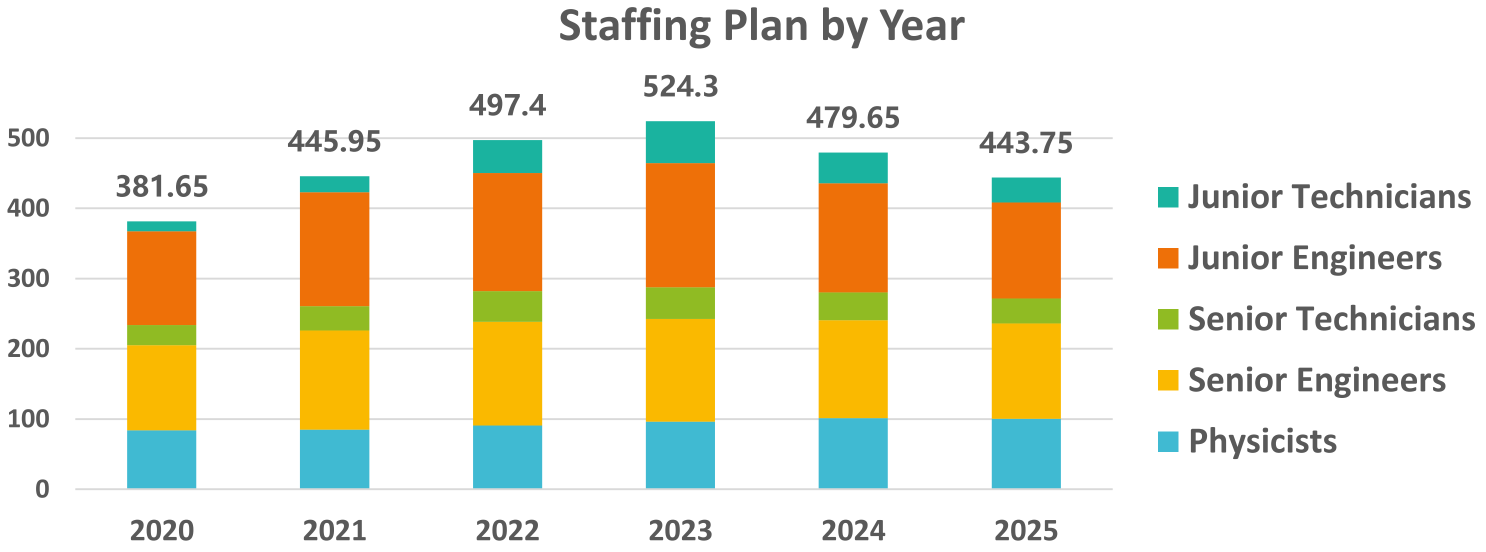

Project Management incl. design + contingency + all fare for admin process + collaboration, etc.

# Manpower




## Project team was formed.

- 275 full-time staff (physicsts-34%,engineers-62%, Technicians-4%)
- ~250 open positions (a 500-person team in 2023 expected)



# ORGANIZATION

- The new project management was announced on Feb. 20,2020.

Project manager _ Weimin PAN

Executive deputy manager _ Yuhui DONG

Deputy manager _ Gang XU， Jian LIANG， Sheng WANG

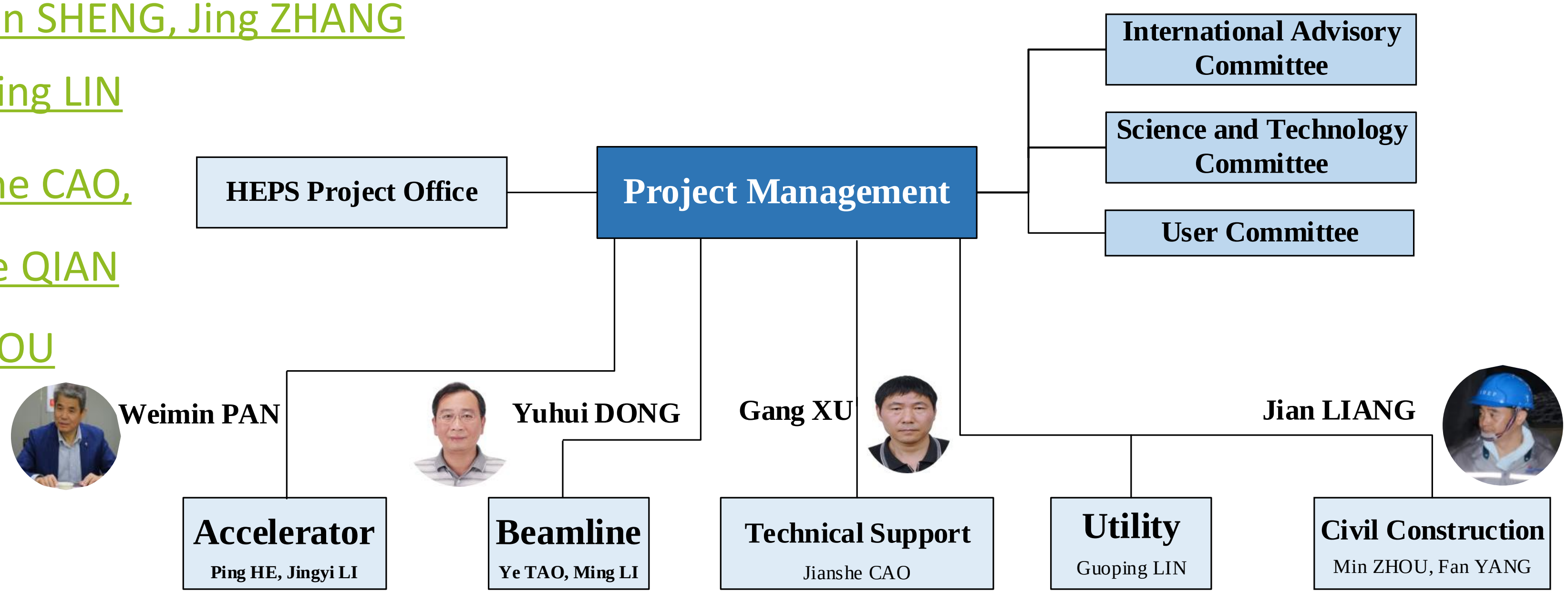
Chief engineer _ Huamin QU

Deputy engineer _ Weifan SHENG, Jing ZHANG

Chief technologist _ Guoping LIN

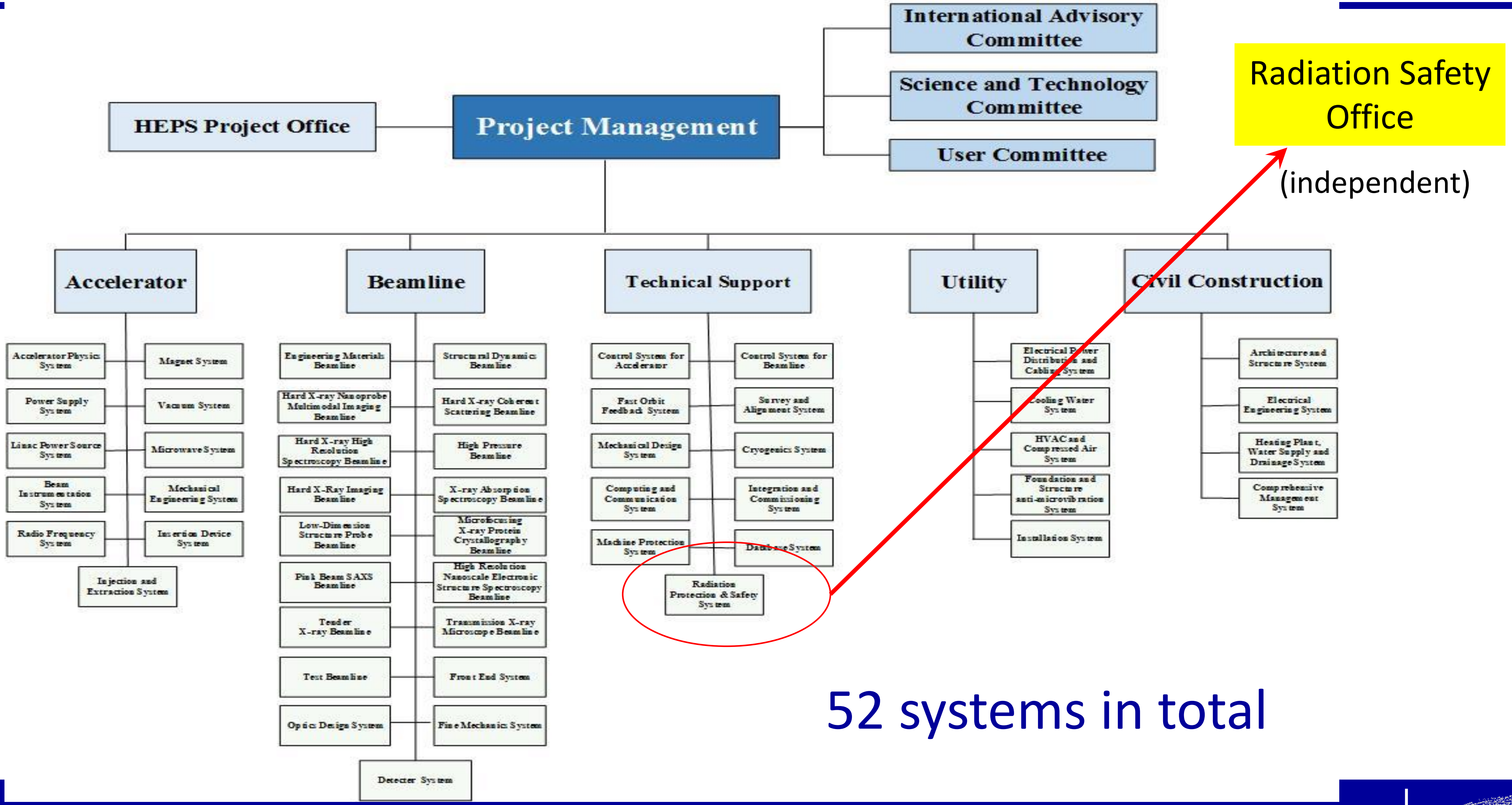
Deputy technologist _ Jianshe CAO, Haijie QIAN

Chief economic manager _ Ya ZHOU




**5 Divisions (52 systems)**

# HEPS Project Organization




52 systems in total

# Accelerator

1. Linac, Booster, Storage Ring
2. Accelerator Physics, Magnet, Power Supply, Vacuum, Mechanical, Insertion Device, RF, Cryogenics, Microwave, Linac Power Source, Injection&Extraction, Alignment

# Proposed Key Performance Parameter Summary

- Accelerator design

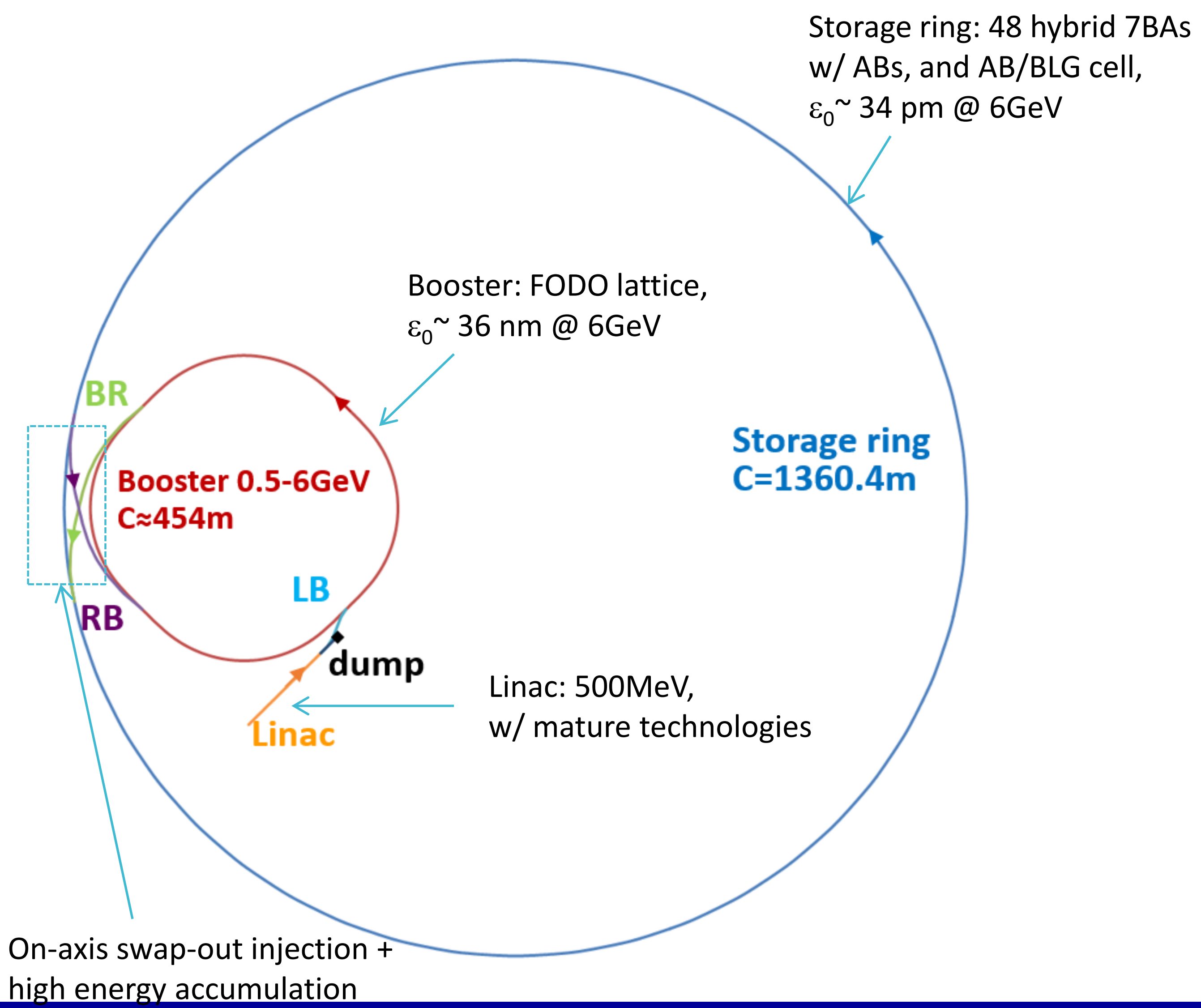
| Main parameter | Design | Goal@12/2025 for test |
|---|---|---|
| Beam energy | 6 GeV | 6 GeV |
| Beam current | 200 mA | 100 mA |
| Circumference of SR | 1360.4 m | |
| Circumference of booster | 454.5 m | |
| Hori. Natural emittance | <0.06 nm·rad | 0.1 |
| Brightness | $>1\text{x}10^{22}$ phs/s/mm$^2$/mrad$^2$/0.1%BW | $2\text{x}10^{21}$ phs/s/mm$^2$/mrad$^2$/0.1%BW |

# Accelerator Physics

**To deal with challenges from technical and engineering design, updated the accelerator physics design** [1,2,3,4]

- 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


[1]. Y. Jiao, et al., RDTM (2020).
[2]. Y. Peng, et al., RDTM (2020).
[3]. C. Meng et al., RDTM (2020).
[4]. Y. Guo et al., RDTM (2020).

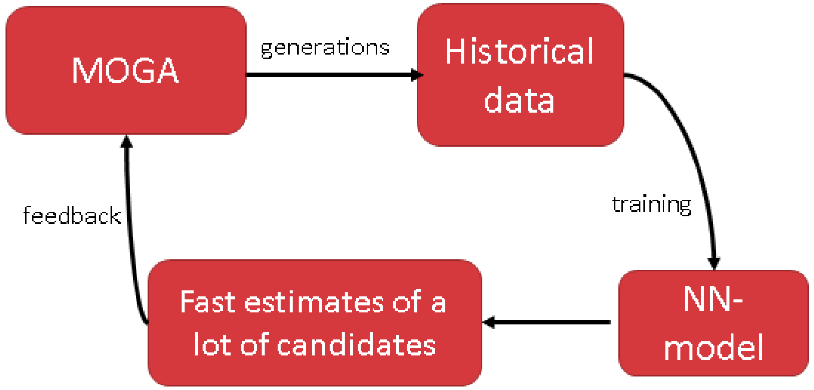
# Accelerator Physics –cont.

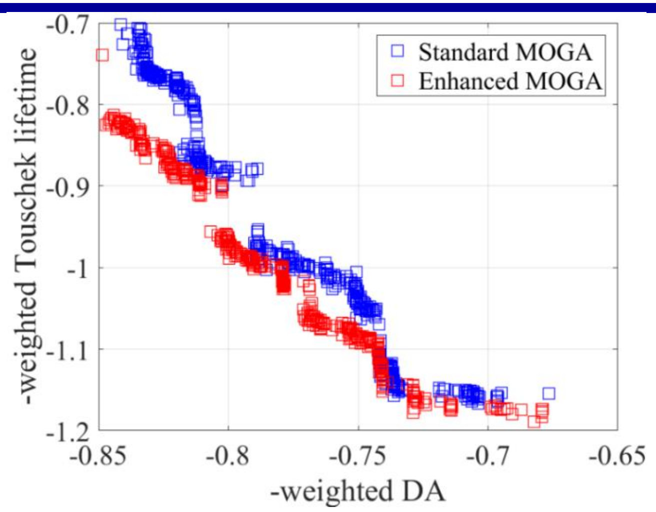
Proposed neural network enhanced MOGA for lifetime optimization [1]

— use the trained model to make fast estimates in a fraction of second (vs. 3 hrs)

—promises less seeds to bring more diversities in solutions

— lifetime further improved by more than 10%



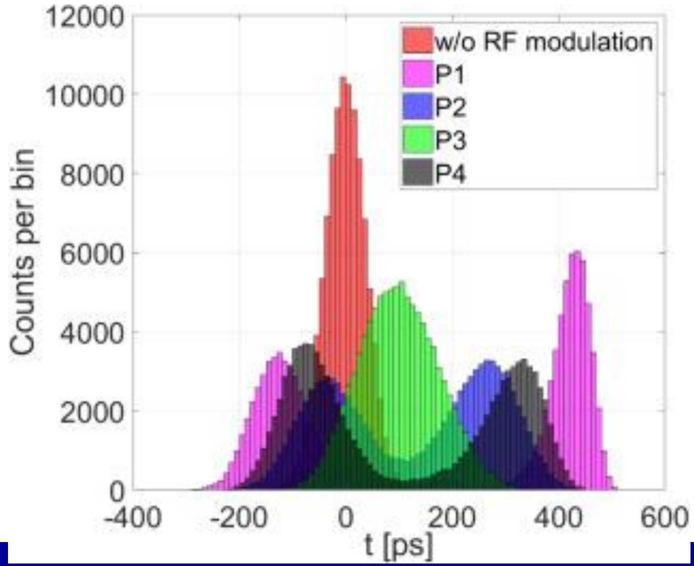


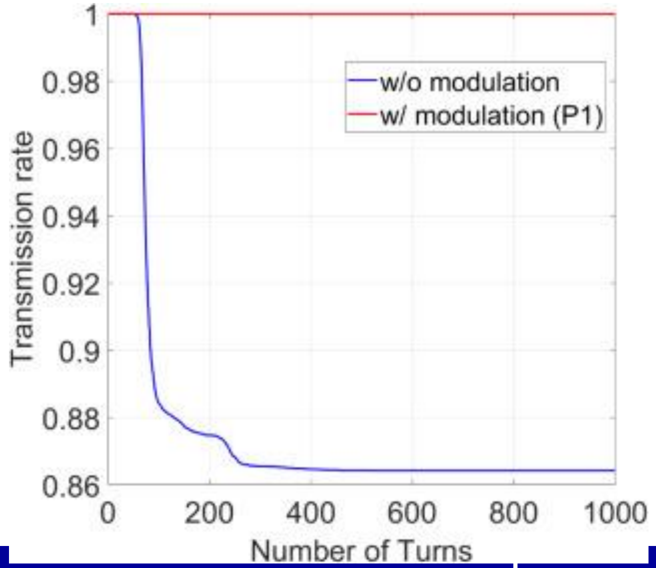
[1]. J. Wan, P. Chu, Y. Jiao, PR-AB (2020).
[2]. H. Xu, Z. Duan, N. Wang, G. Xu, NIM-A (2020).


Possibility studies of applying RF modulation in booster to help injection [2]

— Collective instability in the transient swap-out injection process may limit injection efficiency

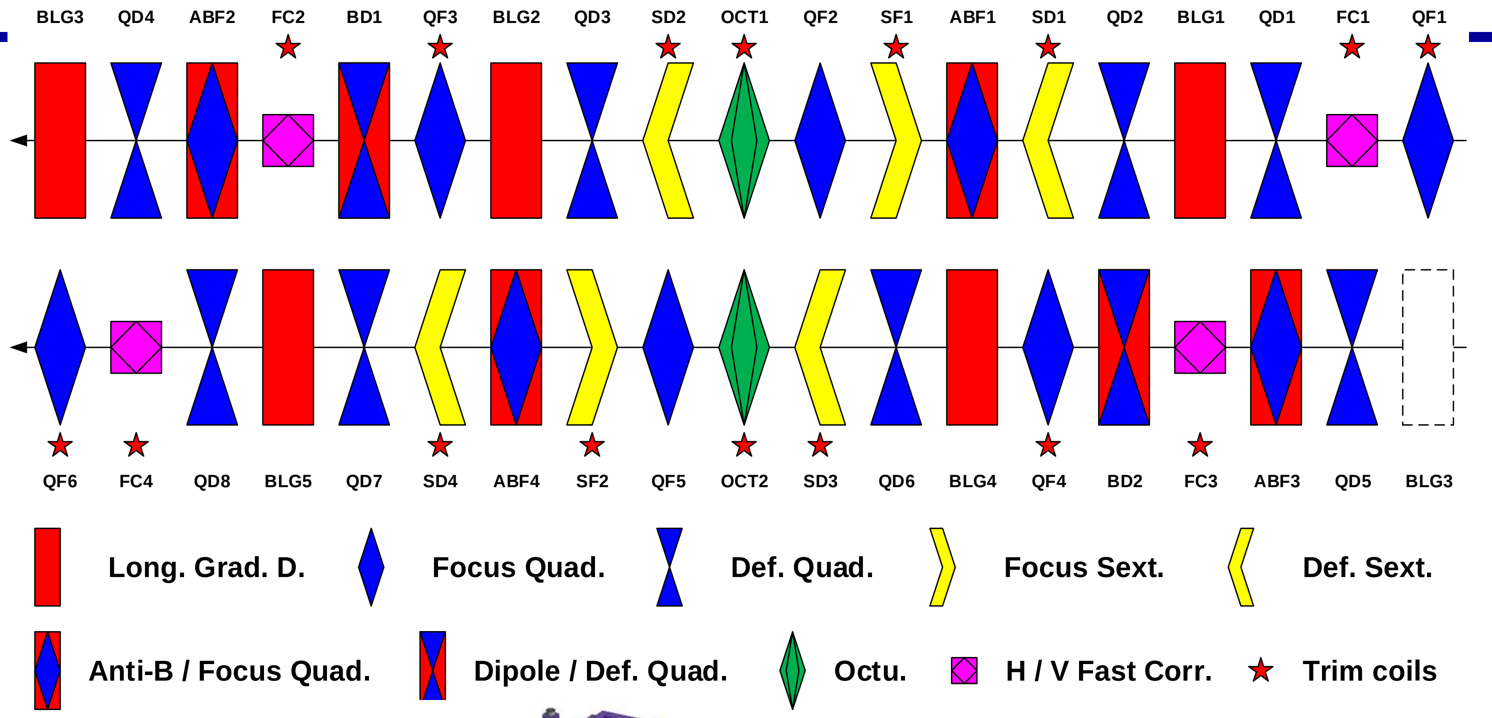
— Lengthen the bunch w/ RF modulations in booster

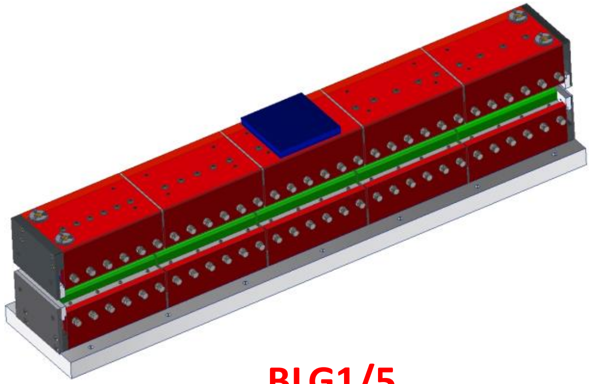


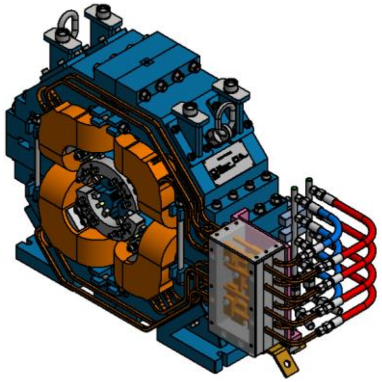
# Magnets of Storage Ring

- Magnets
  - 37 magnets in one 7BA cell
  - BLG 0.11 – 1 T
  - Quad 82 T/m
  - BD 66 T/m
  - Sext 6082 T/m$^2$
  - Oct 512600 T/m$^3$
  - Fast Corr 0.08 T

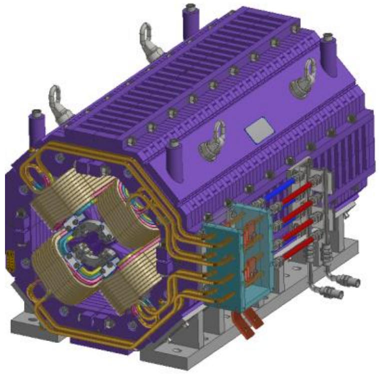


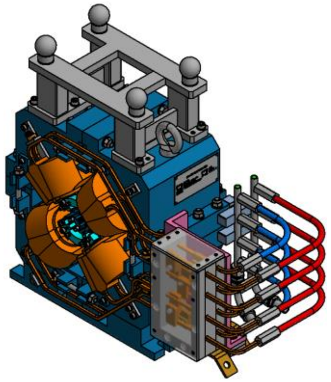
BLG1/5



ABF1/4



BD1/2



QD7

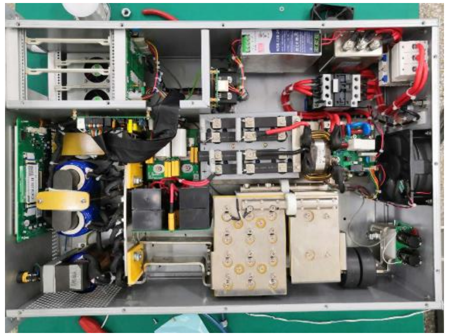
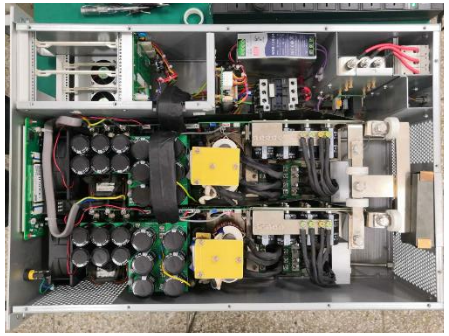
# Storage ring magnet

- Sextupoles and Octupoles begin the mass production
- 1st article prototype.

Core and coils of sextupole

Core and coils of octupole

# High Precision Stabilized DC Power Supply

| Prototype | Scheme |
|---|---|
|  | IGBT,<br>One single module |
|  | MOSFET,<br>Two modules in parallel |
|  | MOSFET,<br>One single module |

## Test result

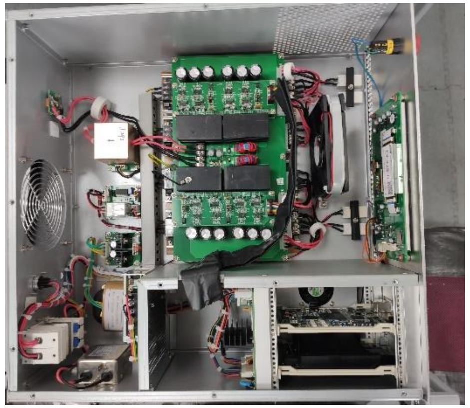
1.Three power supply prototypes with different topologies are produced and tested.

2. The test results of each prototype meet the specification.

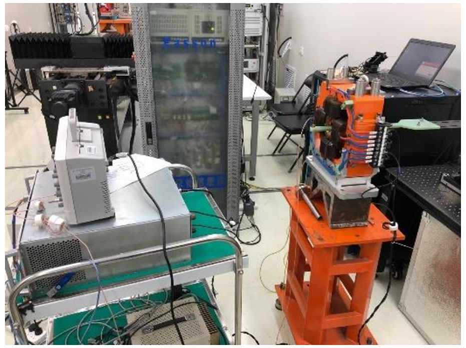
Stability
290A： 5.12ppm
240A： 6.1ppm
150A： 6.0ppm
60A： 9.2ppm

Repeatability
Better than 20 ppm

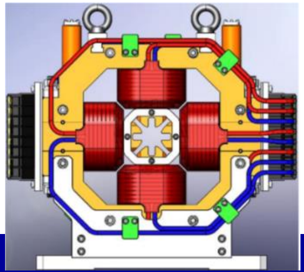
# Fast Correction Power Supply



prototype

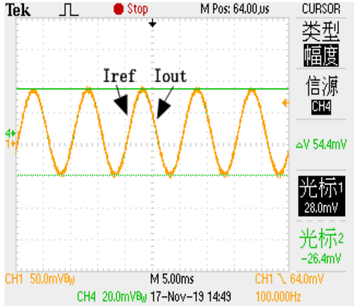


test platform

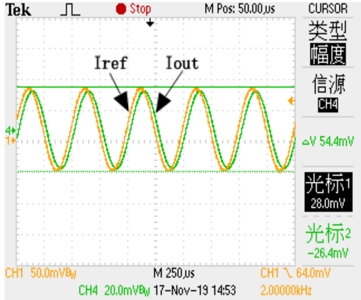


## Test result

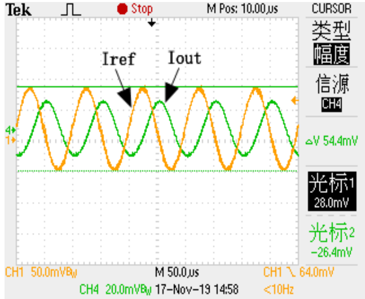
### 1.amplitude-frequency test




0.16A@100Hz



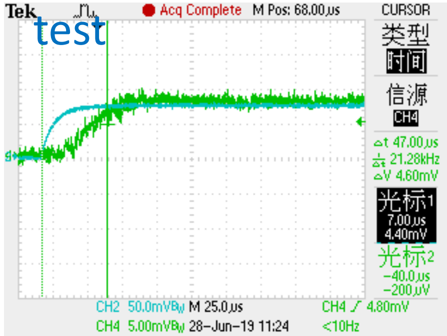

0.16A@2kHz



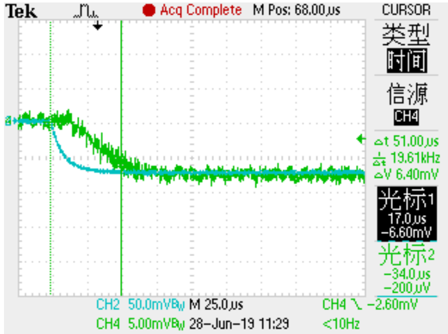

0.16A@10kHz

| Current setting | amplitude attenuation（dB） | phase delay（°） |
|---|---|---|
| 0.16 A@ 100 Hz | -0.08 | 0.7 |
| 0.16 A@ 2 kHz | -0.36 | 36 |
| 0.16 A@ 5 kHz | -1.2 | 72 |
| 0.16 A@ 10 kHz | -2.7 | 105 |

### 2.Step response test



3→3.08A Step



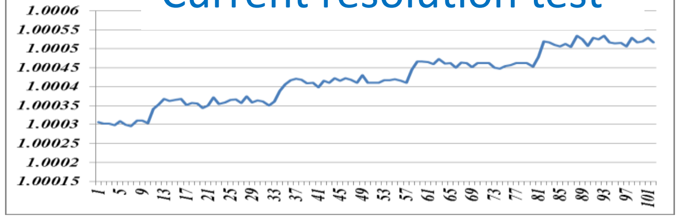
3.08→3A Step

| Current setting（A） | Response time（μS） |
|---|---|
| 0→0.08 | 53 |
| 0→0.16 | 62 |
| 3→3.08 | 57 |
| 3→3.16 | 64 |
| 13.16→13 | 63 |
| 13.08→13 | 52 |
| 3.16→3 | 62 |
| 0.16→0 | 62 |

### 3.Current wave test

| Current setting（A） | 1 | 5 | 10 | 15 | -1 | -5 | -10 | -15 |
|---|---|---|---|---|---|---|---|---|
| FFT RMS（μV | 89.8 | 99.3 | 95.9 | 96 | 88.9 | 98.2 | 92.2 | 91.2 |
| Current wave（ppm） | 17.96 | 19.86 | 19.18 | 19.2 | 17.78 | 19.64 | 18.44 | 18.24 |

### Current resolution test

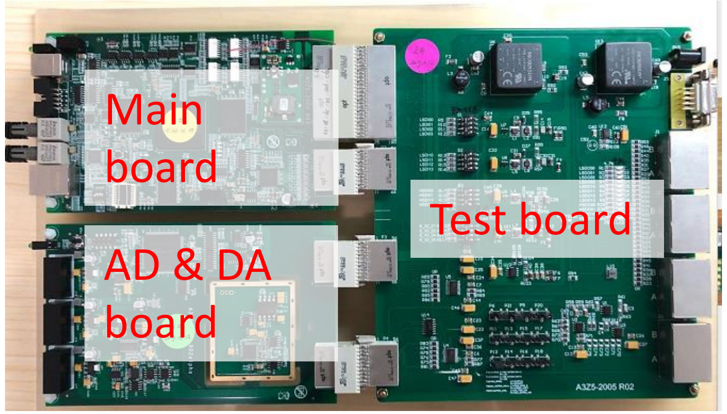


result： 18bit

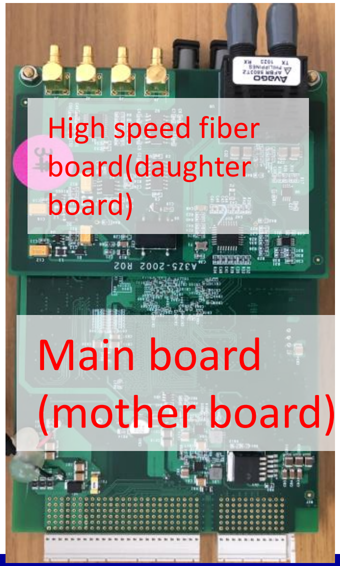
$$I_{resolution} = \frac{I_{vern}}{I_s}$$

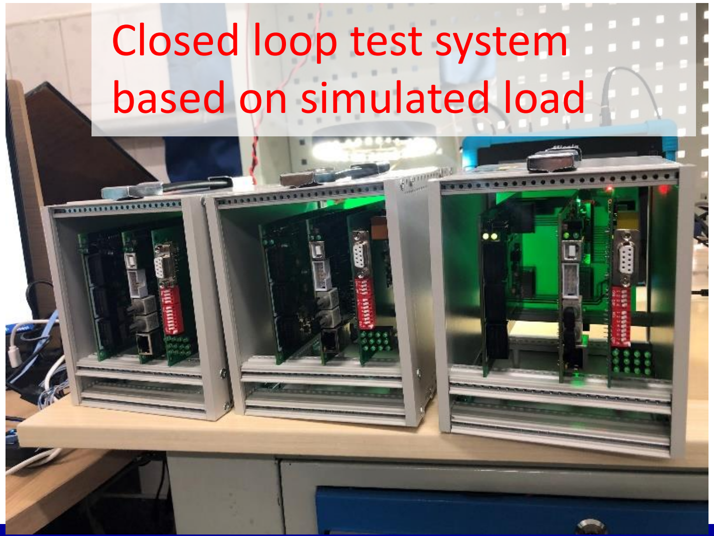
# DPSCM & DCCT

## Digital power supply control module(DPSCM)




finalized and used in PS prototype



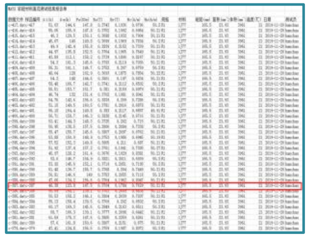




## DCCT

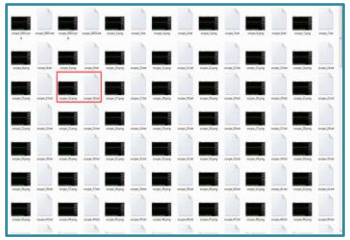
In mass production stage

Each DCCT data records and technical specifications, which can be traced in detail.

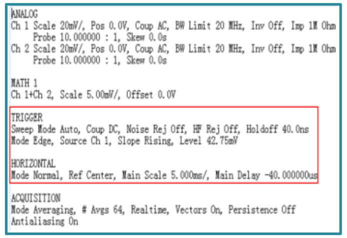
Single ring test record



Test data



Paired waveform record



ANALOG
Ch 1 Scale 20mV/, Pos 0.0V, Coup AC, BW Limit 20 MHz, Inv Off, Imp 1M Ohm
Probe 10.000000 : 1, Skew 0.0s
Ch 2 Scale 20mV/, Pos 0.0V, Coup AC, BW Limit 20 MHz, Inv Off, Imp 1M Ohm
Probe 10.000000 : 1, Skew 0.0s

MATH 1
Ch 1+Ch 2, Scale 5.00mV/, Offset 0.0V

TRIGGER
Sweep Mode Auto, Coup DC, Noise Rej Off, HF Rej Off, Holdoff 40.0ns
Mode Edge, Source Ch 1, Slope Rising, Level 42.75mV

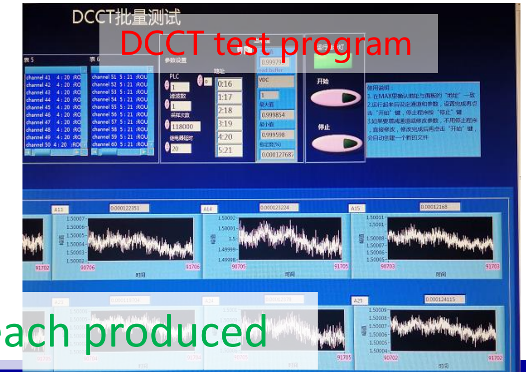
HORIZONTAL
Mode Normal, Ref Center, Main Scale 5.000ms/, Main Delay -40.000000us

ACQUISITION
Mode Averaging, # Avgs 64, Realtime, Vectors On, Persistence Off
Antialiasing On

Matching error record

Up to now, 1450 of 20a and 580 of 300A have been produced.

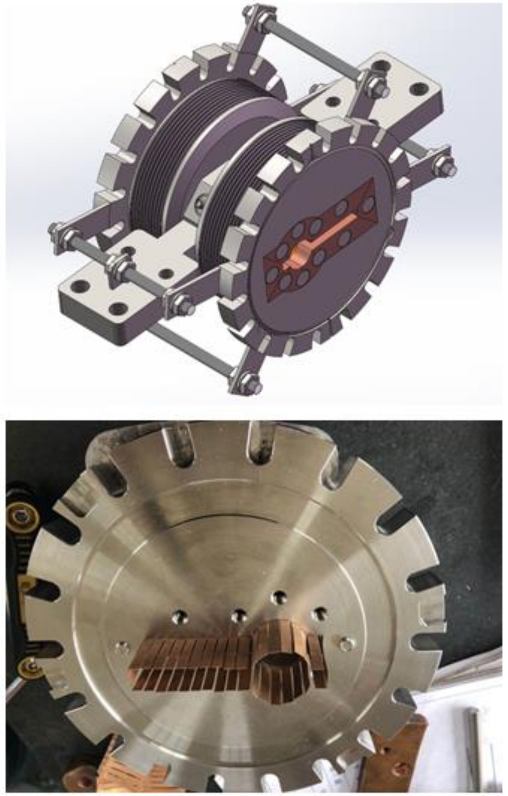




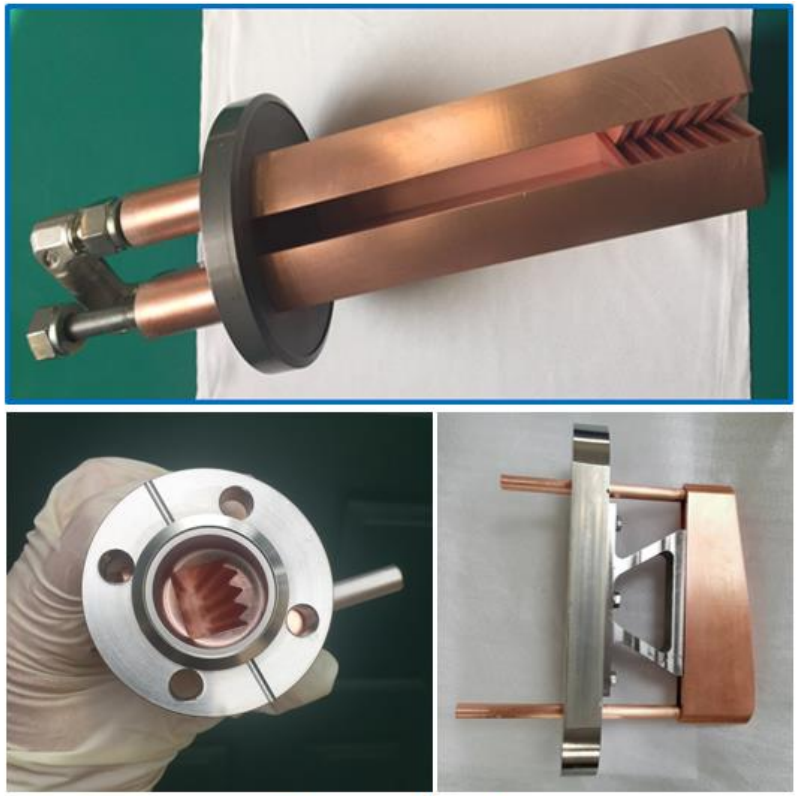

strict testing has been taken to each produced

# Vacuum

Vacuum chamber



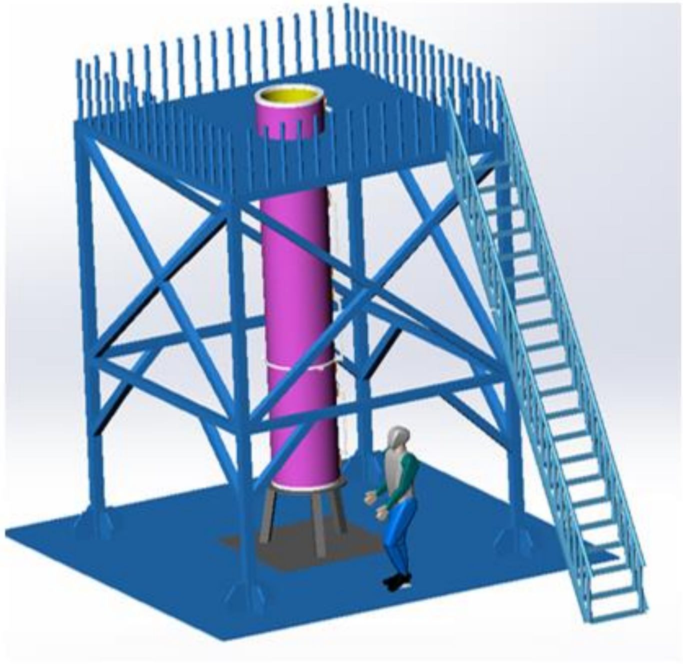
RF shielding bellows

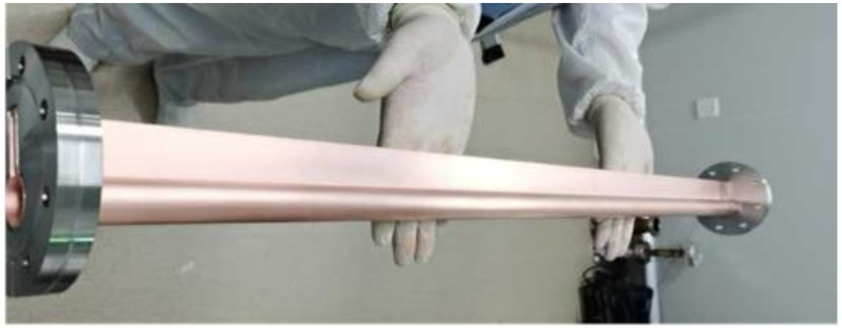


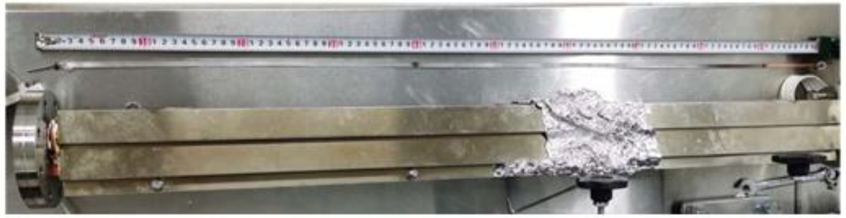
Photon absorber

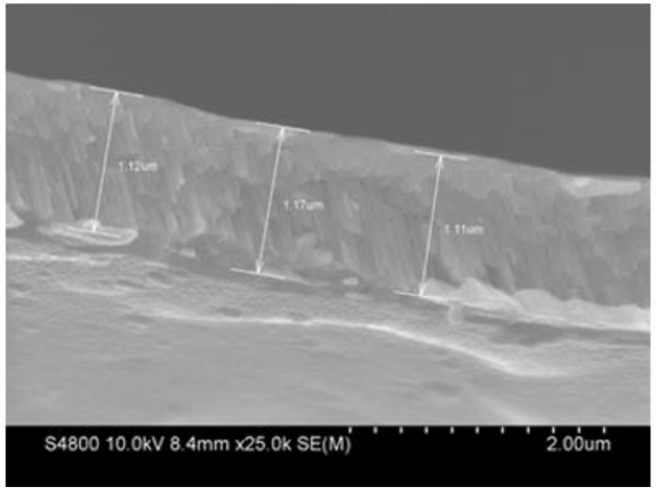
- The engineering drawings of the vacuum components for Linac, transport lines and booster have been completed, and the bids of massive production are underway.
- The prototypes of some key components in storage ring such as vacuum chambers, RF bellows and photon absorbers are being manufactured.

# Vacuum









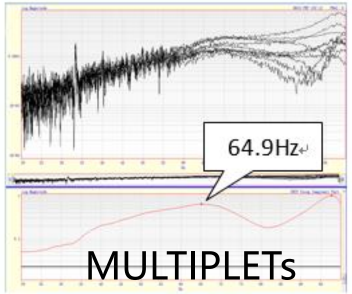

### NEG Coating

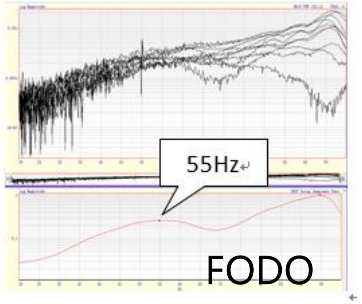
- The synchrotron radiation light channel of antechamber with a height of 6 mm has been coated with NEG films based on many times experiments.
- The setup of the massive NEG coating for the vacuum chambers has been designed, and started to produce.

# Girder & Magnet Support

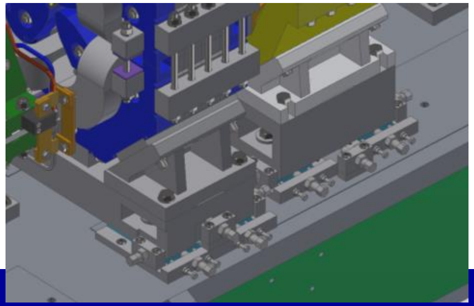
- SR Magnet support system
  - Factory acceptance of the girder prototype has been finished. Adjusting and stability performance meet the design requirements.
    - ✓ Adjusting resolution :1μm
    - ✓ 1st natural frequency :>54Hz(requirement)

1st natural frequency



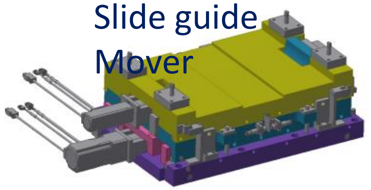




  - Prototypes of concrete plinth are manufactured and grouted in the test hall. Modal test has been performed and the result is better than expected.
    - ✓ Transverse modes >400Hz(most concerned)
  - Adjustable magnet support on girder has been designed.
    - ✓ Ultra-thin wedge are adopted to give good performance on both adjustability and stability.

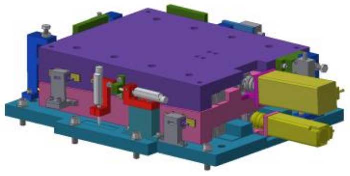


# Mechanical system

- SR Sextupole Mover
  - Fully test of the 1st prototype accomplished.
  - Modified prototypes are designed and in manufacturing to secure reliability.
    - Scheme of slide guide without motion coupling  is preferred.
    - 1scheme will also be studied to test the possible stability.

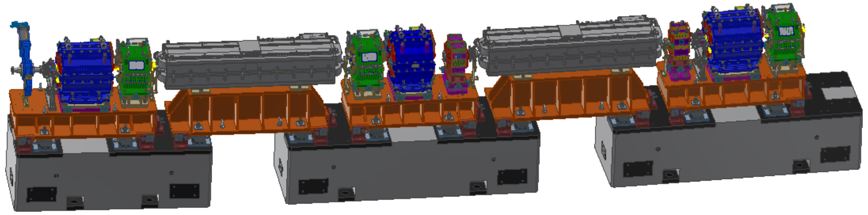


Slide guide Mover

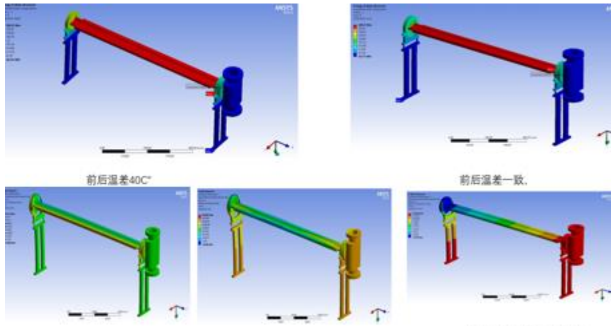


Rolling guide Mover

- BS Magnet support
  - Design finished and reviewed.
  - Tender is under way.

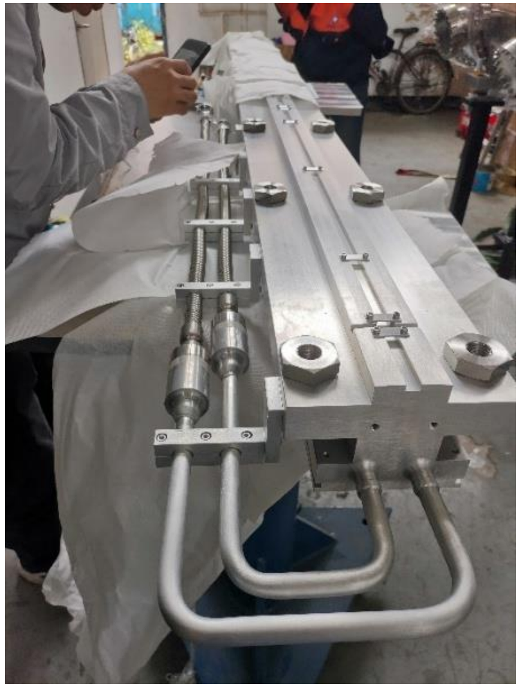


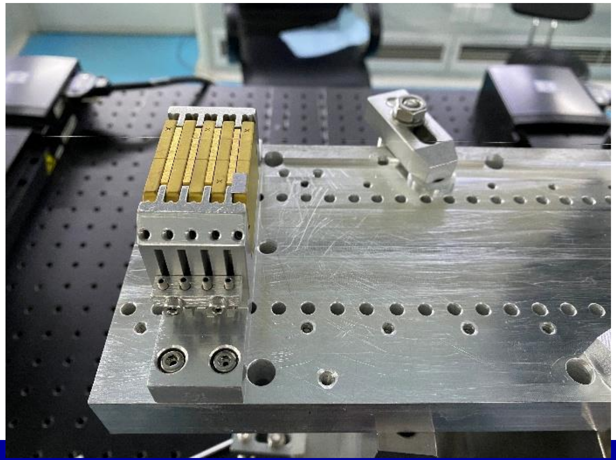
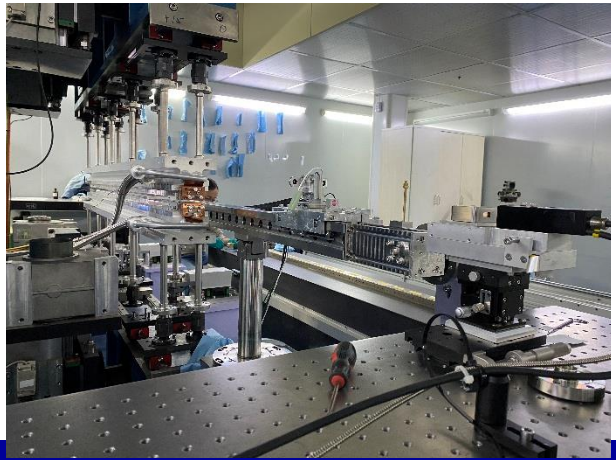
- Support of vacuum chamber
  - Installation manipulating space has been checked.
  - Thermal stress has been evaluated for the support of VC with high power deposition in Apple knot light beam line.
  - Prototype will be fabricated to test the adaptation of VC baking expansion.



# AA ID System Progress CPMU Engineering Prototype

- CPMU engineering prototype is the key task this year. Magnets and poles with TiN coating are ready, the production of modified mechanical structure is done, assembly is ongoing, commissioning will be started soon.
- In-vacuum Hall probe bench is upgraded, under tuning.

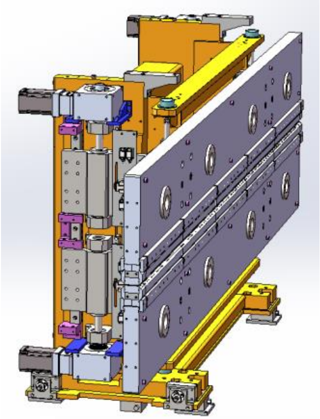
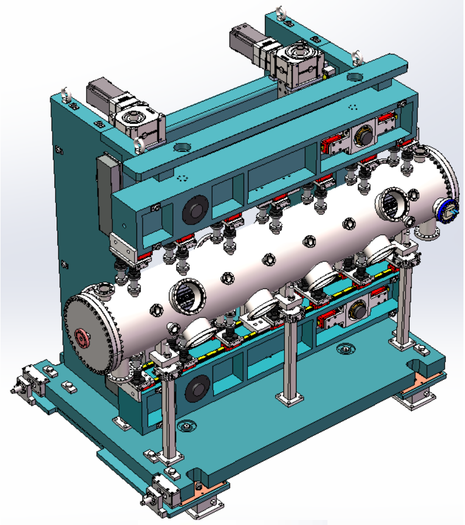
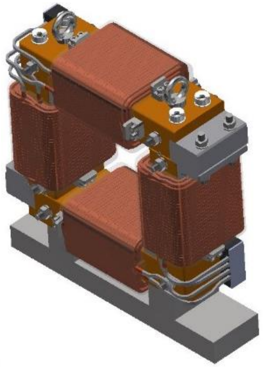
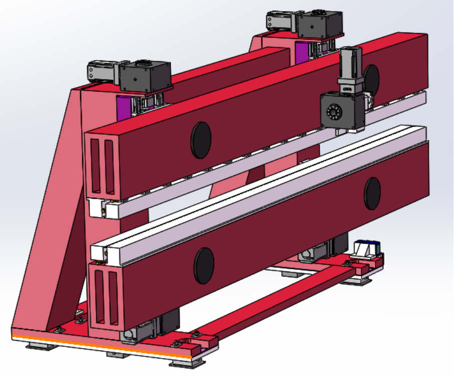
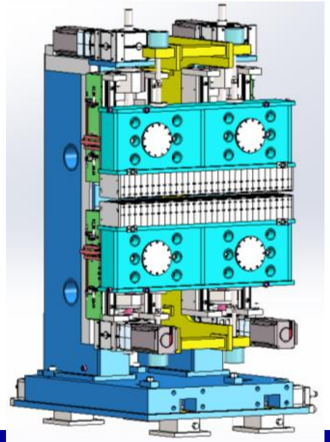
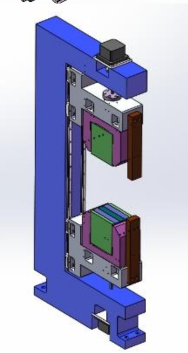
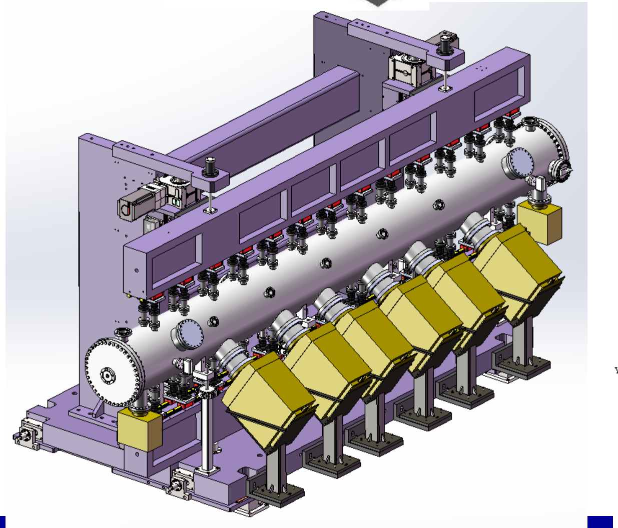
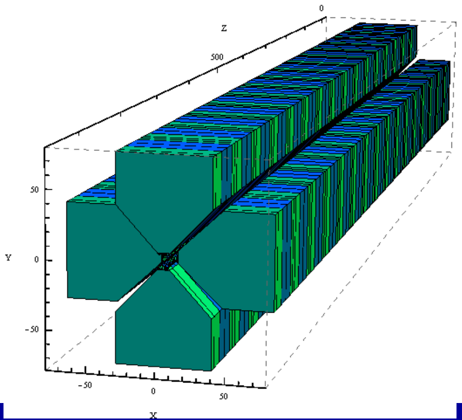



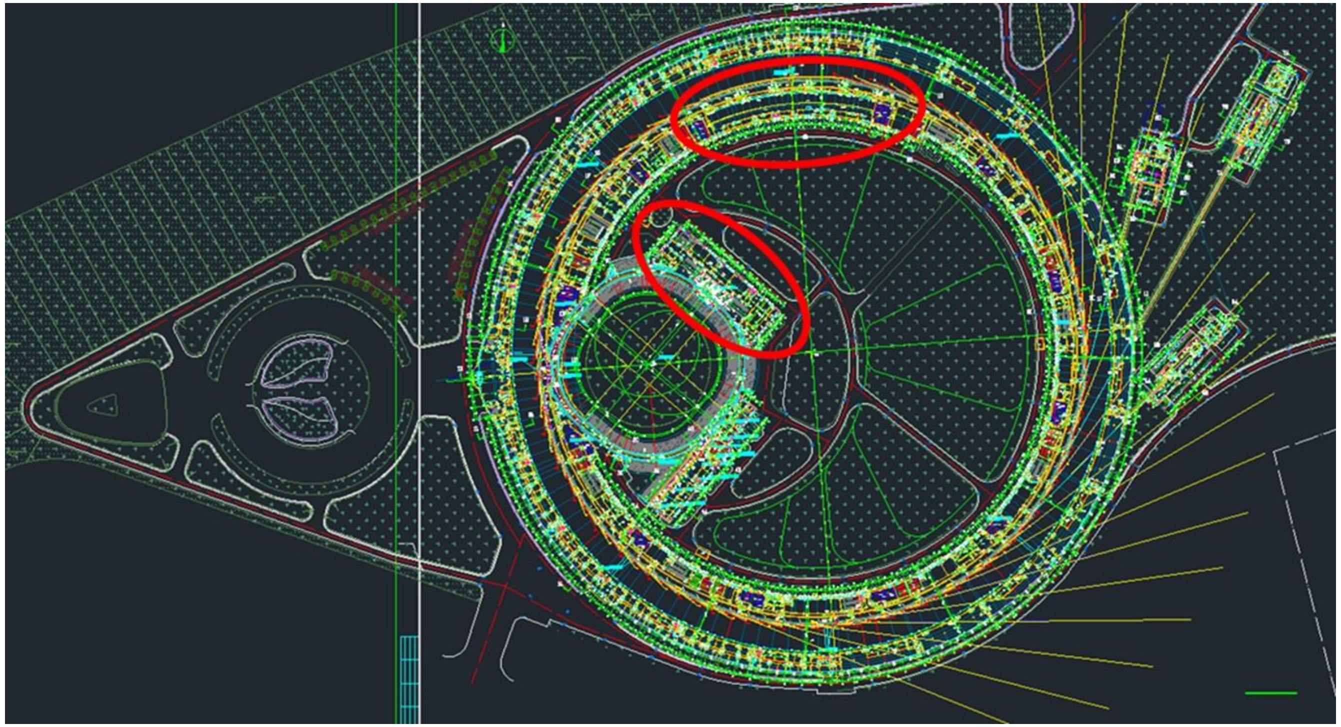
# AA ID System Progress

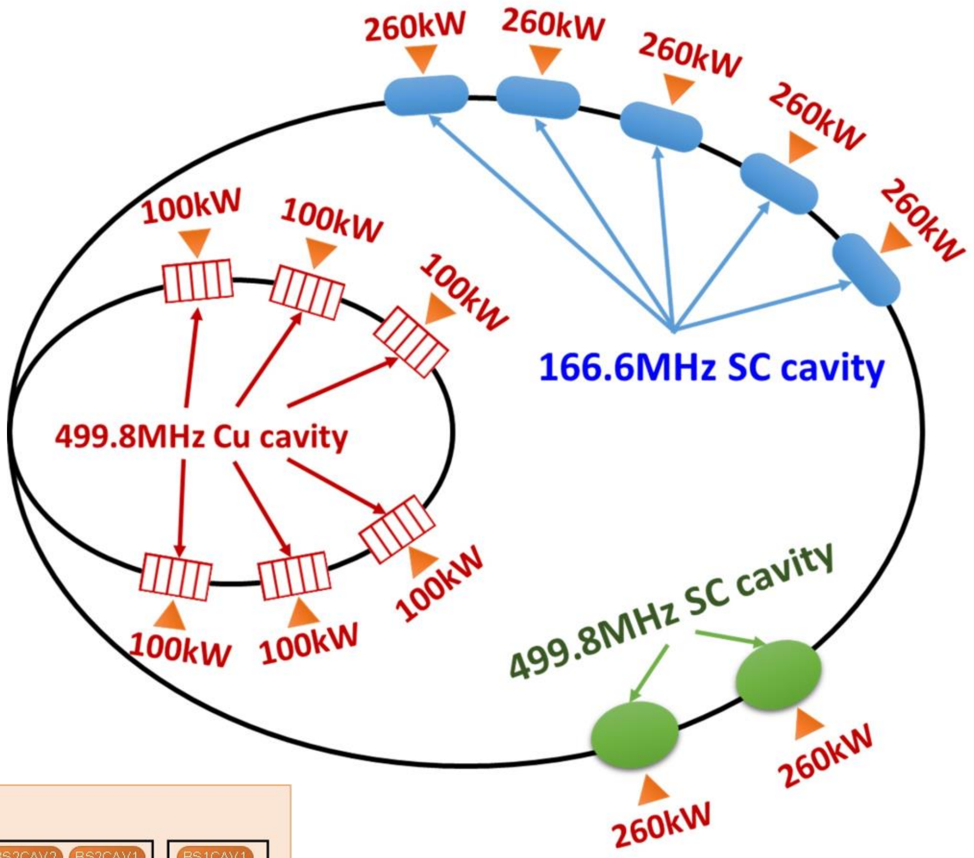
## Other IDs' progress

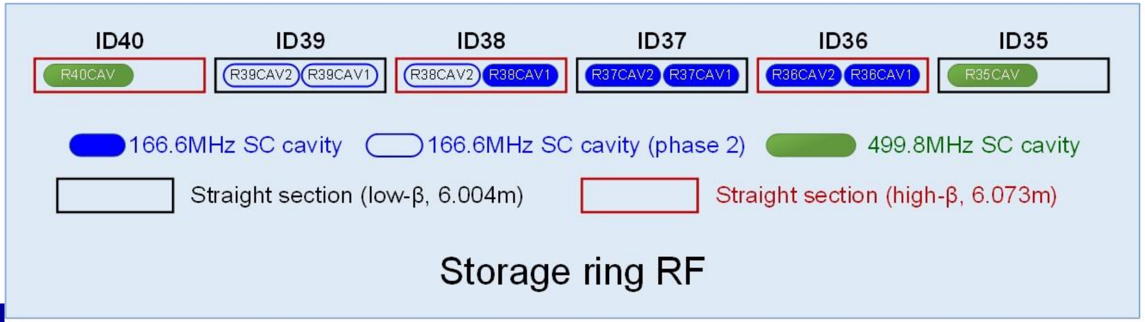
- The design review of IAU、IAW、IVU is finished. Call for tender and procurement are carrying out.
- The preliminary design of AK undulators, Mango wiggler is done.

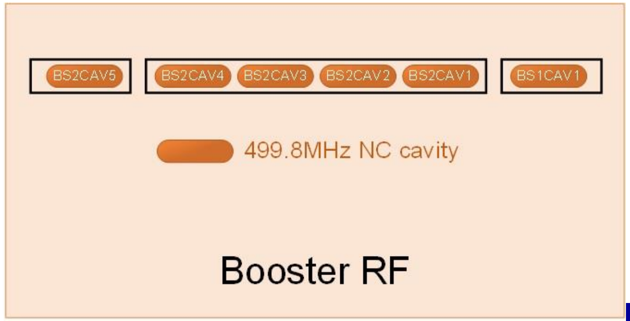









# RF system



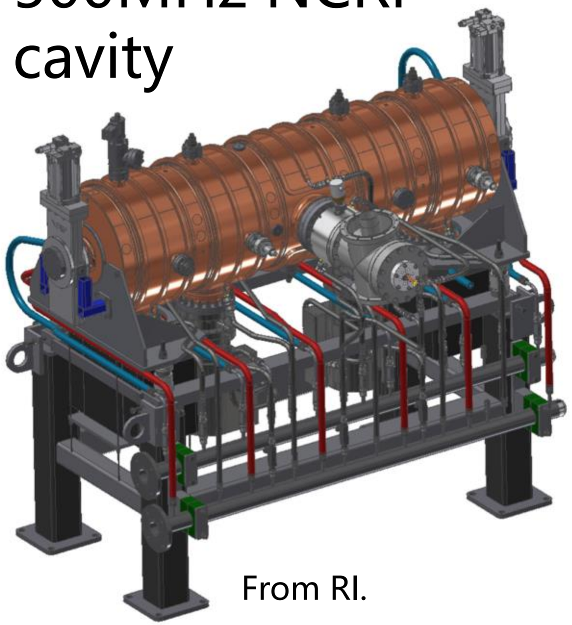

260kW
260kW
260kW
260kW
260kW
100kW
100kW
100kW
166.6MHz SC cavity
499.8MHz Cu cavity
100kW
100kW
100kW
499.8MHz SC cavity
260kW
260kW


ID40
ID39
ID38
ID37
ID36
ID35
R40CAV
R39CAV2
R39CAV1
R38CAV2
R38CAV1
R37CAV2
R37CAV1
R36CAV2
R36CAV1
R35CAV
166.6MHz SC cavity
166.6MHz SC cavity (phase 2)
499.8MHz SC cavity
Straight section (low-β, 6.004m)
Straight section (high-β, 6.073m)
Storage ring RF


BS2CAV5
BS2CAV4
BS2CAV3
BS2CAV2
BS2CAV1
BS1CAV1
499.8MHz NC cavity
Booster RF

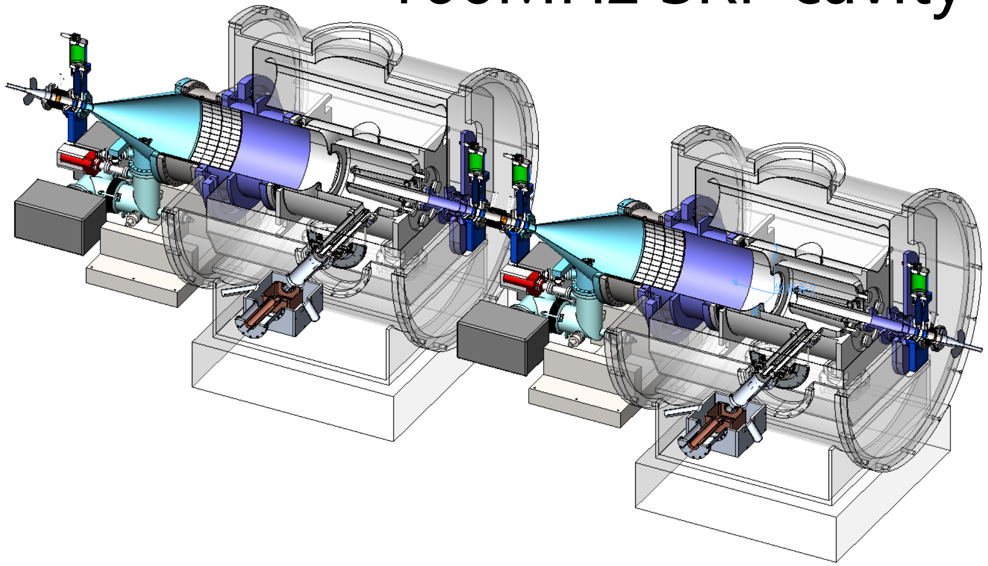
# Cavity system

500MHz NCRF cavity

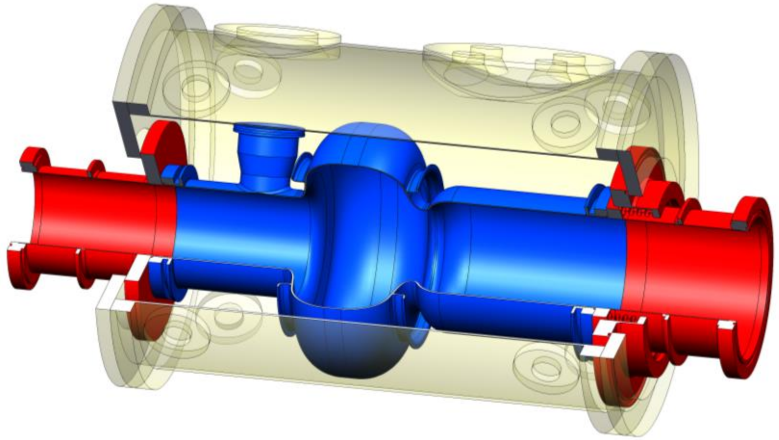


From RI.

166MHz SRF cavity



500MHz SRF cavity



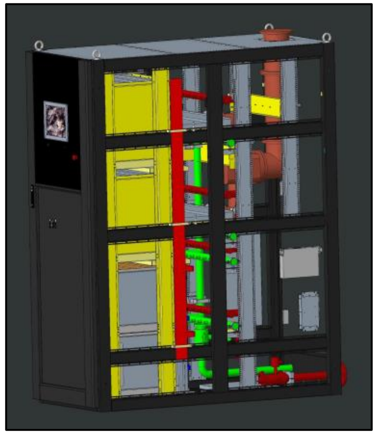
- **500MHz NCRF cavity**
  - Contract awarded (03.2020)
  - Final design review approved (08.2020)
  - Production underway
  - 1st cavity expected 10.2021

- **166MHz & 500MHz SRF cavity**
  - Cavity technical design reviewed (08.2020)
  - Cavity & FPC contract awarded (10.2020)
  - Cryomodule design underway
- **500MHz SRF cavity**
  - Mechanical optimization completed (09.2020)
  - Technical design to be reviewed

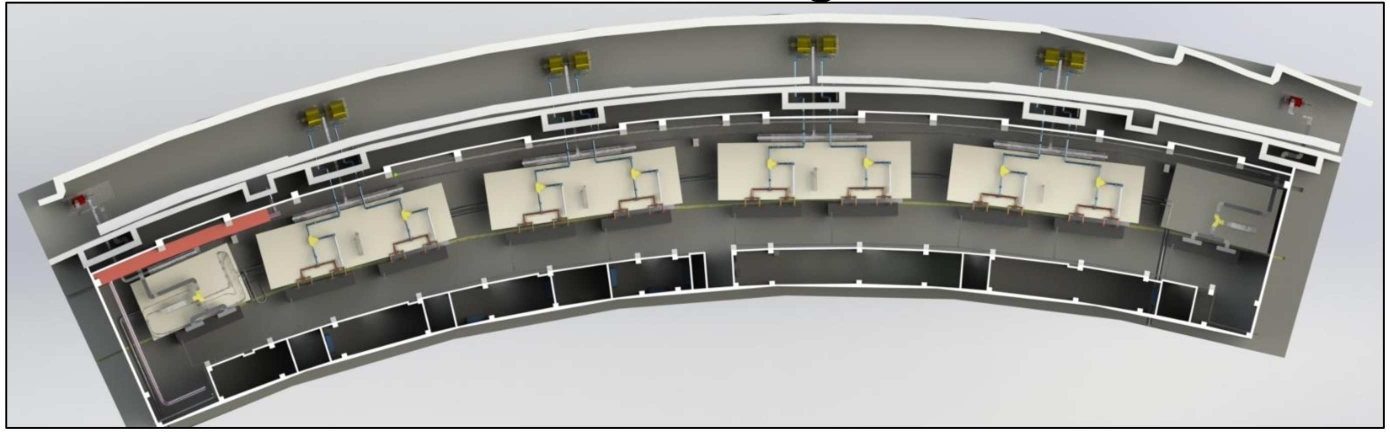
# High-power RF & control

300kW load

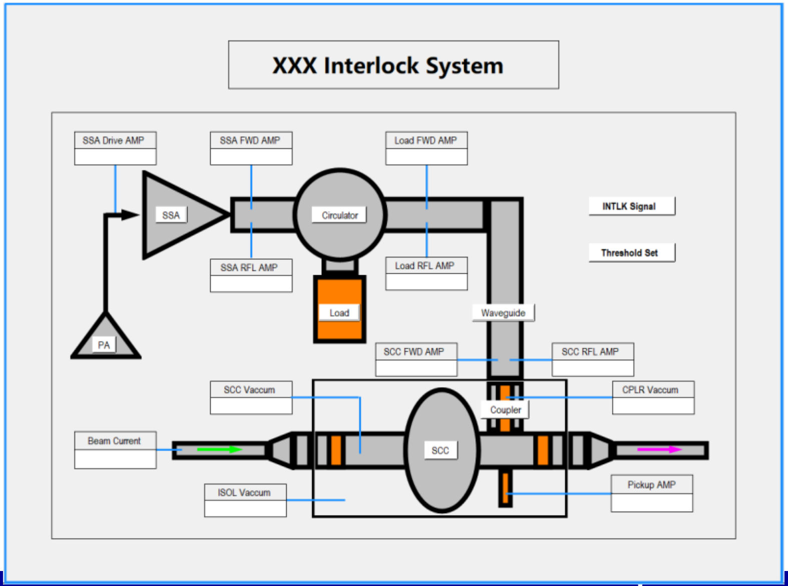
SSPA



RF hall design

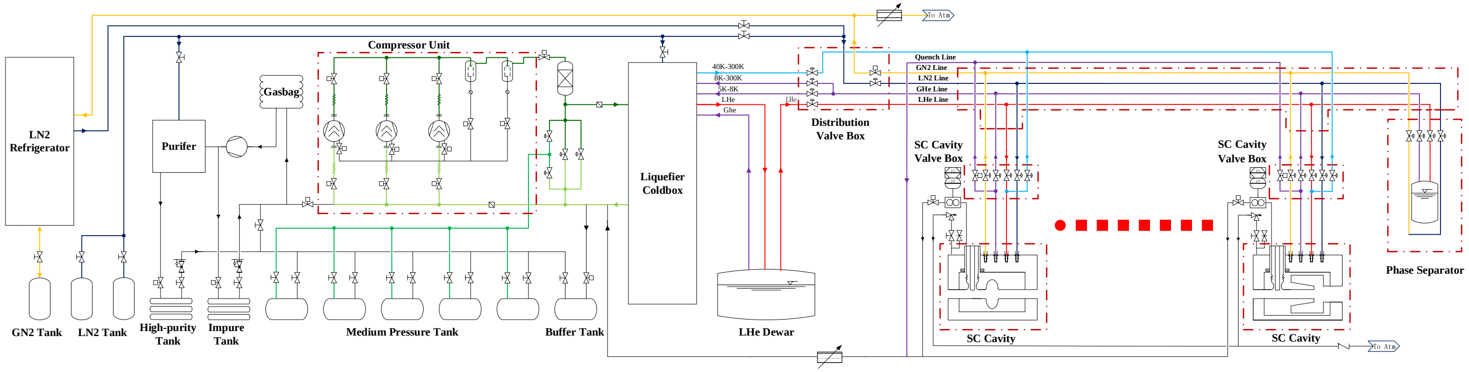


- **High-power RF**
  - 166.6MHz/260kW and 500MHz/150kW solid-state amplifiers under development (early 2021)
  - High-power trans. prototype to be completed (end 2020)
- **RF control**
  - Low-level RF 2nd prototype to be complete (end 2020)
  - Interlock system prototype under development (end 2020)
- **Interface**
  - RF hall design being continuously updated

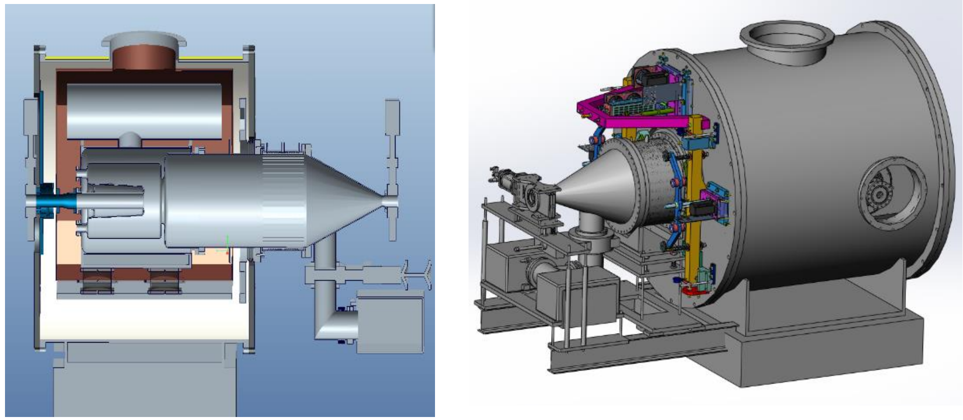


## Helium cryogenic system

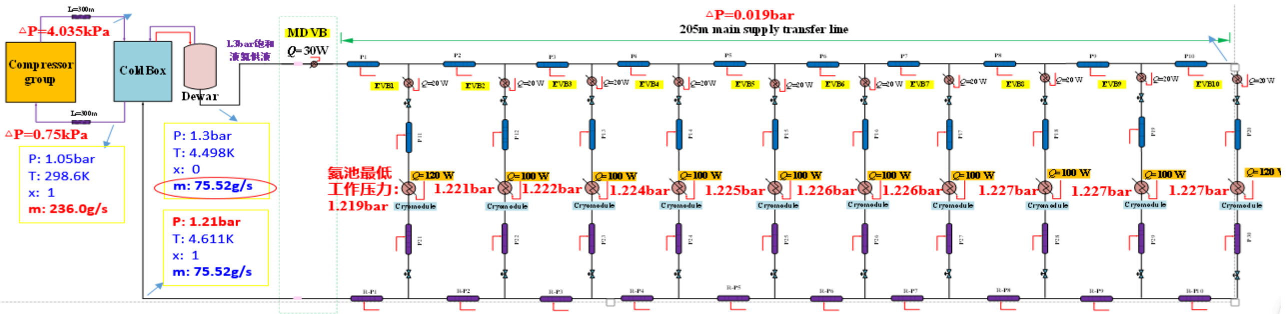
1) Helium cryogenic system flow was finished
2) Technical requirements helium refrigerator was finished and invitation for bid at November 12.
3) Helium fluid cryogenic transfer and distribution was calculated
4) Preliminary design of SRF cavity cryomodule
5) Designed multi-channel cryogenic transfer line test plate



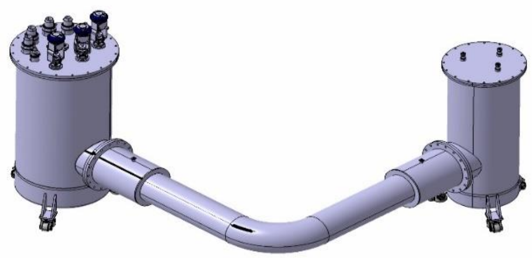

helium cryogenic system flow



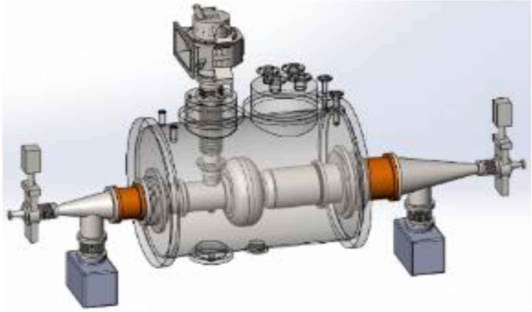
166.6MHz SRF cavity cryomodle




helium cryogenic transfer and distribution



Multi-channel cryogenic line test plate

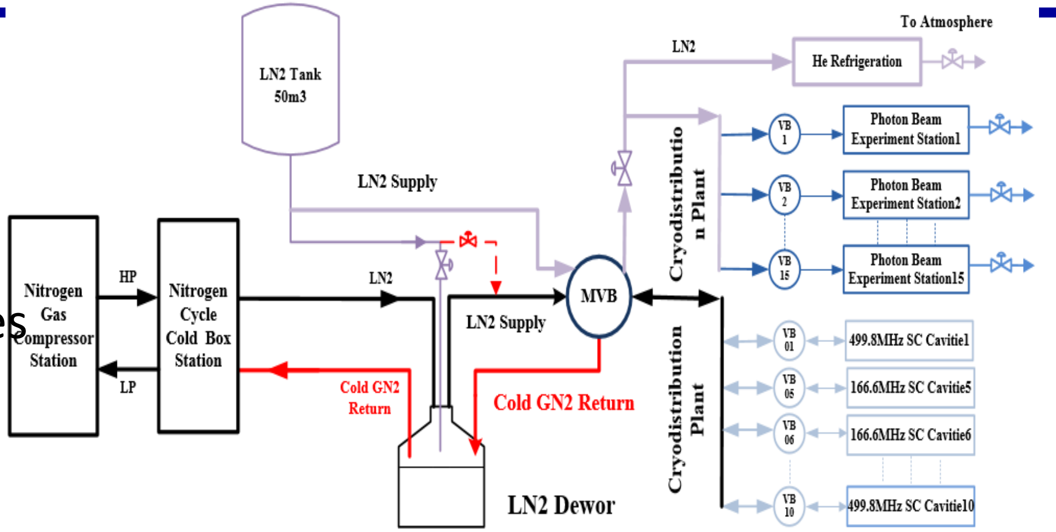


499.8MHz SRF cavity cryomodle

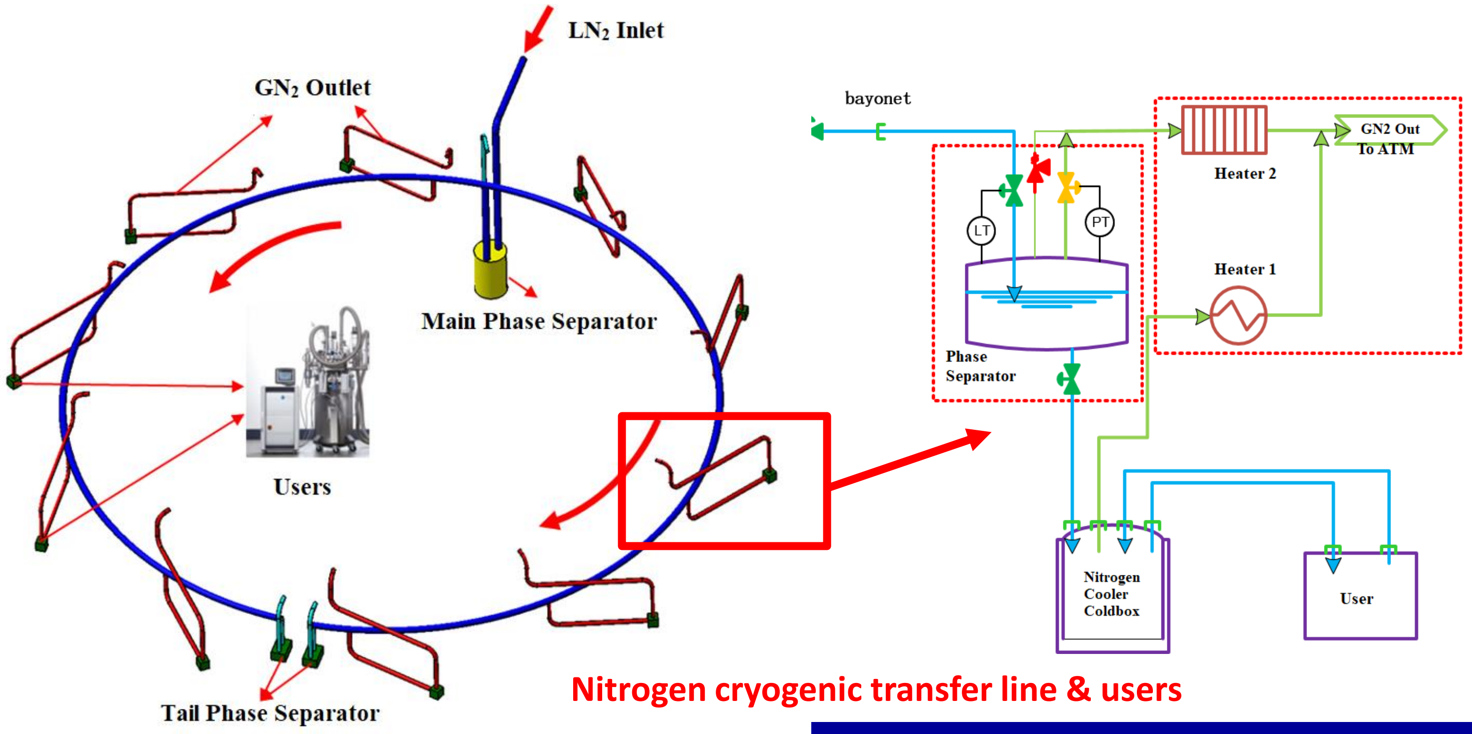
# HEPS cryogenic system

## Nitrogen cryogenic system

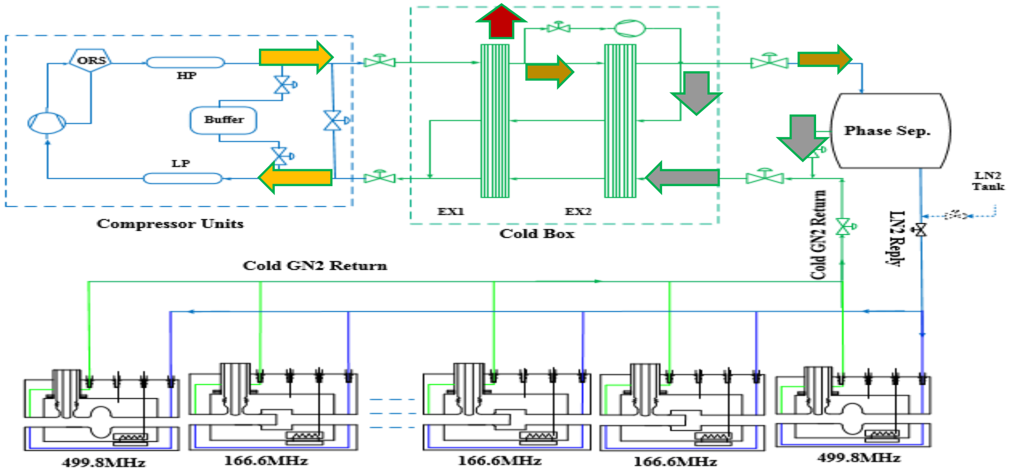
1) Nitrogen cryogenic system flow was finished
2) Nitrogen cryogenic refrigerator was designed
3) Nitrogen cooler coldbox of CPMU was designed.
4) Nitrogen fluid cryogenic transfer and distribution for beam lines




Nitrogen cryogenic system flow



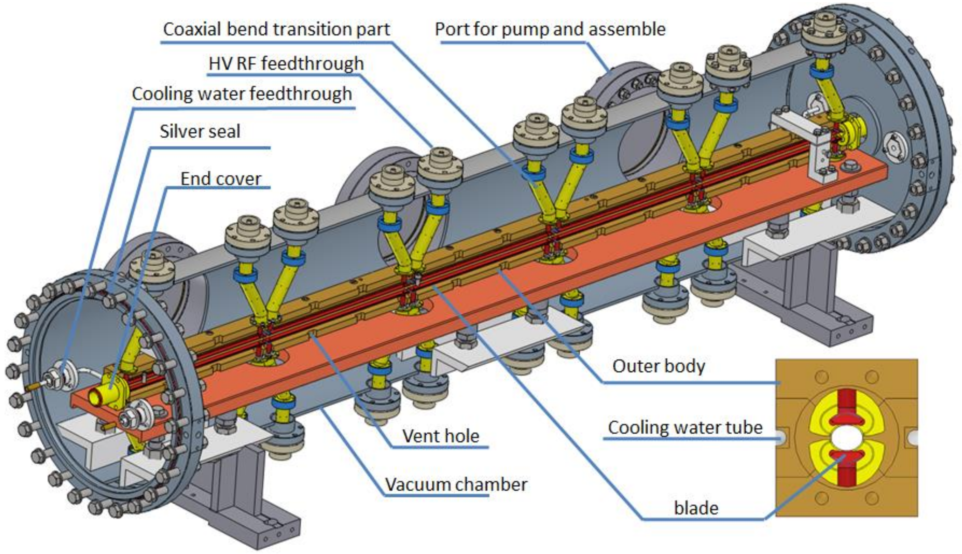

Nitrogen cryogenic transfer line & users

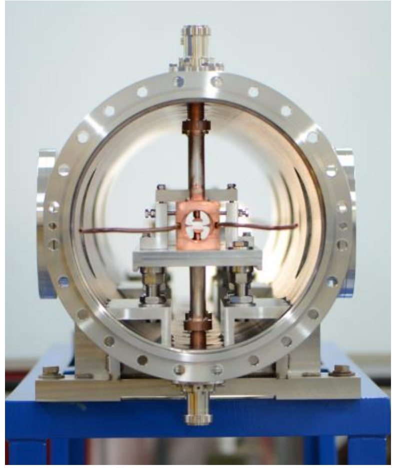



Nitrogen cryogenic refrigerator flow

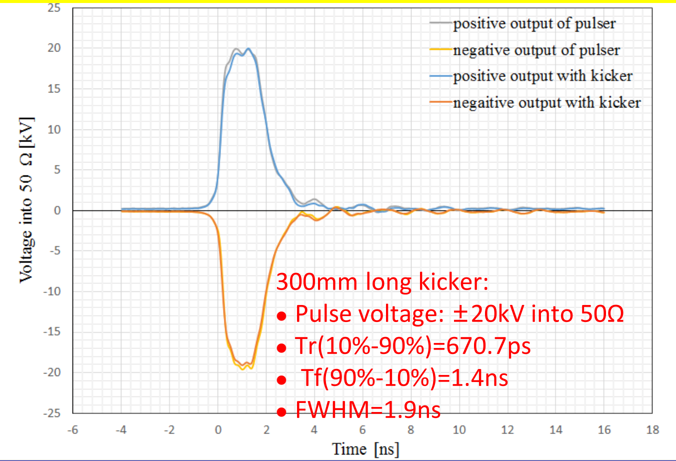
# Strip-line kicker prototype completed

- Features： 5-cell 300mm-long strip-line kicker （10mm gap） in a single module

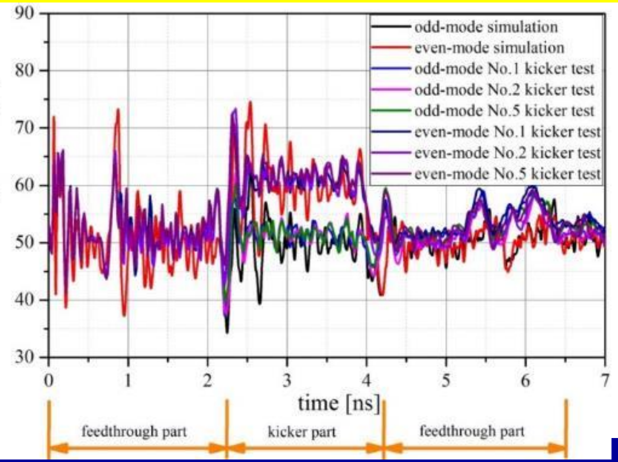


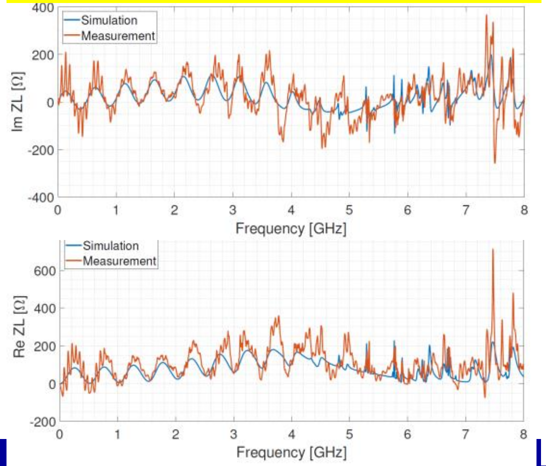
HV pulse testing at ± 20kV



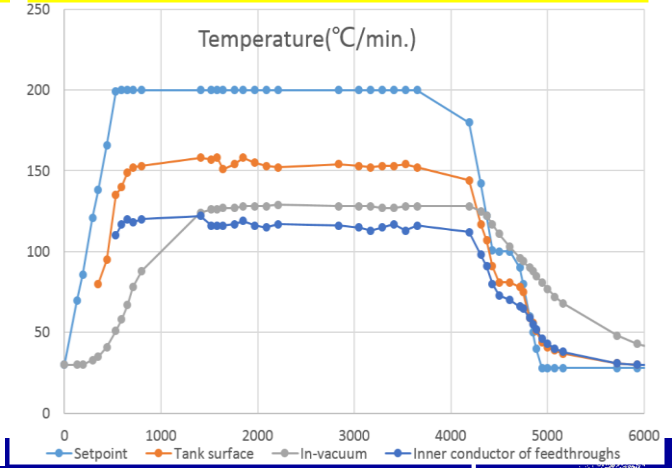

TDR measurement




Beam coupling impedance measurements

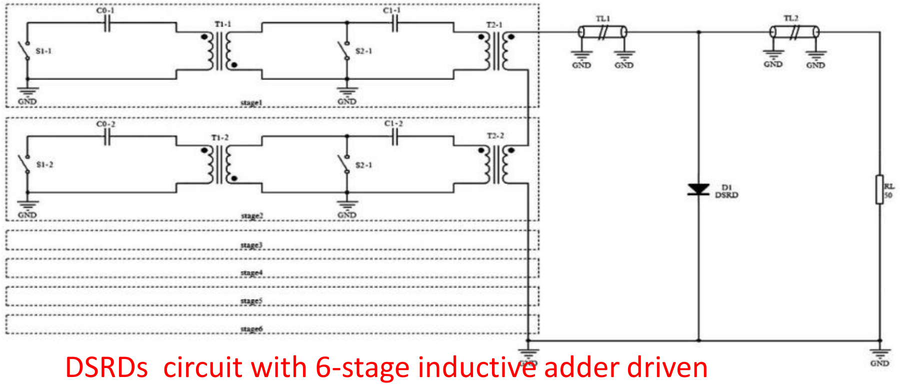



Vacuum backing test

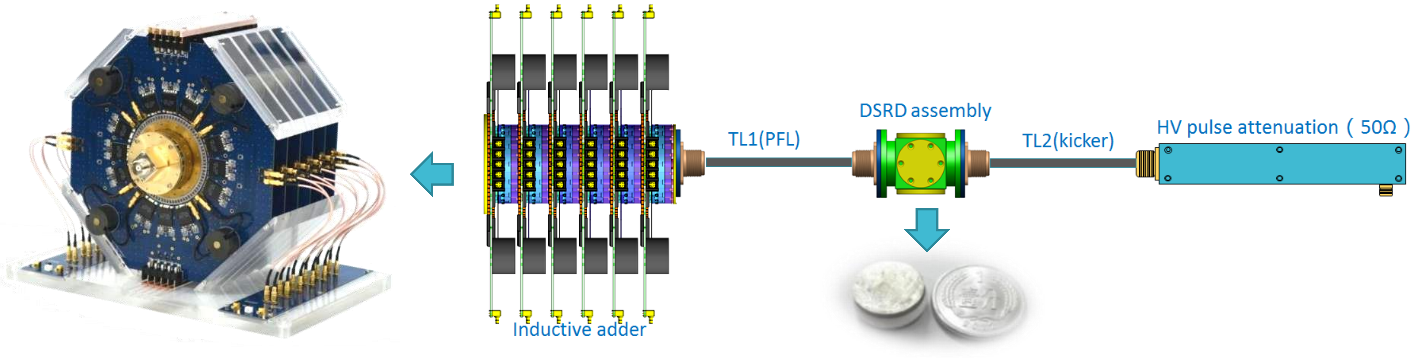


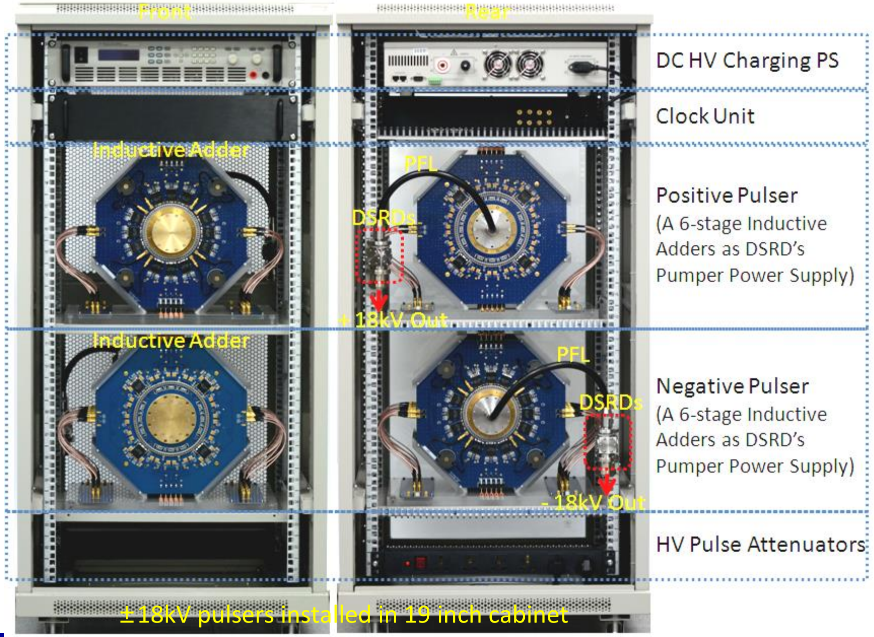
# Fast pulser prototype completed

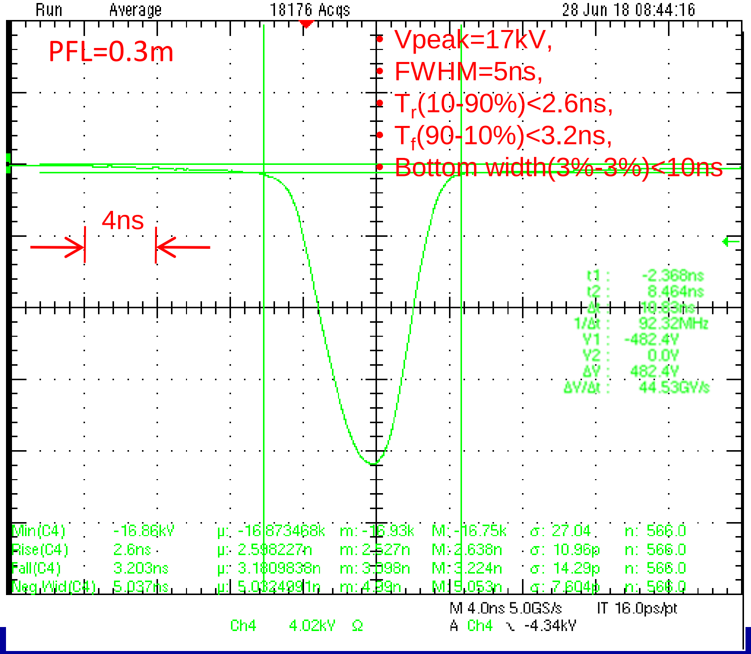
- Features： fast pulser based on DSRDs driven by 6 stage inductive adder; pulse width=10ns

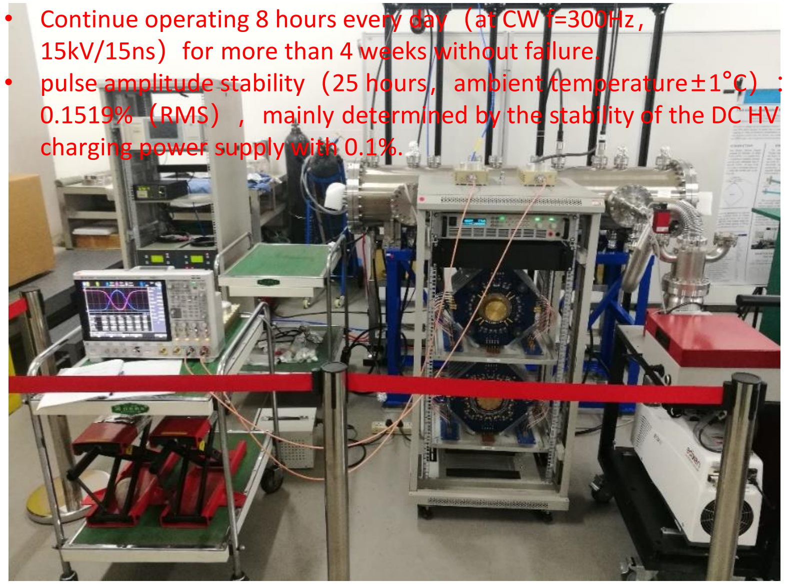



DSRDs circuit with 6-stage inductive adder driven



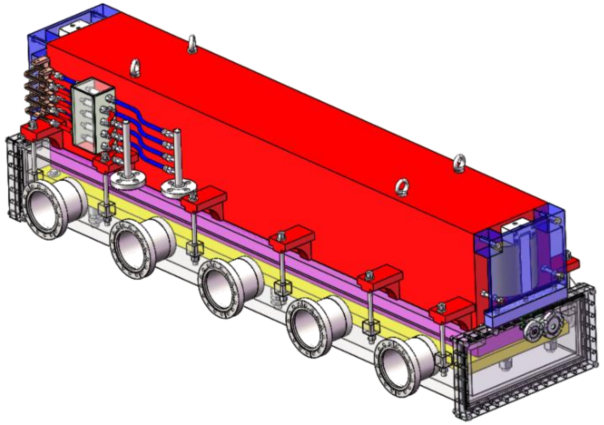


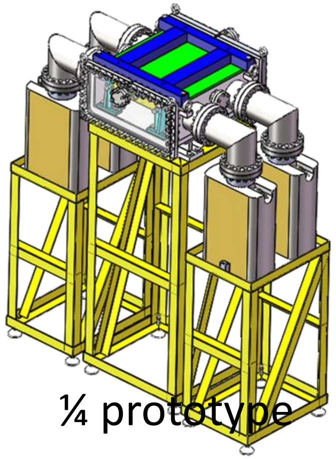


J.H. Chen, Strip-line kicker and fast pulser R&D for the HEPS on-axis injection system, NIMA 920(2019)1-6

# Lambertson Magnet prototyping

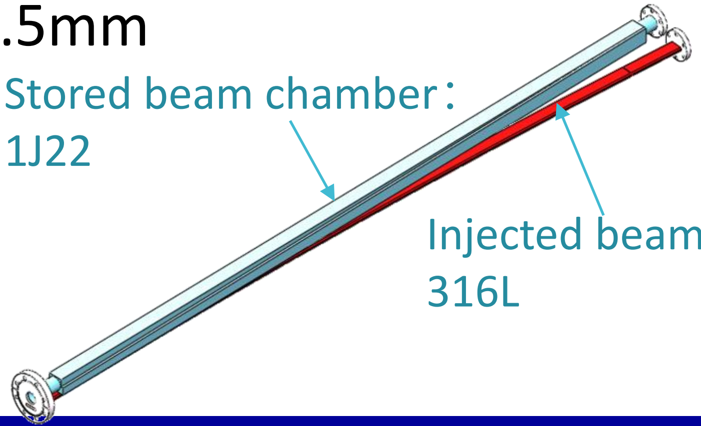
- Type1： Partially in-vacuum Lambertson magnet for SR； total thickness of septum wall=2mm







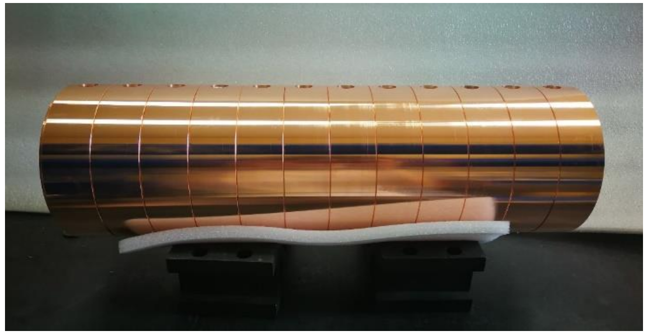

- Type2： Out-of-vacuum Lambertson magnet for BST； total thickness of septum wall=3.5mm





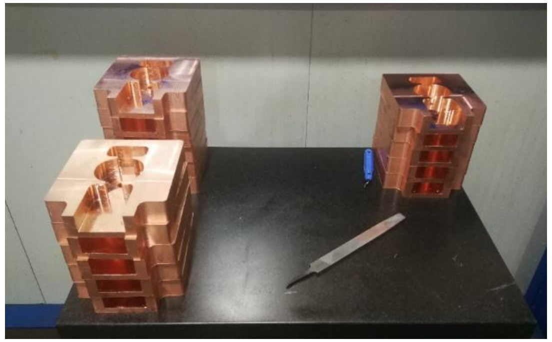
# Microwave system

- Accelerating structure



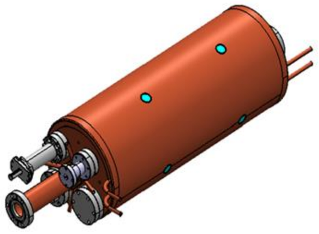
The prototype cavity after welding

The cavities

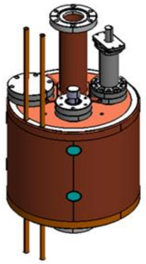


The rough machining couplers

- Sub-harmonic buncher (SHB)

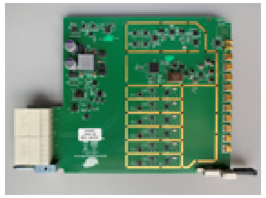


SHB1



SHB2

- Waveguide

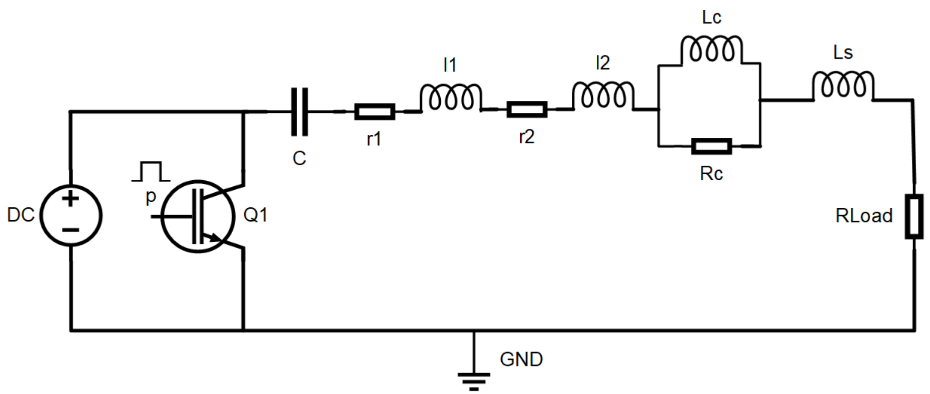


□ LLRF

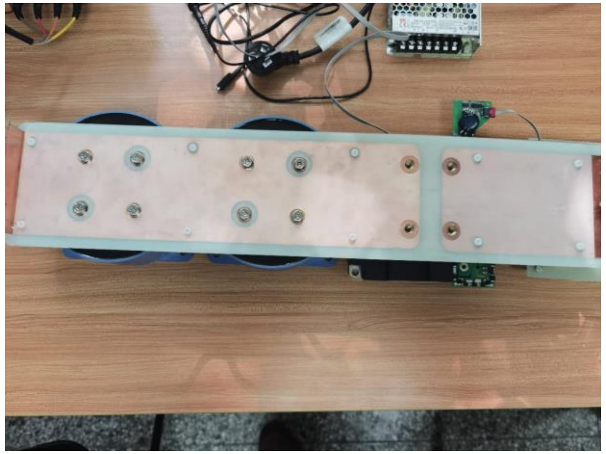
- The processing, welding and debugging of the first edition of direct sampling RF front end are completed
- The design of direct sampling algorithm is completed, and the test environment is built to test the system

# Solidstate modulator

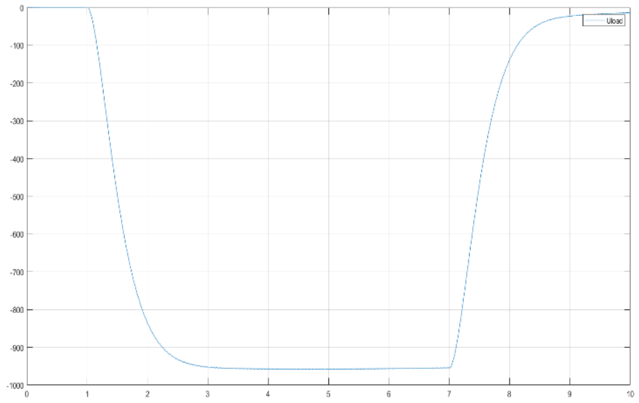
- Discharging unit calculation



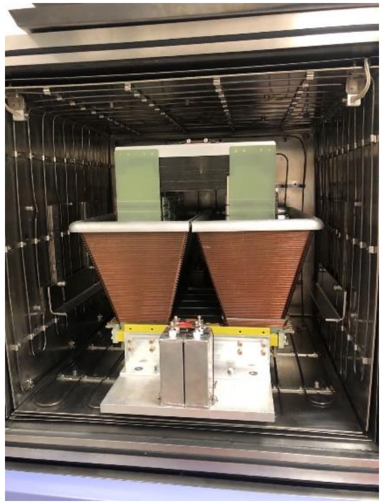

Schematic of discharging unit



Dischaging unit



Lc & Rc calculation

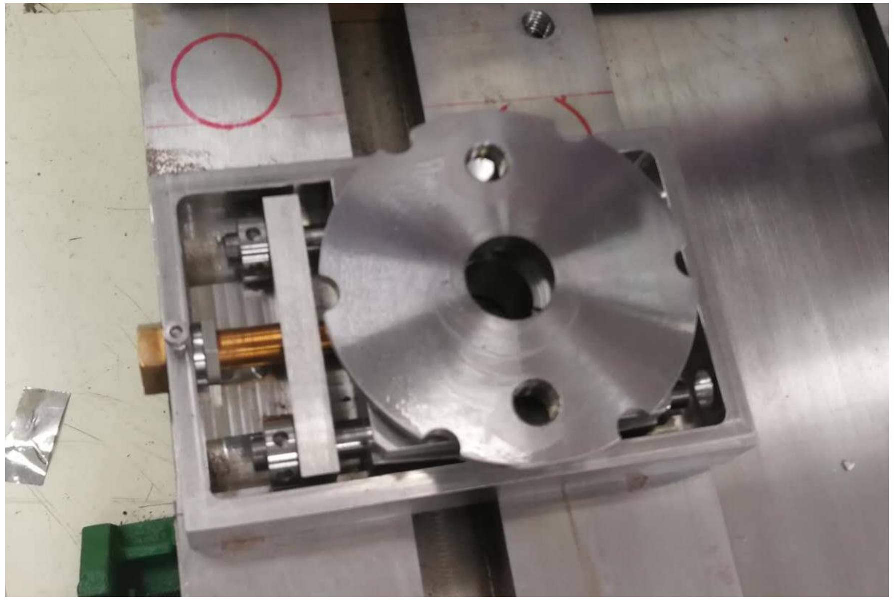


Pulse transformer

# Alignment

1. Finished multi-line measurement scheme design, adjustment software programming, set up measurement circumstances and finished the measurement test in which 6μm accuracy in single direction is achieved.
2. Finished design and R&D of high precision and stability adjust mechanism for magnet pre-alignment, test is finished and 1μm adjust accuracy and 2μm locking stability achieved.

Multi-line pre-alignment test circumstance



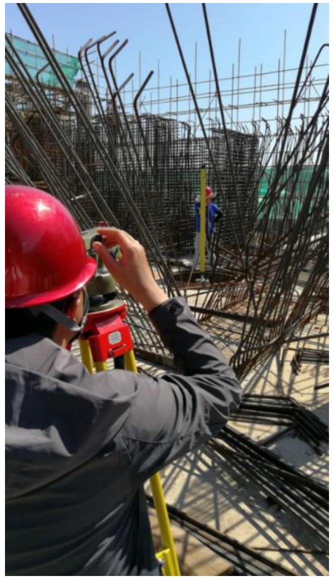
High precision and stability adjust mechanism

# Surface Network Measurement

**1. Finished 1st time HEPS surface network measurement during construction period. To obtain position in horizontal, GPS static survey is executed at 8 facility permanent points、5 construction control points and 2 land control points, 2mm point accuracy achieved which meet requirement.**

**2. For levelling measurement, back and forth observation is carried out at 8 facility permanent points、5 construction control points and 4 land control points, back and forth closure is 1.2mm, head-to-tail closure is 0.7mm, all meet requirement.**

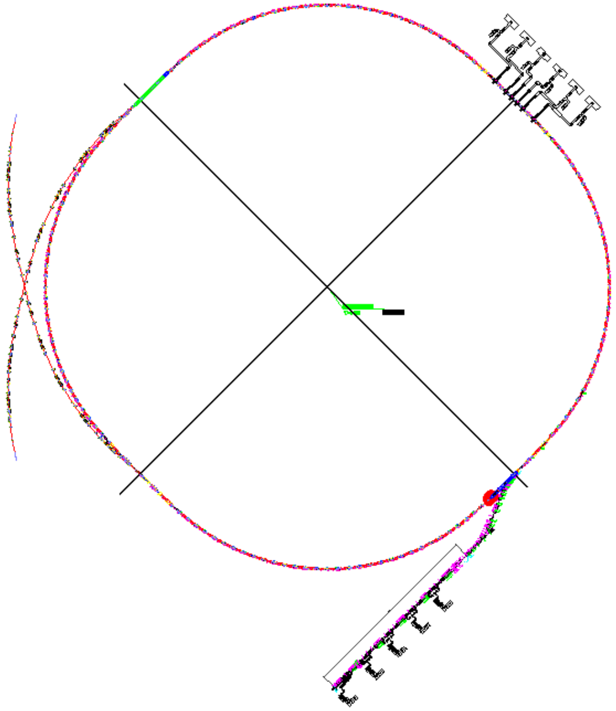
GPS survey at facility permanent point

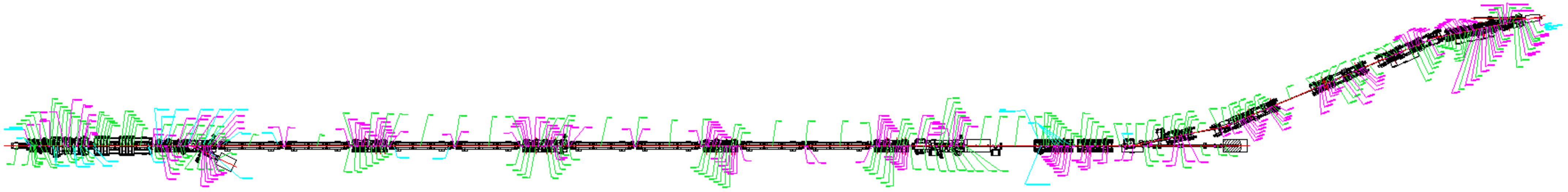


Facility permanent point levelling

# The design of the injector layout

- The LINAC, LTB and BST layout have completed the layout of magnets, vacuum, beam measuring components, injection and extraction components, etc.
- The BTS&BST layout have completed the magnets and beam measuring components design. Vacuum and mechanical layout are being calculated and designed.





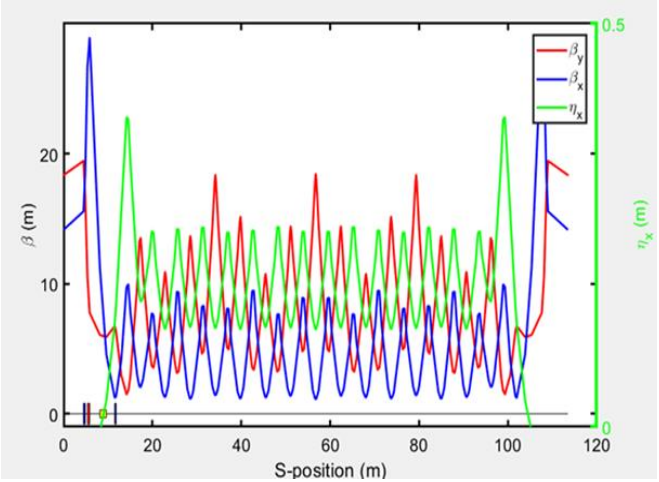
# Accelerator physics design of booster

## Requirements from storage ring (SR)

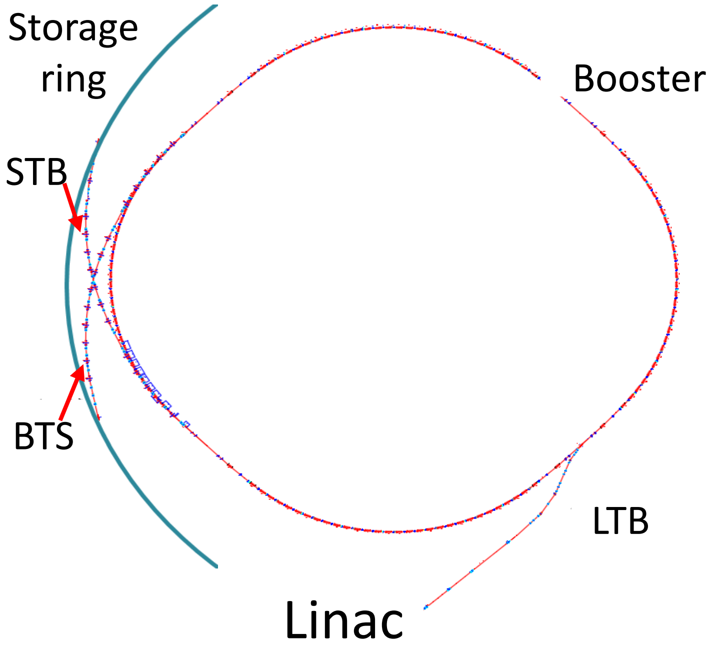
- Emittance less than 20nm
- 15nC for high bunch charge mode
- Setting in a separate tunnel

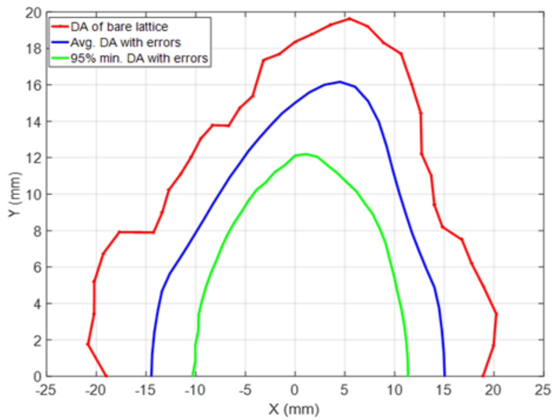
## Design consideration

- "High energy accumulation" to reduce the affect of TMCI @500MeV
- The emittance as lower as better , with $\alpha_c$>2E-3 (requirement from TMCI)
- π section for 2 kicker re-injection



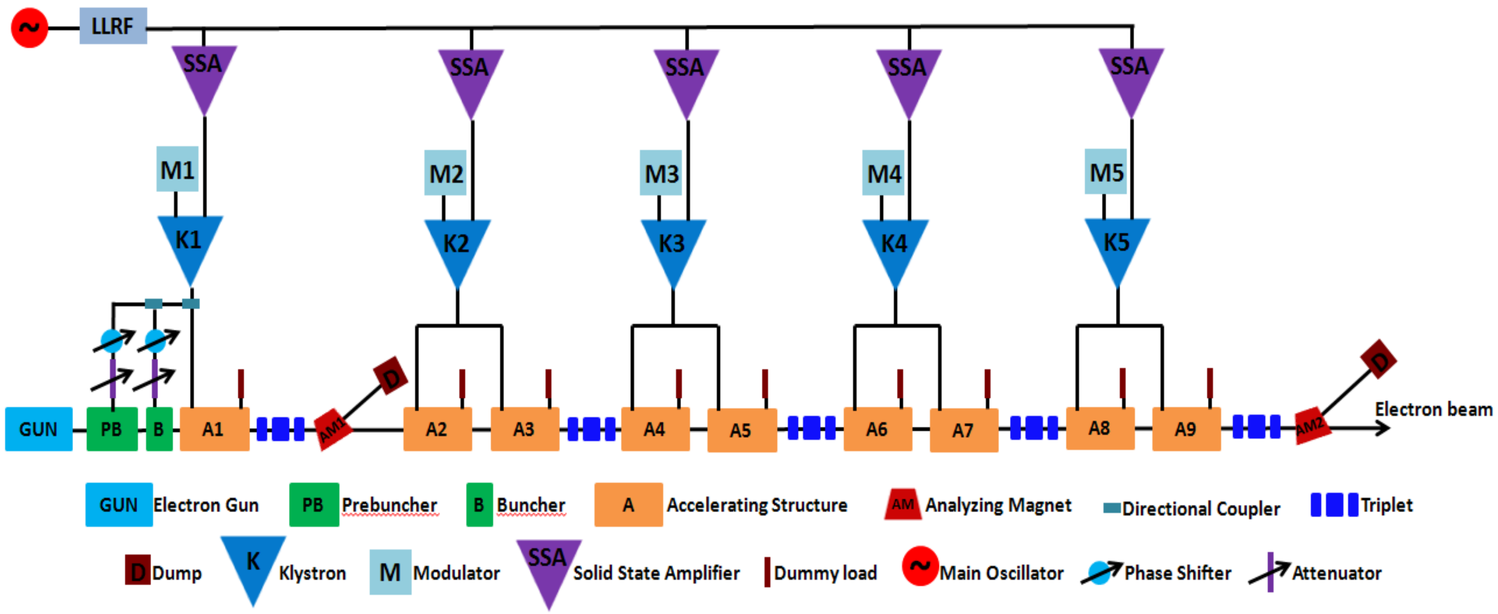

| parameters | Value |
|---|---|
| Circumference | 454.0665 m |
| Tune | 21.30/10.19 |
| Mom. compaction $\alpha_c$ | 2.2E-3 |
| Average βy | 8.6m |
| Emittance@6GeV | 16 nm |
| Energy loss per turn | 3.89MeV |
| Energy spread | 9.5E-4 |

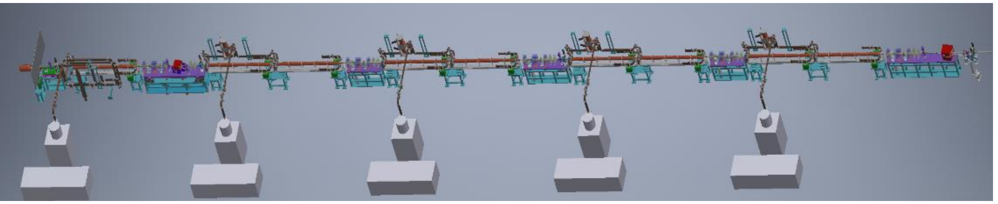


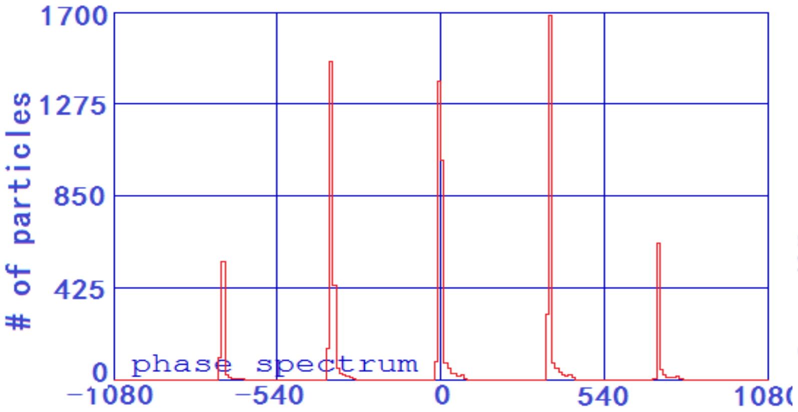



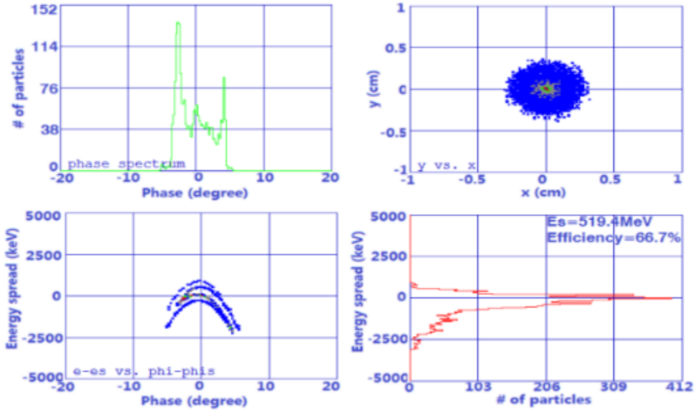
# Linac design

| Parameters | Value | Unit |
|---|---|---|
| Charge/pulse @ linac exit | ≥2.5 | nC |
| Bunch number per pulse | 5 | - |
| Pulse width | 1.6 | ns |
| Energy | ≥500 | MeV |
| Energy spread | ≤0.5 | % |
| Energy stability | ±0.25 | % |
| Repetition frequency | 50 | Hz |
| Un-normalized rms emittance | ≤41 | nm·rad |
| Normalized rms emittance | ≤40 | μm·rad |





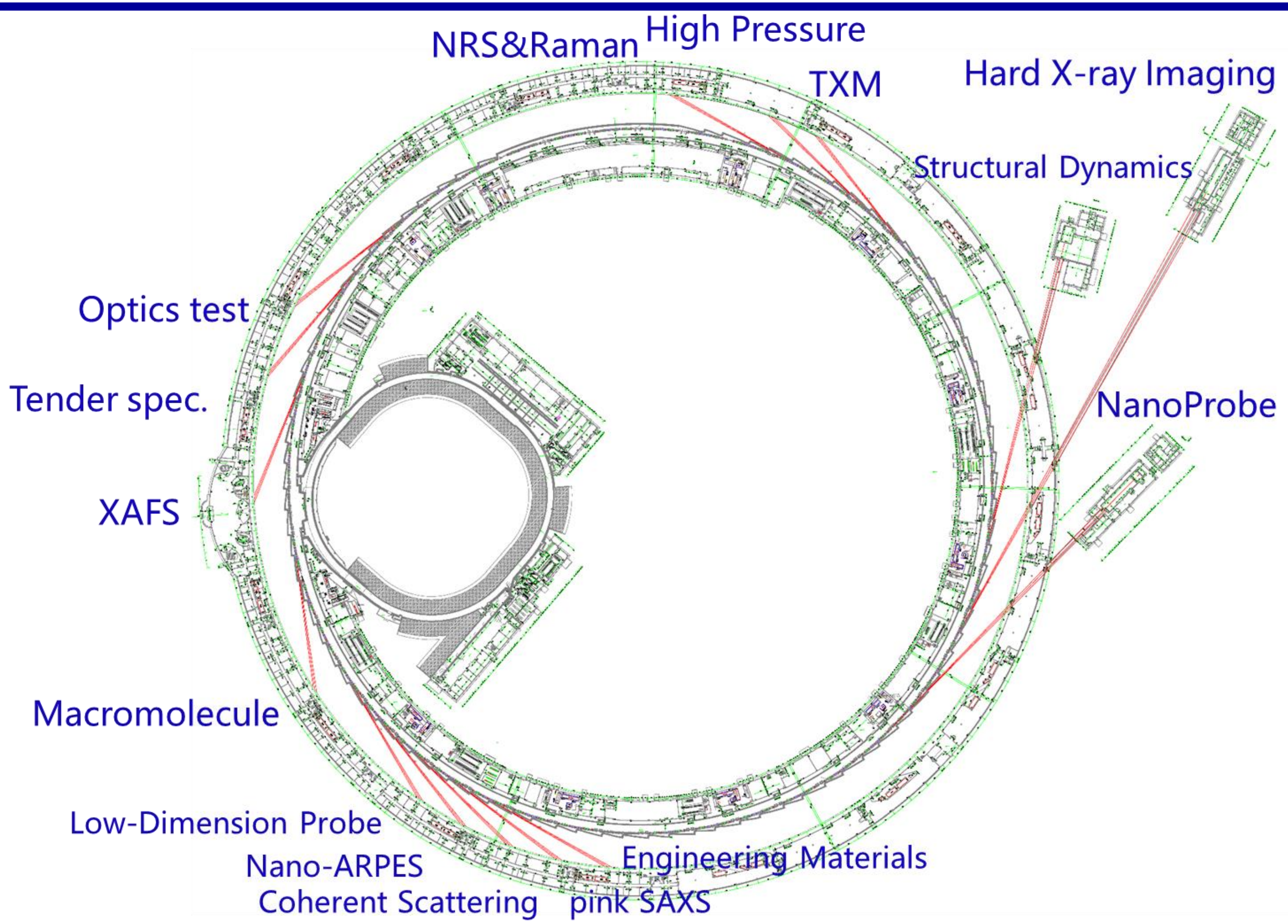
# BEAMLINE

1. Beamlines design
2. R&D for beamline technologies

# Beamlines design

## Layout of 15 beamlines in Phase I

- 14 public beamlines: 13 IDs (3 long) + 1 BM
- 1 ID beamlines for optics test



# Phase I Beamlines list

| | Beamlines | Features |
|---|---|---|
| High Energy | Engineering Materials | 50-170keV， XRD, SAXS, PDF |
| | Hard X-Ray Imaging | 10-300keV, Phase and Diffraction contrast imaging, 200mm large spot, 350m long |
| High Brightness | NanoProbe | Small probe, <10nm; InSitu nanoprobe, <50nm; 180m long |
| | Structural Dynamics | 15-60keV, single-shot diffraction and imaging; < 50nm projection imaging |
| | High Pressure | 110nm focusing, diffraction and imaging |
| | Nano-ARPES | 100-2000eV， 100nm focusing, 5meV@200eV, APPLE-KNOT undulator |
| High Coherence | Hard X-ray Coherent Scattering | CDI(<5nm resolution), sub-μs XPCS |
| | Low-Dimension Probe | surface and interface scattering, surface XPCS |

# Phase I Beamlines description

| | Beamlines | Features |
|---|---|---|
| General beamlines | NRS&Raman | Nuclear Resonant Scattering and X-ray Raman spectroscopy |
| | XAFS | routine XAFS， plus 350nm spot and quick XAFS |
| | Tender spectroscopy | Bending magnet， 2-10keV spectroscopy |
| | μ-Macromolecule | 1μm spot, standard and serial crystallography |
| | pink SAXS | pink beam, lest optics |
| | Transmission X-ray Microscope （TXM) | full field nano imaging and spectroscopy |
| Test beamlines | Optics Test | with undulator and wiggler source for optics measurement and R&D |

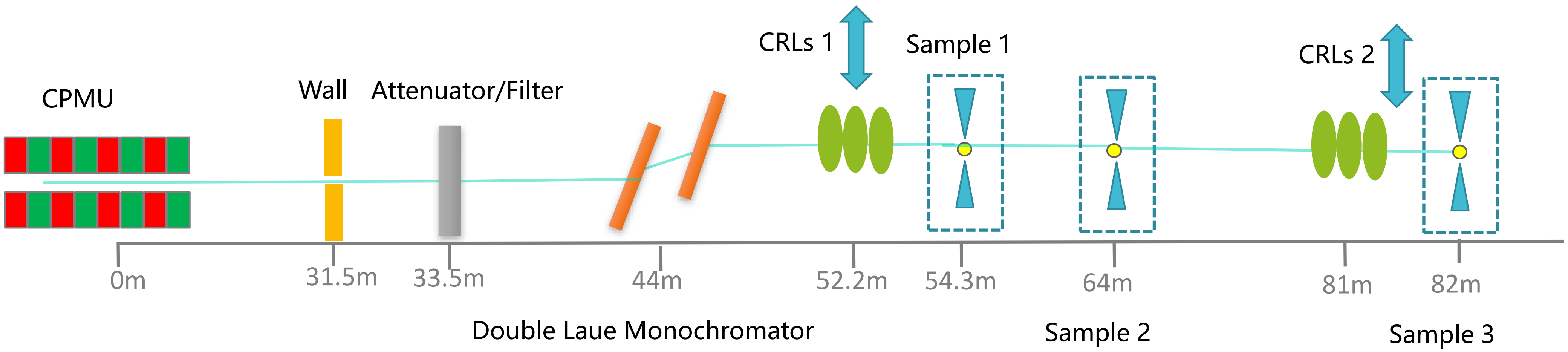
# Engineering Materials Beamline – High energy

**High energy X-ray for engineering materials**

- Source, 2 x CPMUs for **photon flux >1×10$^{12}$ @100keV**
- Mono, Laue monochromator, asymmetrically cut crystal, Double crystal, fixed exit

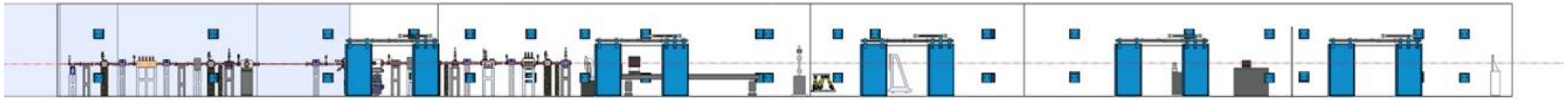
**50keV~170keV , ΔE/E ~1×10$^{-3}$ @100 keV**

- Focusing, Home made Nickel-based Kinoform, **~2μm×2μm and submicron**

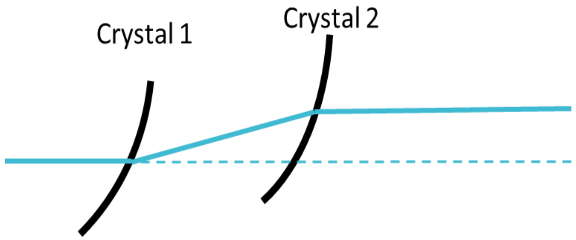


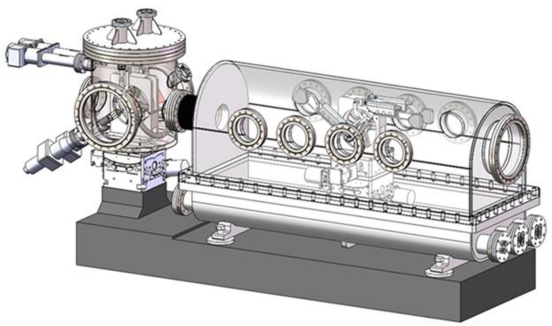
# Engineering Materials Beamline

## Layout of beamline and endstations

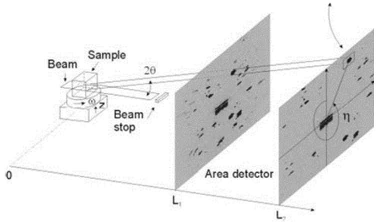


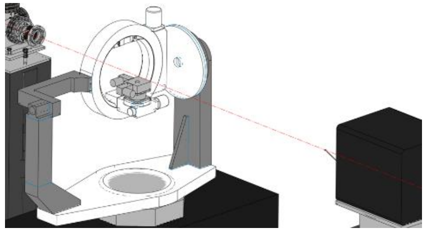
### FOE: Laue optics



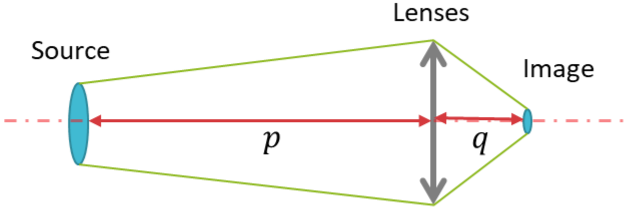
### Hutch A: powder diffraction/3D XRD

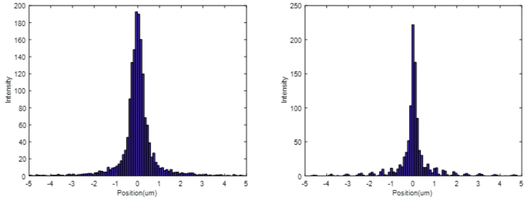


### Hutch B: large samples tensile mode heating mode

### Hutch C: SAXS/micro XRD



100keV, ~500nm×200nm, ~5×10$^{10}$phs/s

# Hard X-ray Imaging Beamline - High energy

Goals: High sensitivity, Deep penetration, Multiscale mesoscopic spatial resolution, Large FOV, Multiple contrast mechanisms and compatible with diverse sample environments.

Probes： In-line phase contrast imaging; Diffraction Contrast Imaging

Application: Biomedicine: whole organ mesoscopic imaging

Engineering Materials

Fossils and Human Relics

Features: Large FOV and high Resolution

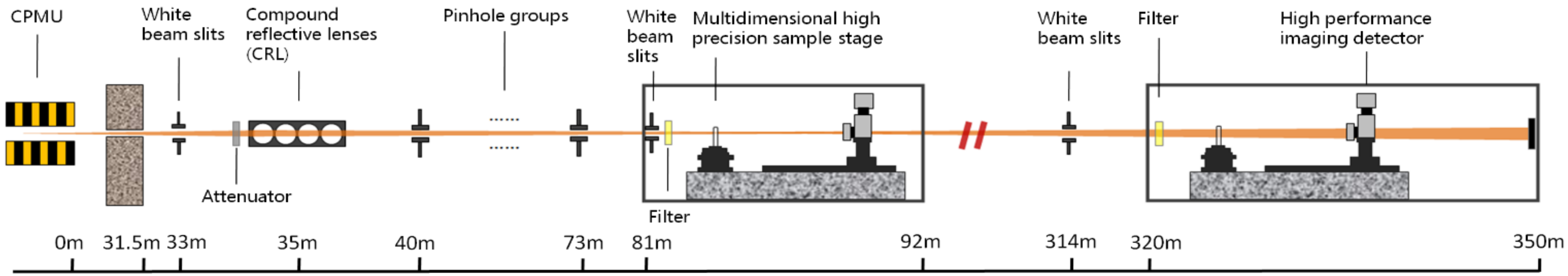
Ratio of spot size and PSF increase from 2k to 20k, 1000 times of voxels one CT

High sensitivity at high resolution & deep penetration case, very small PSF

# 1xCPMU + 1xWiggler+1x Mango Wiggler； 350m long beamline

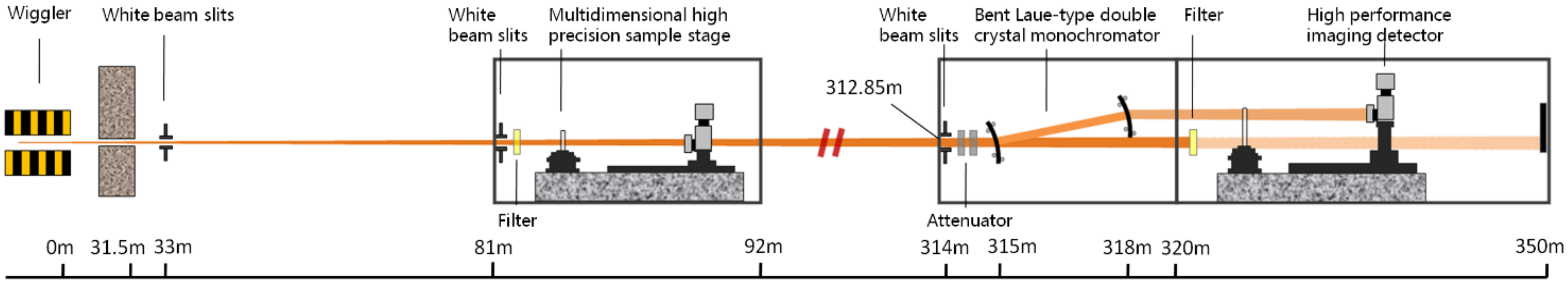
CPMU branch

10-90 keV



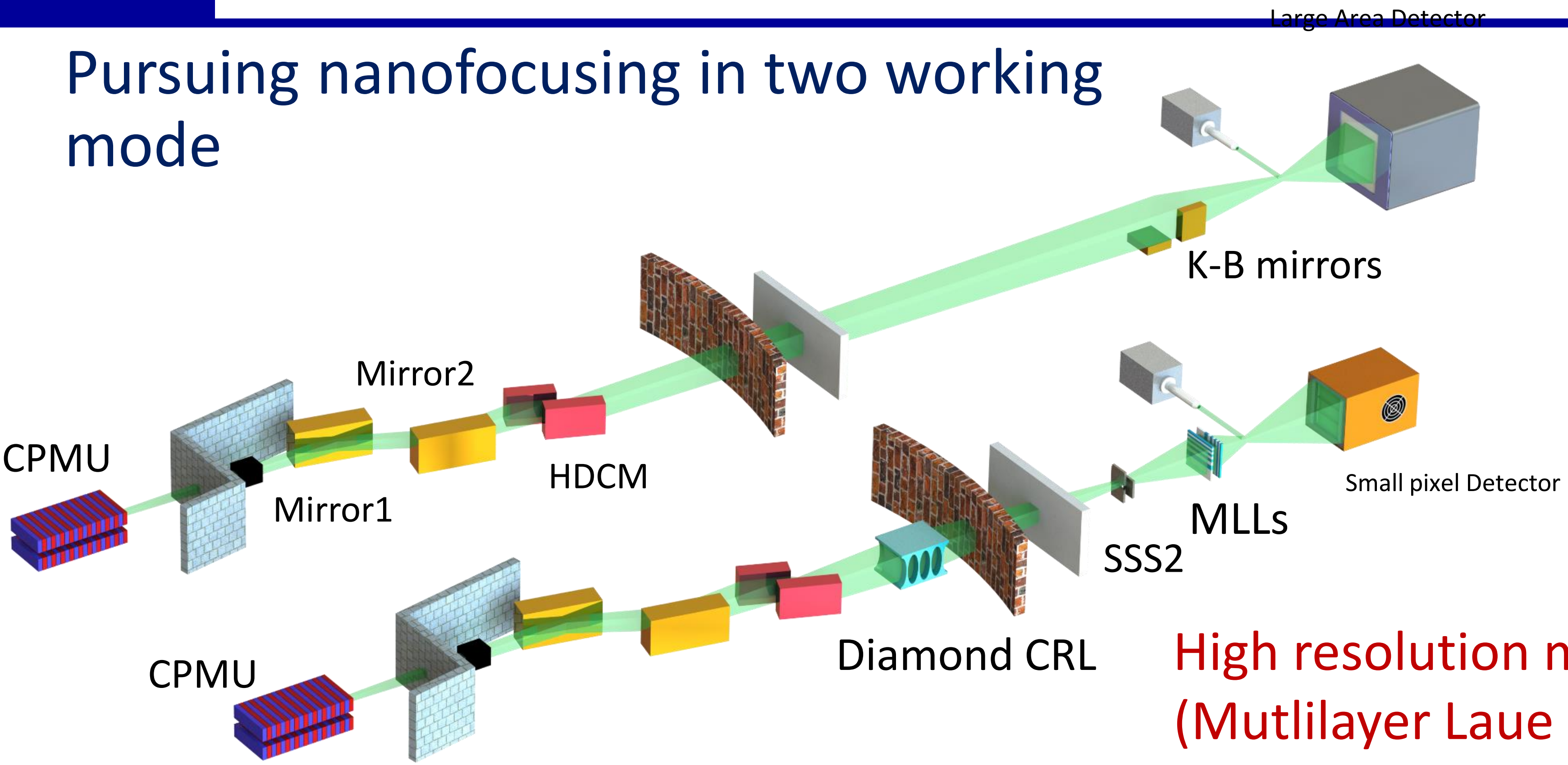

Wiggler branch

20keV—300keV



# NanoProbe beamline - High brightness

Pursuing nanofocusing in two working mode




In-situ mode
(K-B mirror)

Probe Size: ＜50nm
Work Distance: 50mm
Flux: $10^{11}$-$10^{12}$ phs/s

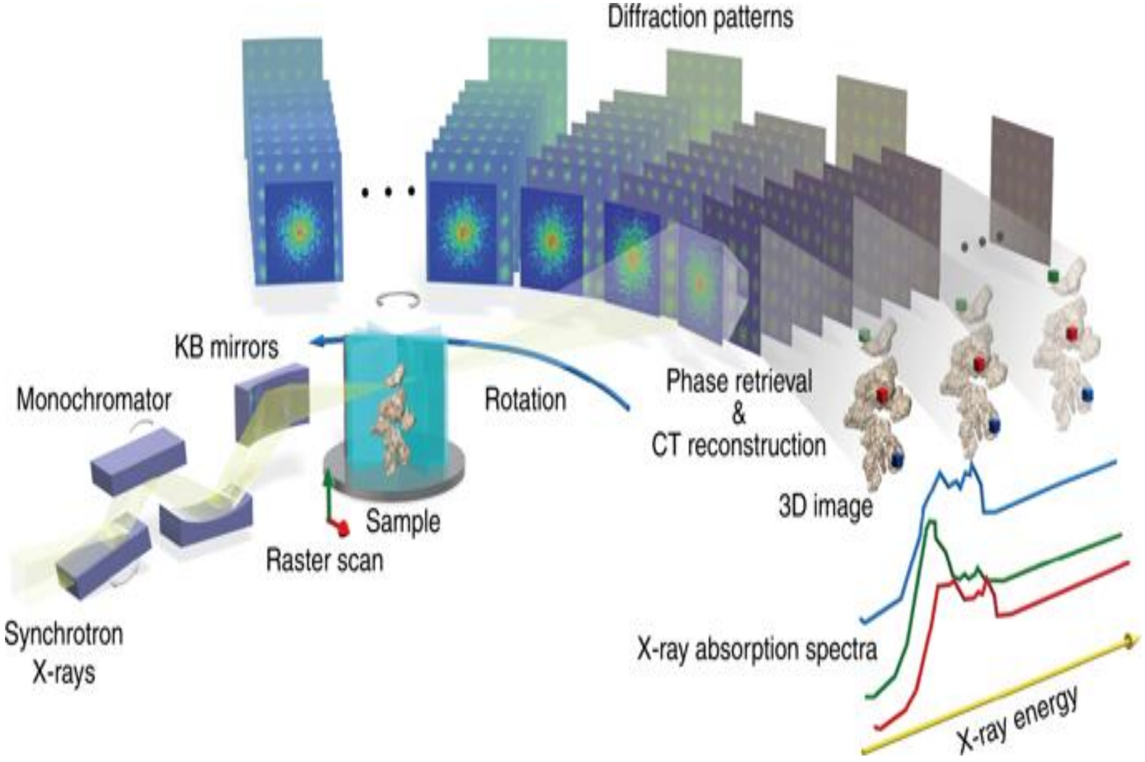
High resolution mode
(Mutlilayer Laue Lens)

Probe Size: ＜10nm
Work Distance: 2mm
Flux: $10^{10\sim11}$ phs/s

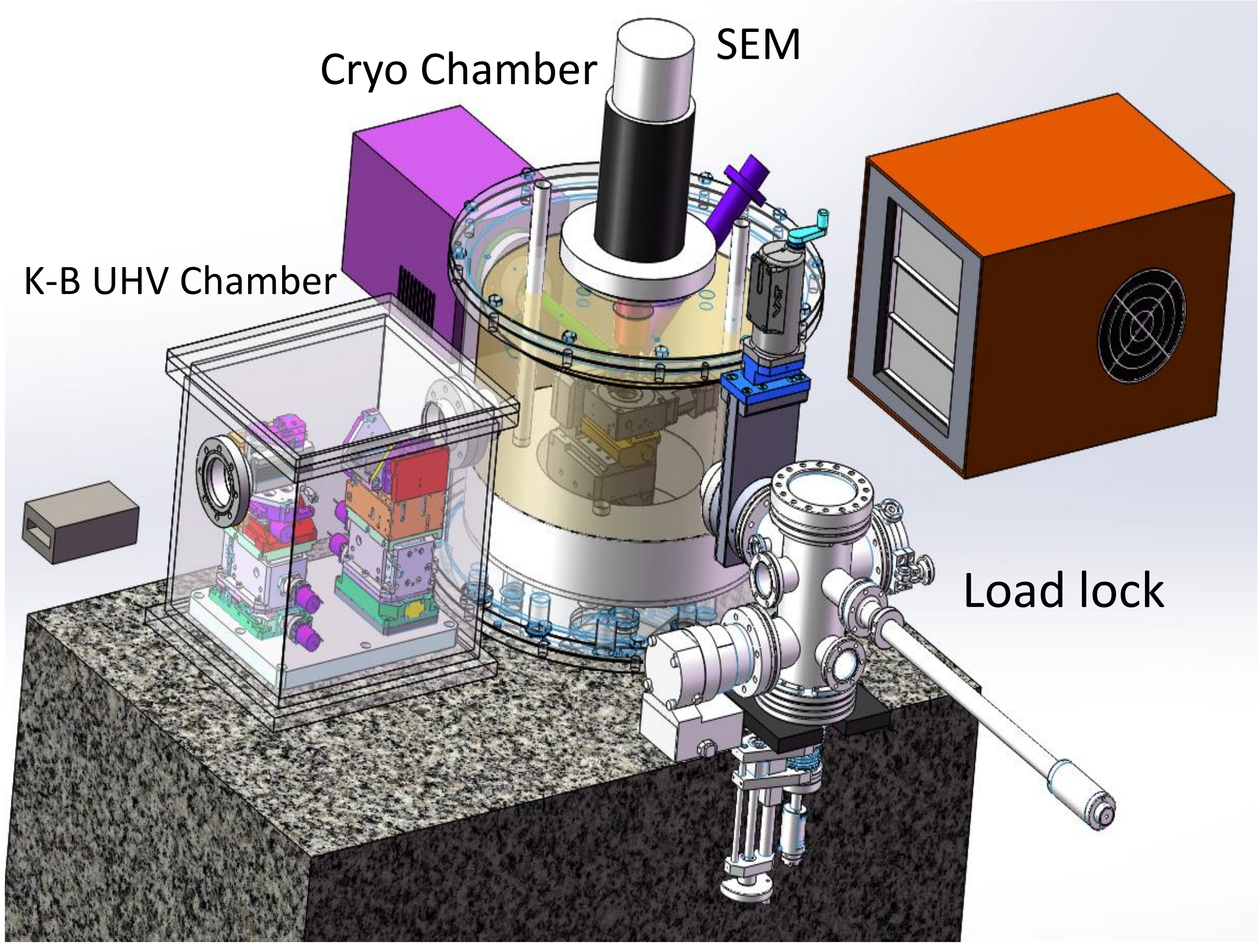
Optical Layout of Nanoprobe beamline

# Multimodal Probing

nano-XRF, nano-XRD, nano-XANES
Ptychography, Spectra-Ptychography



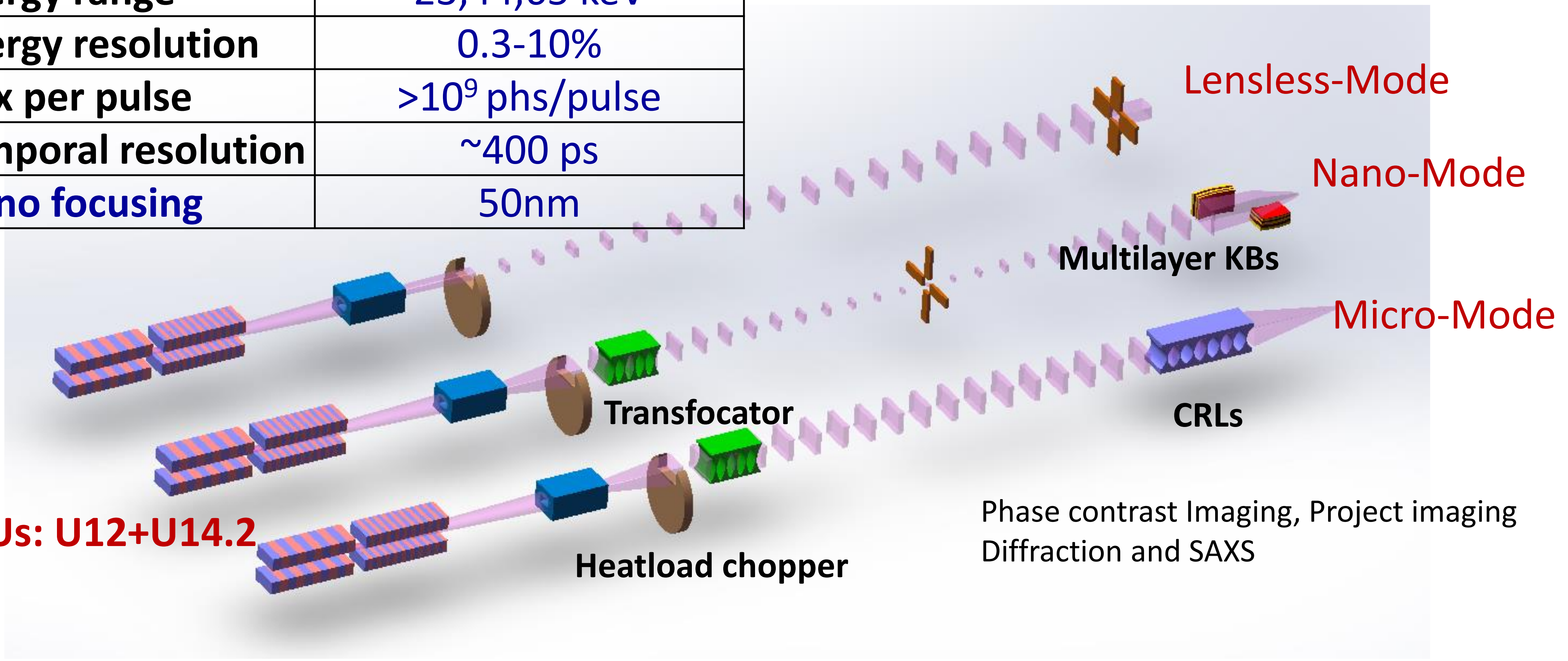

M. Hirose, Nature communication,2019



# Structural Dynamic Beamline - High brightness

Single shot probes for Irreversible progress

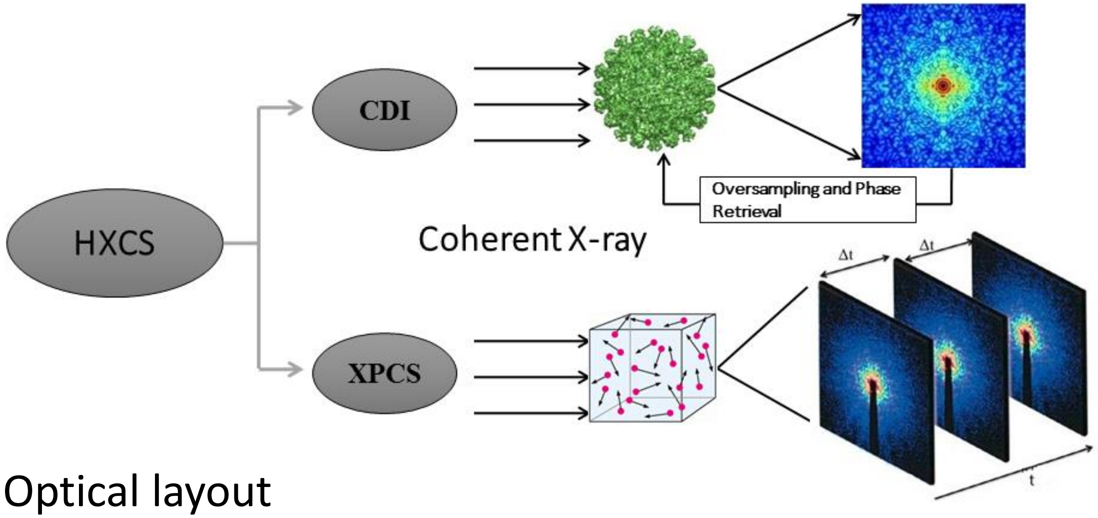
| | |
|---|---|
| **Energy range** | 23,44,65 keV |
| **Energy resolution** | 0.3-10% |
| **Flux per pulse** | >$10^9$ phs/pulse |
| **Temporal resolution** | ~400 ps |
| **nano focusing** | 50nm |




Phase contrast Imaging, Project imaging
Diffraction and SAXS

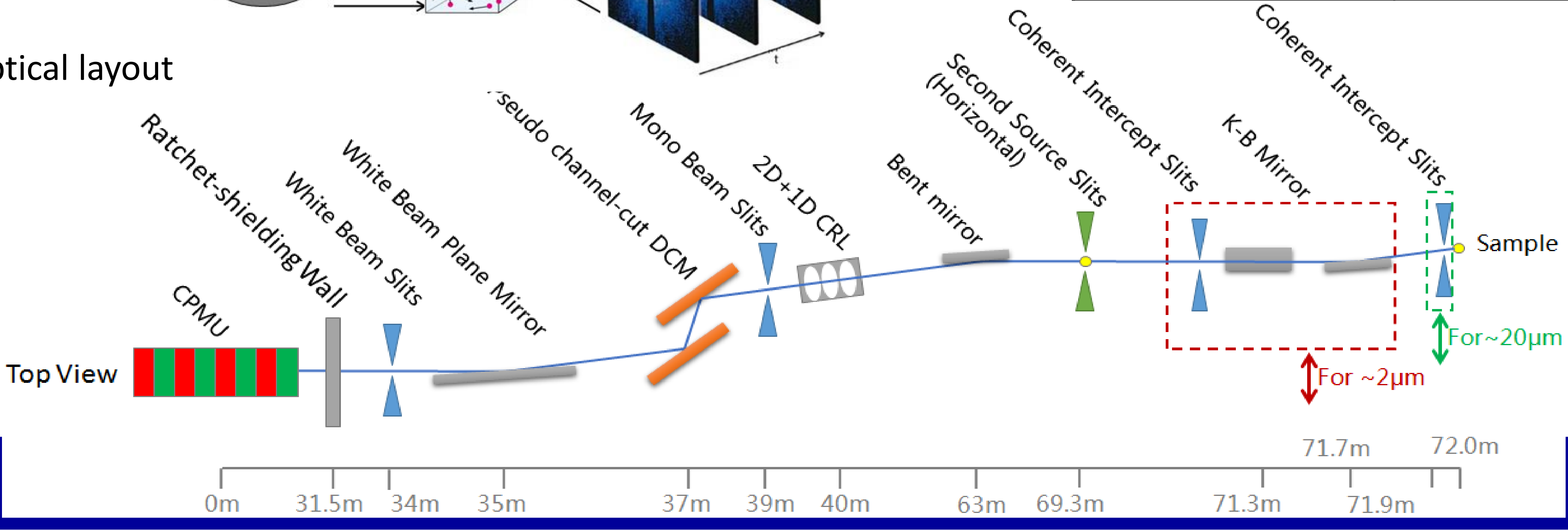
# Hard X-ray Coherent Scattering beamline – High coherence

Dedicated to Coherent Diffractive Imaging (CDI) and X-ray Photons Correlation Spectroscopy (XPCS)

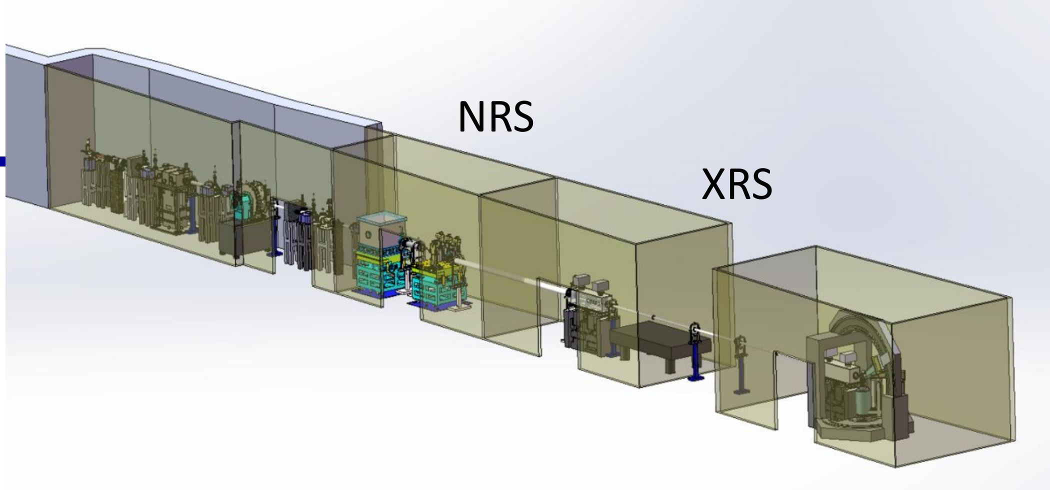



| | Specifications |
|---|---|
| **Energy range** | 7-25keV |
| **Energy resolution** | $10^{-4}$ Si(111) |
| **Coherent flux** | $>10^{12}$ph/s @12.4keV |
| **Beam size** | 2μm (WAXS CDI&XPCS)<br>20μm (SAXS CDI&XPCS) |
| **Endstastion** | CDI (resolution<5nm)<br>XPCS (resolution<1μs) |

Optical layout



# NRS & Raman beamline



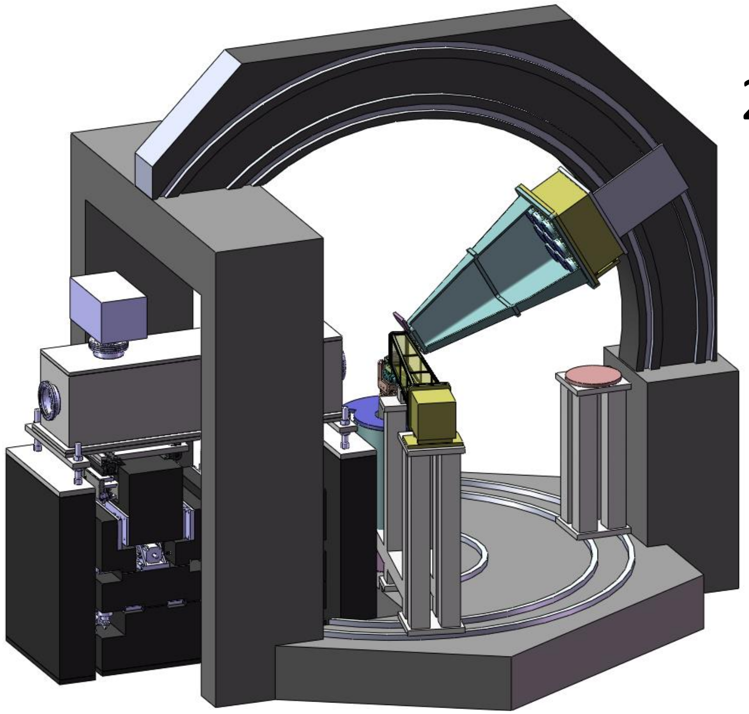

Dedicated for Nuclear Resonant Scattering and X-ray Raman spectroscopy(XRS )

| Probes | Parameters | Specifications |
| --- | --- | --- |
| NRS @Fe-57 | Energy resolution | High flux mode： 2.2meV@14.4keV<br>High-resolution mode： 1meV@14.4keV |
| | 4 μm ×2 μm (non dispersive, 2meV)<br>5.9μm ×20 μm (dispersive, 1meV)<br>Flux at sample position(focused mode) | High flux mode： $2\times10^{10}$phs/s@100mA<br>High-resolution mode： $9\times10^{9}$phs/s@100mA |
| XRS | Energy resolution | 0.8eV@10keV |
| | 2μm ×2 μm<br>Flux at sample position | $2.6\times10^{13}$ phs/s@200mA |

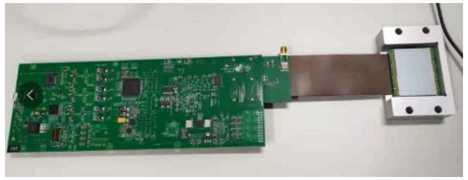
# X-ray Raman Spectrometer， low-q + high-q

- Q-dependent XRS, 30 - 130 degree, Vertical and horizontal scattering
- 3*5 array Si(nn0) analyzer crystal, Rowland circle = 1-2m
- 55-µm pixel 2D detector

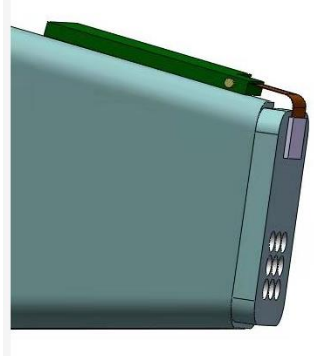
✓ Larger-solid-angle realized by multiple analyzer modules
✓ Large scattering angle
✓ home-made analyzer crystals and small pixel array detectors



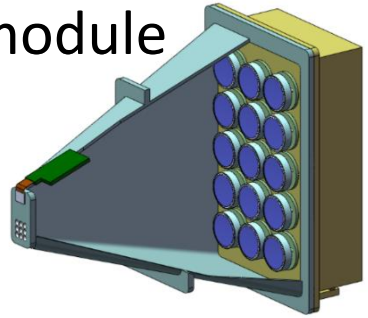
2D detector by IHEP



Detection nose



analyzer module



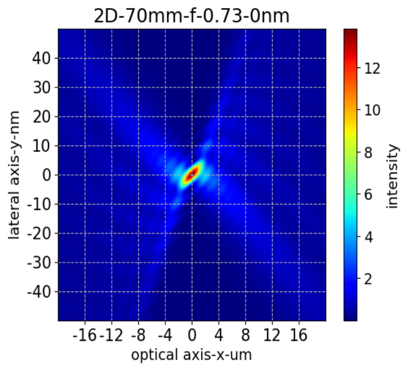
# R&D for beamline technologies

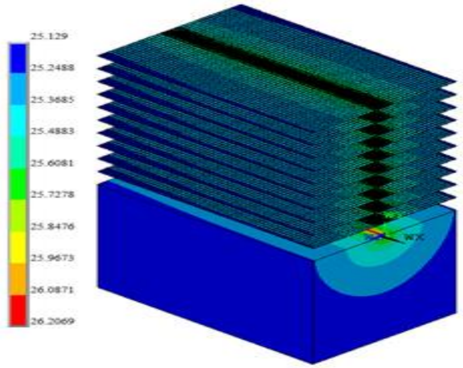
- Novel Insertion Device design
- Optical design
- X-ray metrology
- Monochromators
- Mirror systems
- X-ray optics fabrication
- Nano-positoning instrumentation
- Time-resolved instrumentations
- X-ray pixel array detector

# Optical design

- Redshift design for transmission X-ray microscopy beamline
- Collimation design for high focus stability  servicing spectrosocpy beamline
- Duo deflection mirror design for high stability servicing pink SAXS beamline
- Novel numerical simulation based on FEA for nano KB multilayer mirror

Development of Finite-element simulation for X-ray volume diffractive optics based on wave optical theory



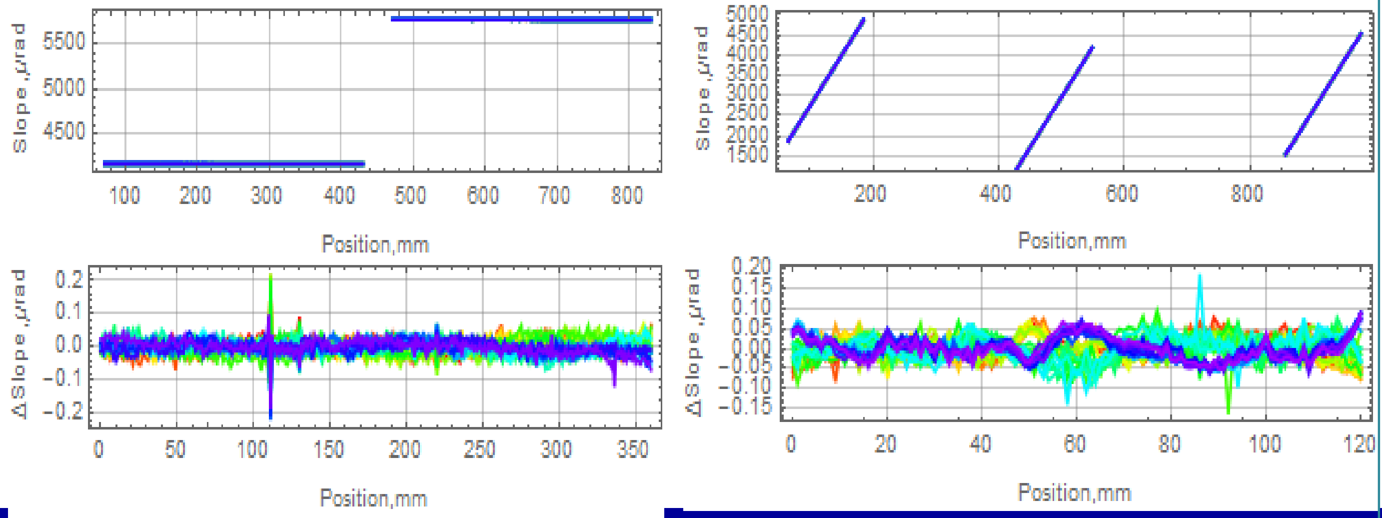



# X-ray Metrology- Flag-type Surface Profiler(FSP)

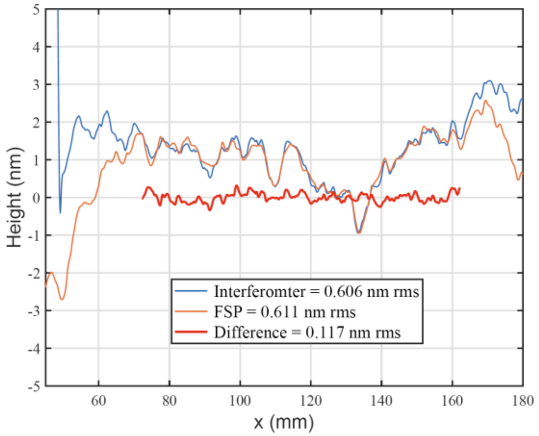
## Features:  High accuracy, High Speed

### 1. Self-comparison Test Accuracy

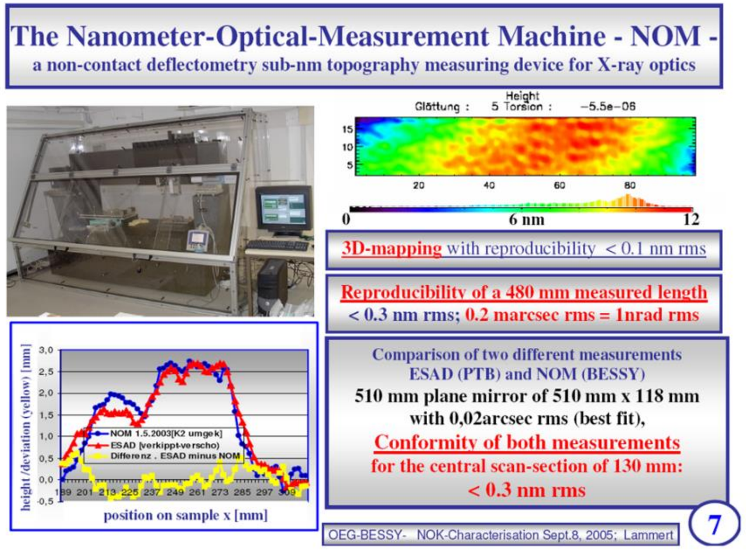
**Flat mirror: RMS 25nrad** | **3mrad Curved : RMS 32nrad**




### 2. Cross-check Test Accuracy



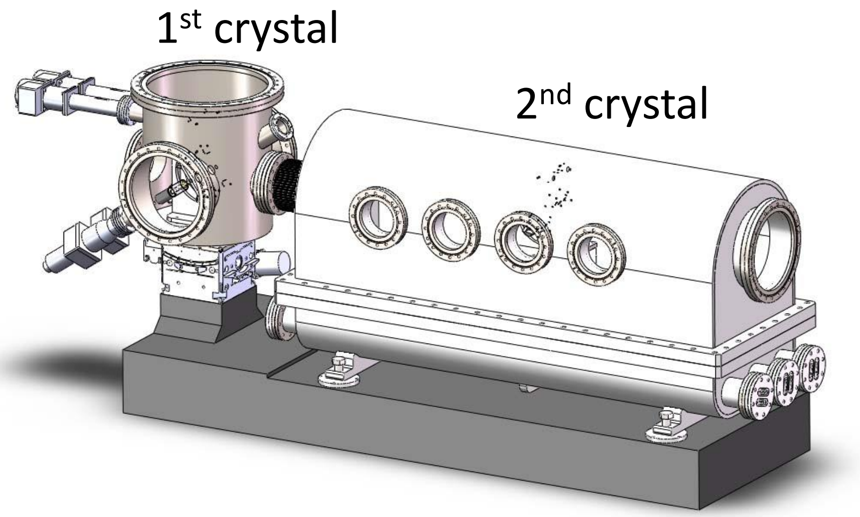

**FSP@BSRF**
**– Interferometer**
**0.1nm rms**



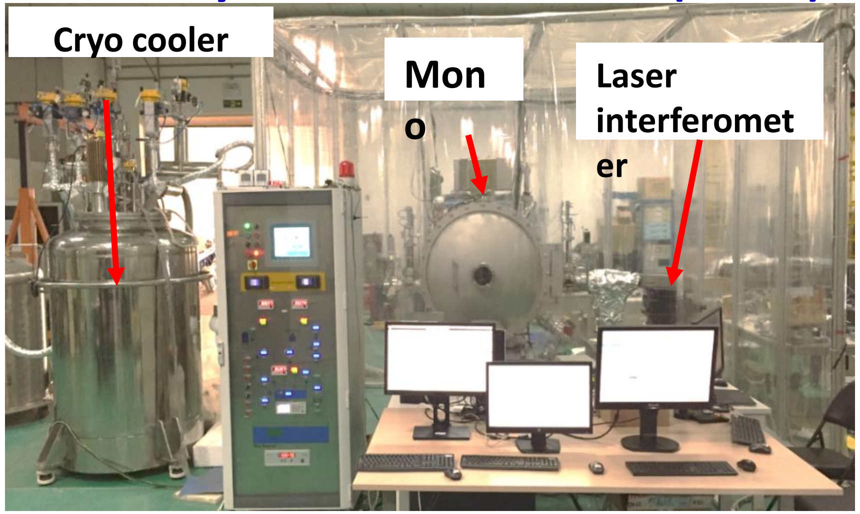

Reference:
**NOM@BESSY**
**– ESAD@PTB**
0.3nm rms

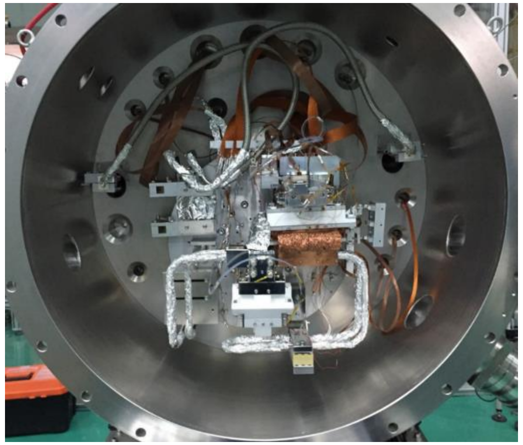
# Monochromators - Prototype

## Laue Monochromator: 60-150keV

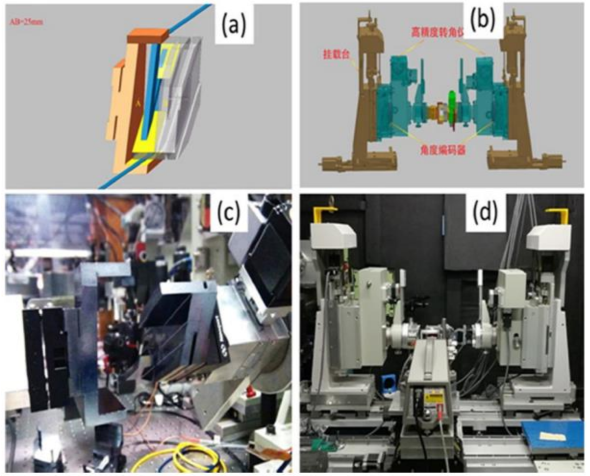


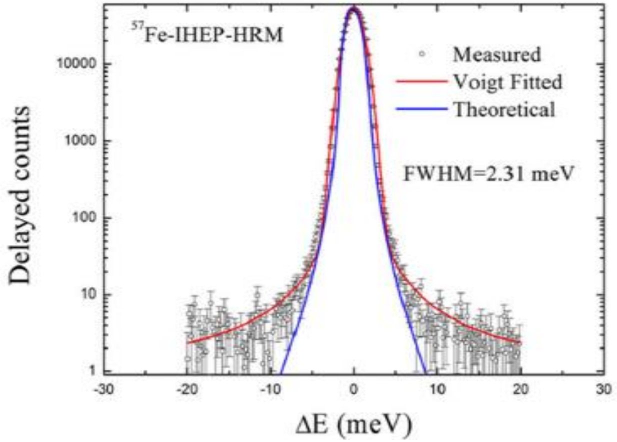

## High heatload liquid nitrogen double crystal monochromator (800W)



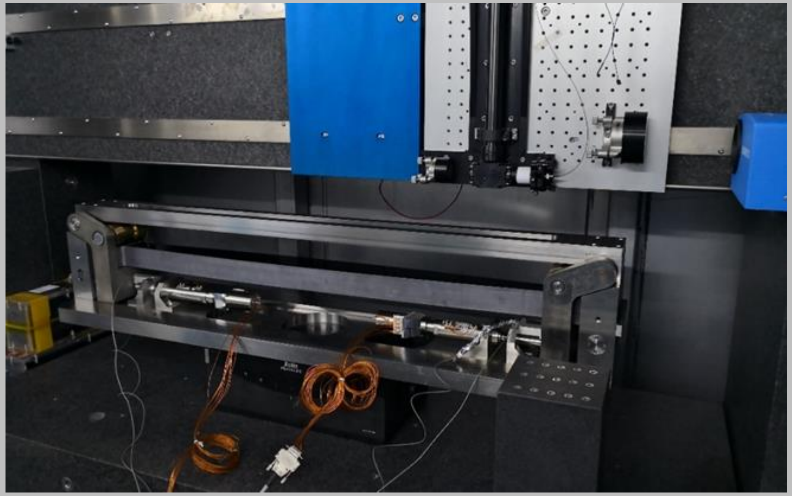
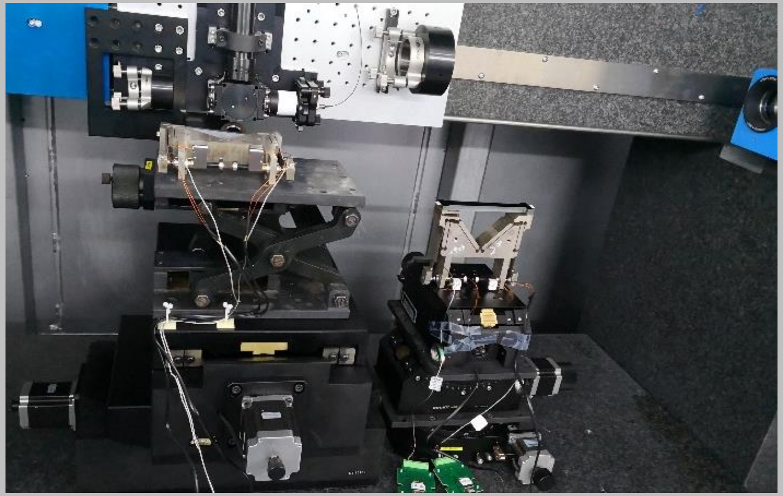
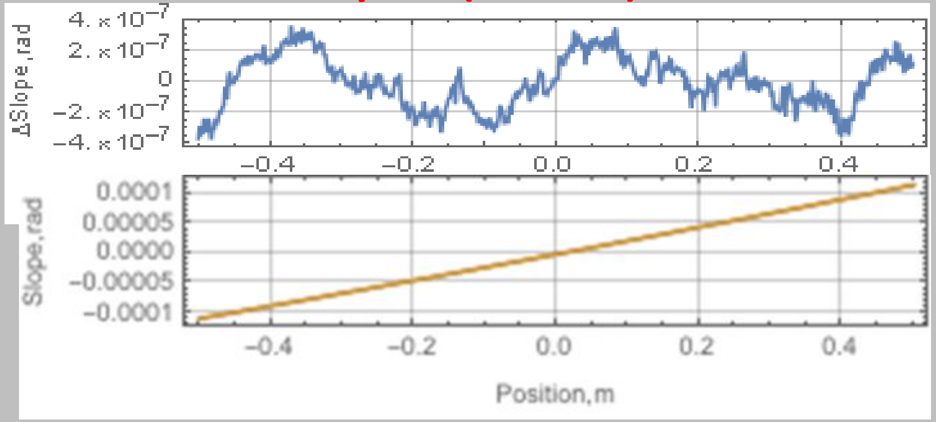
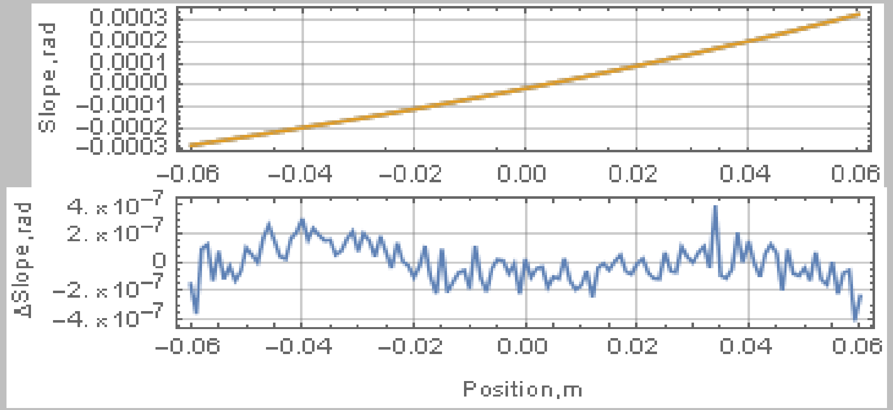
## High energy resolution meV monochromator (2.3meV)



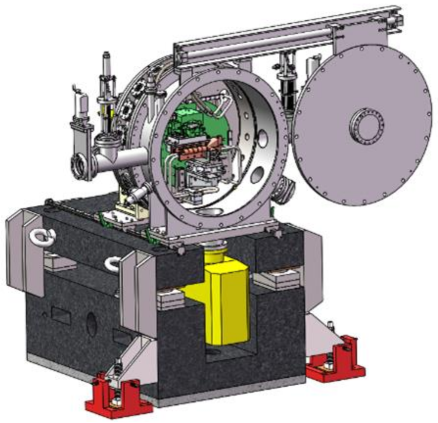



# Bent mirrors for sub-micron focusing

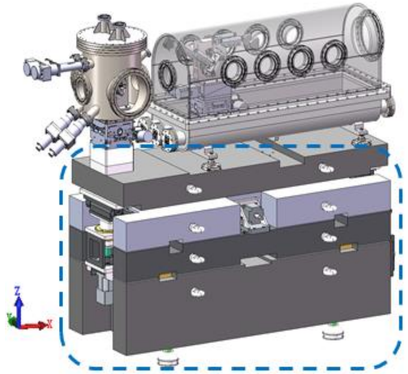
## Features: Torpedo shape , Non-gravity compensation

| | 1m long elliptically bent mirror | 120mm short elliptically bent KB mirrors |
|---|---|---|
| **Bender and metrology setup** |  |  |
| **Test results for shape accuracy** | **0.17 μrad (Vertical)**   | **0.19 μrad (Vertical) 0.13μrad(Horizontal)**   |

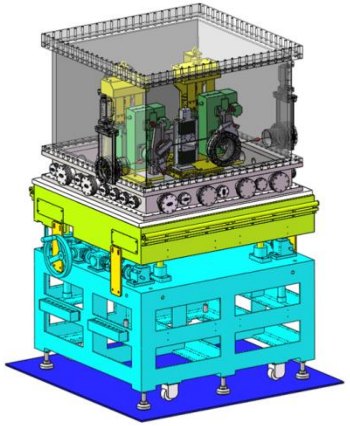
# Versatile monochromators: Preliminary designs under the way



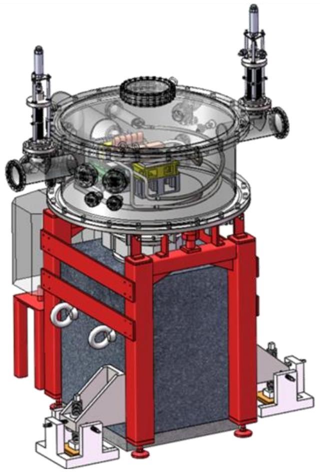
VDCM



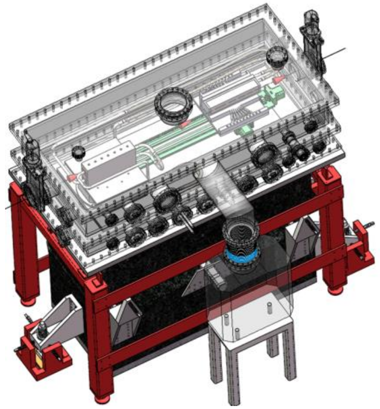
Laue Mono upgrade



HRM upgrade

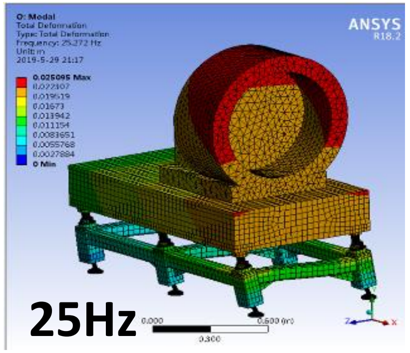


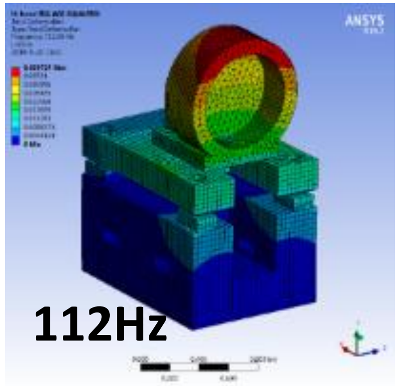
HDCM



HDMM

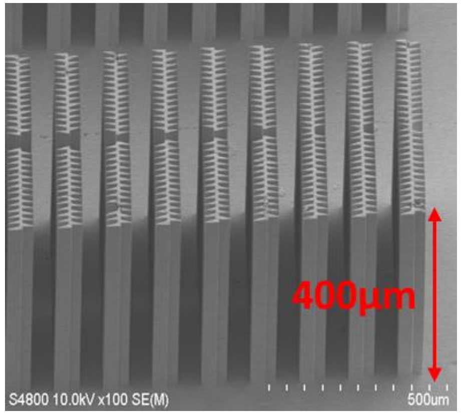
**DCM support optimized to higher eigenfrequency**

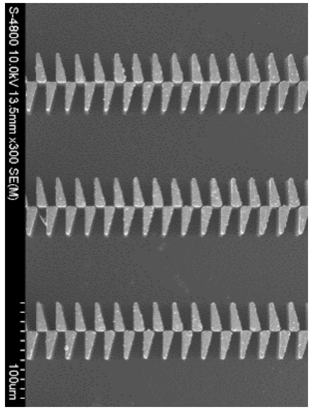


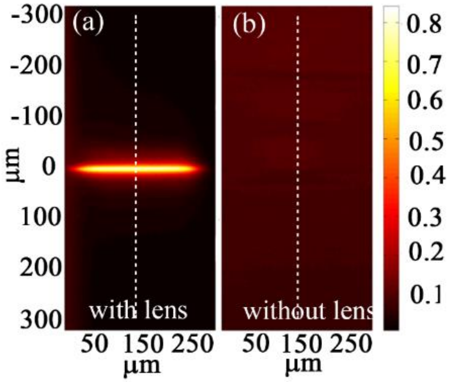



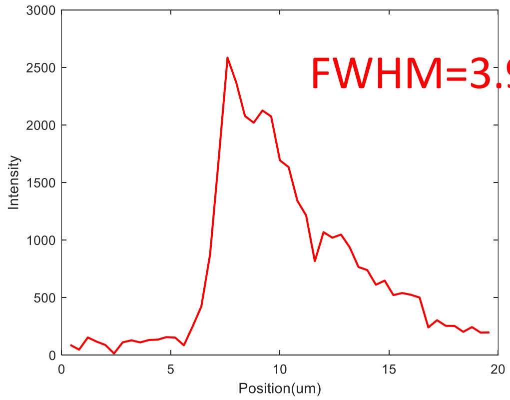
# X-ray focusing optics, by LIGA using a LIGA beamline in BSRF

## High Energy X-ray Kinoform by LIGA technique
## Ni based, 4μm @87KeV measured@PETRAIII



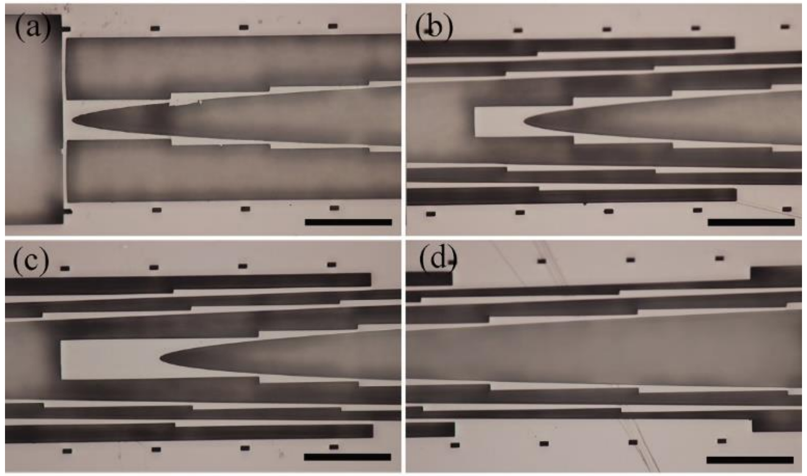



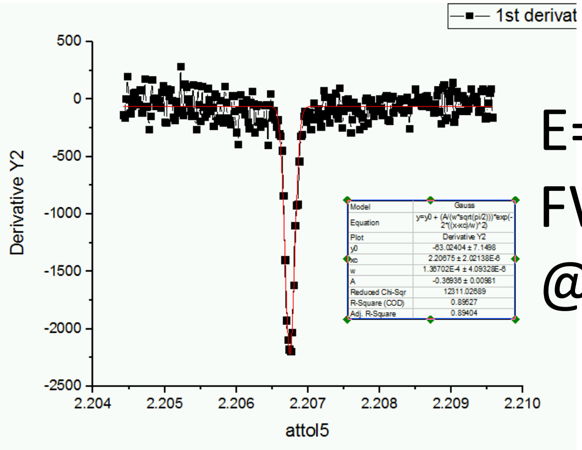




FWHM=3.95μm

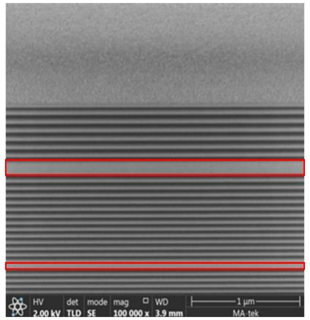
## X-ray PMMA Kinoform

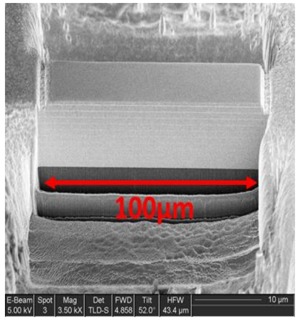


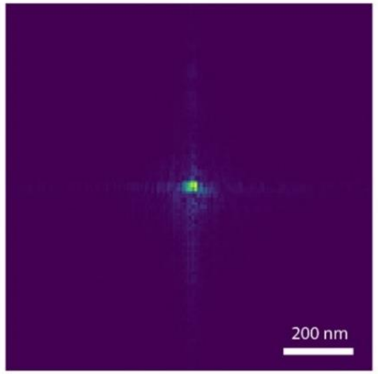




E=12keV
FWHM:~140nm
@Diamond

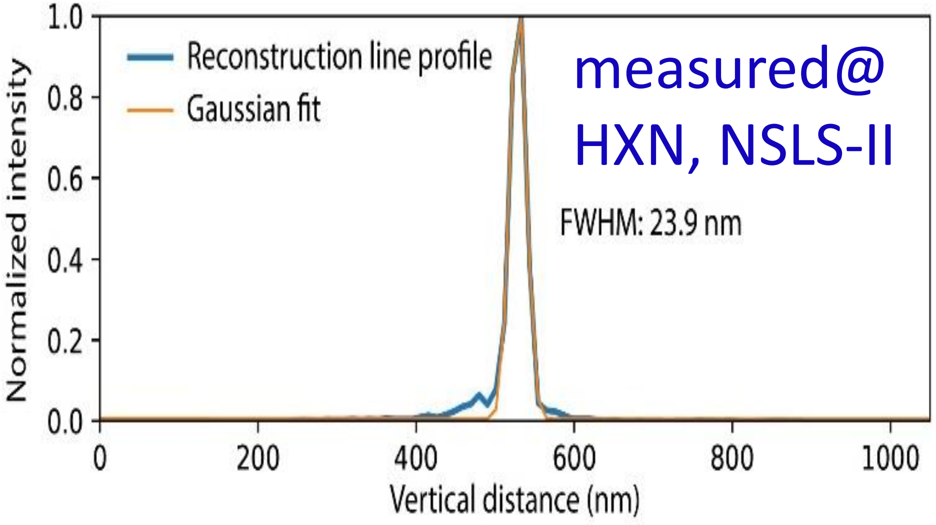
## Nanofocusing - Multilayer Laue Lens



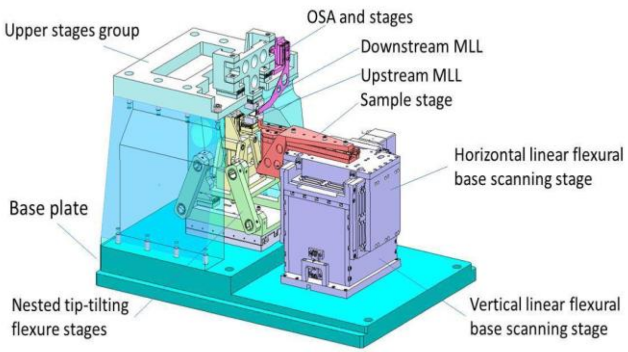


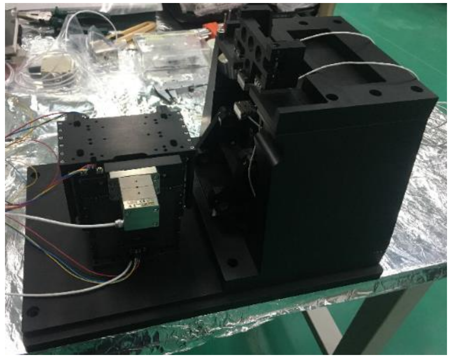



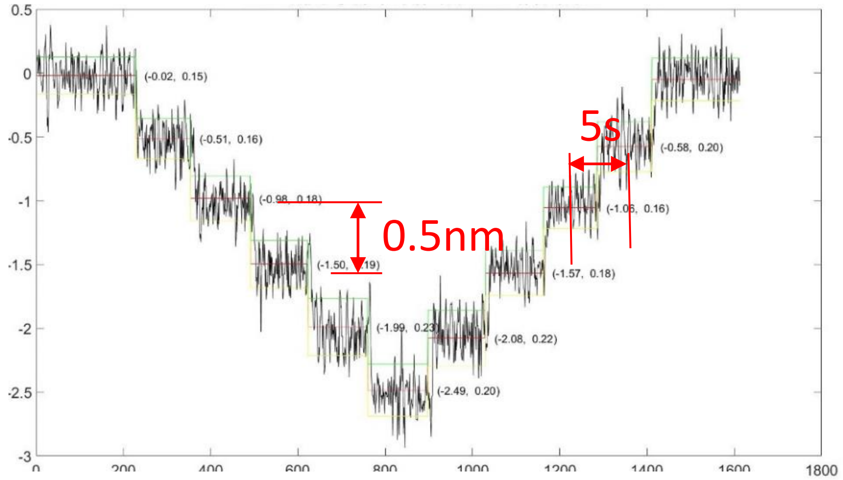

Multilayers and Mark layersFIB Polishing




## Nano manipulator



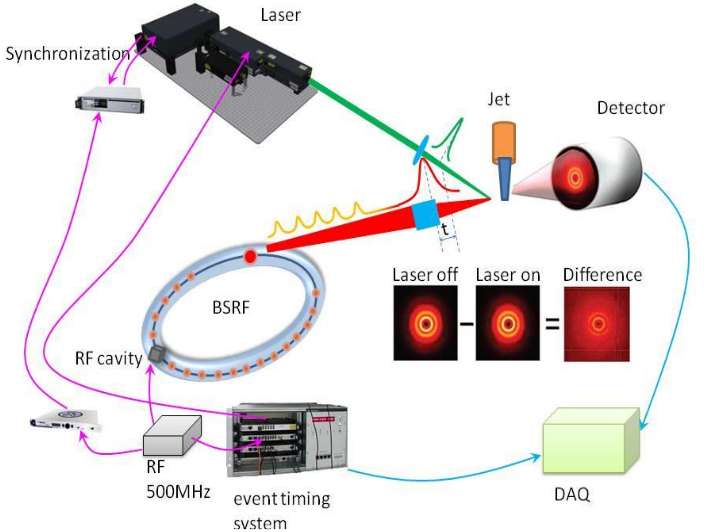



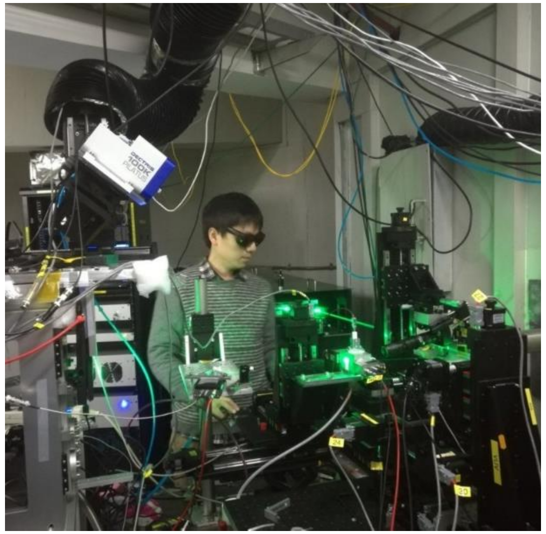


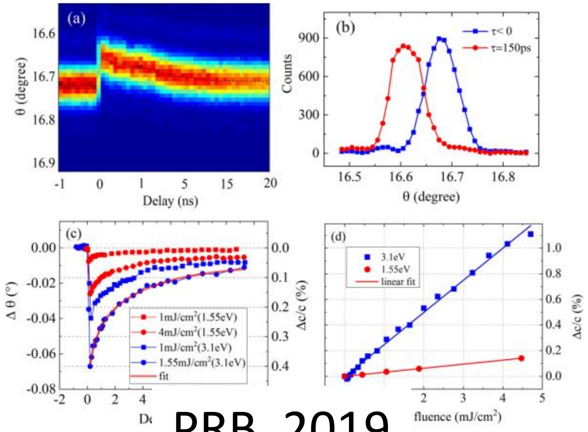

Test result in metrology lab at IHEP
Step scan: 0.5nm, stay time: 5s

# Time-resolved:

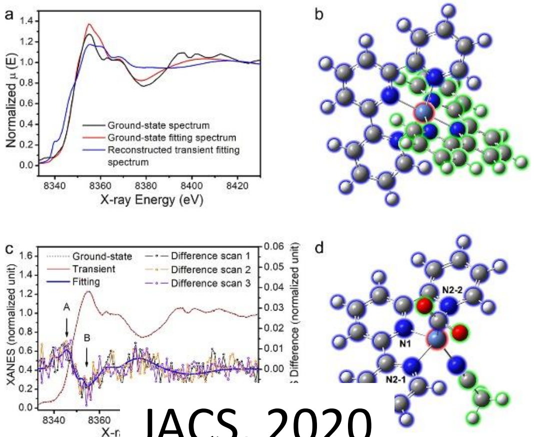
## Reversible: High repetition rate laser Pump/X-ray Probe for picosecond XRD&XAS



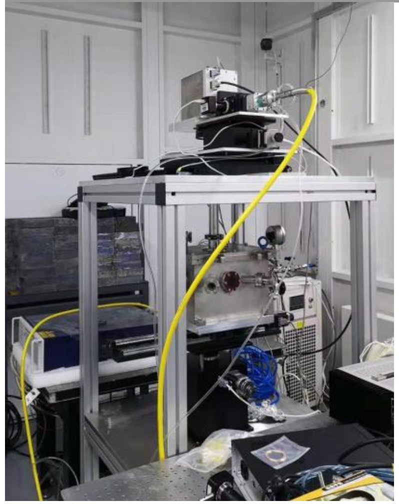



PRB, 2019




JACS, 2020

## Irreversible: metal laser 3D printing process by fast X-ray imaging



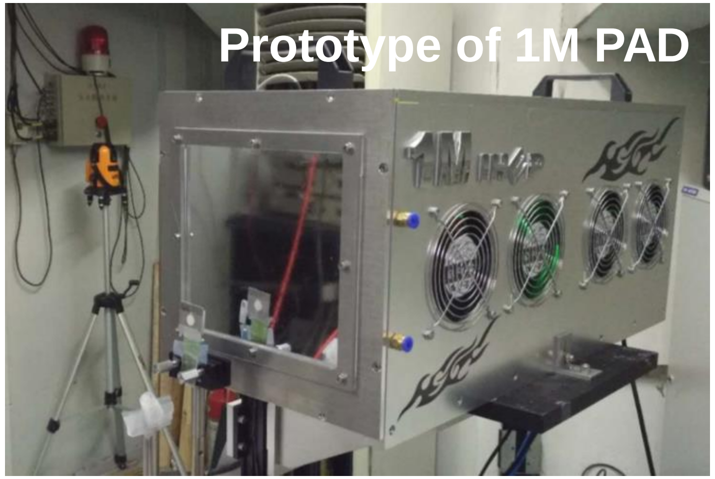
**Demo test :**

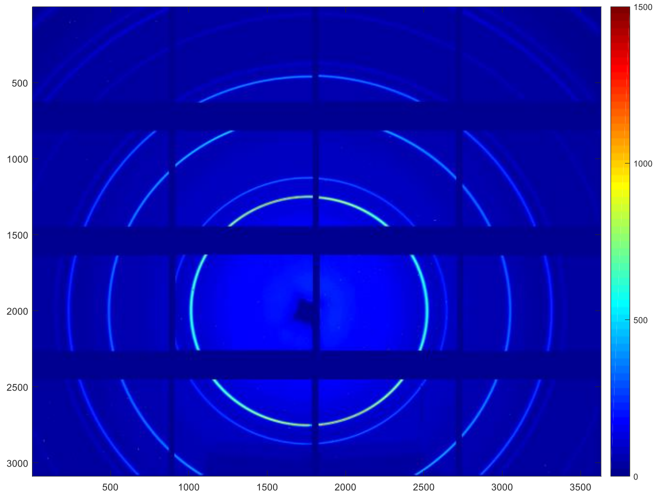
White light from SCW

600 μm Ti6Al4V powders molten by 350W laser；

20kfps， 20μs exposure

# X-ray Pixel Array Detector



Pixel size：  150 x 150μm

Pixel number: 1M

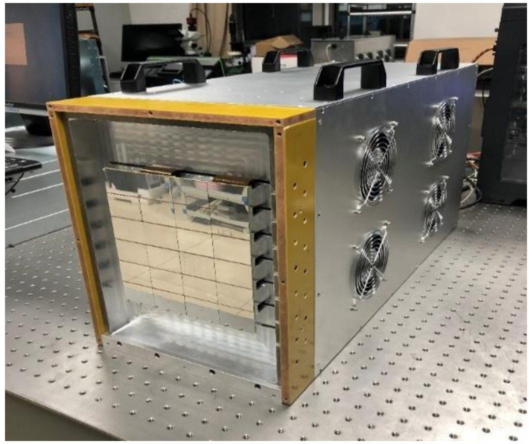
Active area: 12.24cm╳17.28cm

Frame rates： 1 KHz

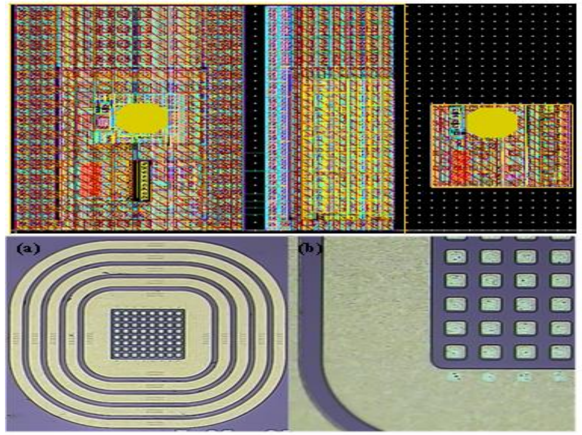
Dynamic range:  20bits

Energy range: 8-20keV, Si-based

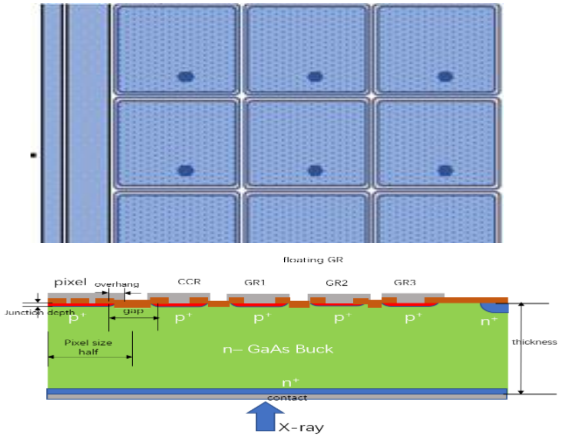
Mini gap upgrade



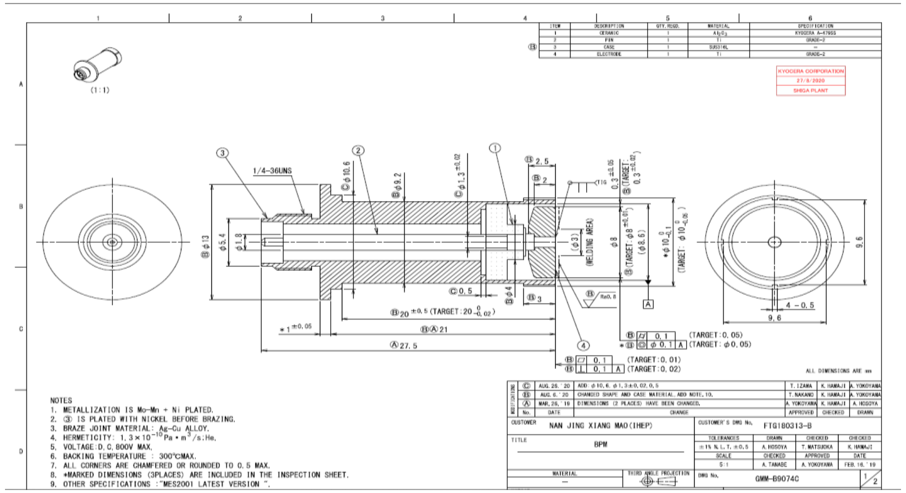
55 μm pixel module nearly finished



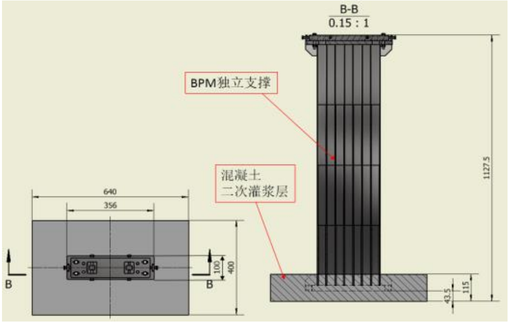
high-energy sensor module under way



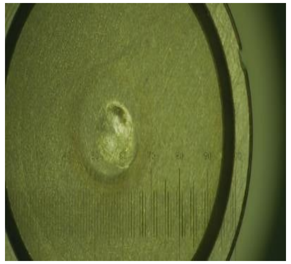
# Beam Diagnosics & Control



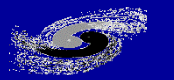
The design of feedthrough is finished.
Calling for Bids will be finished in one month.




The gird is pouring by concrete into the ground, the first order frequency of gird is **above 55Hz**

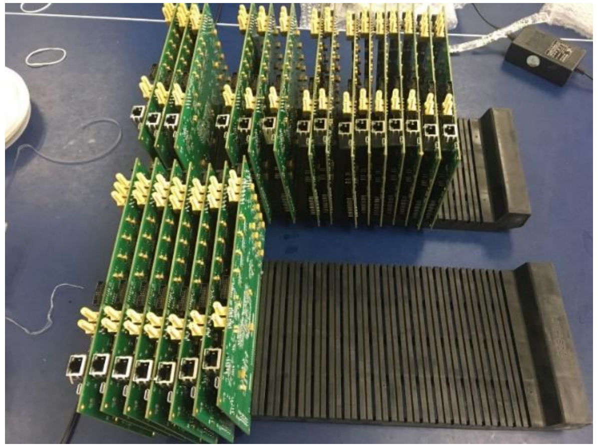


The small amounts feedthroughs manufactured by companies meets our requirements

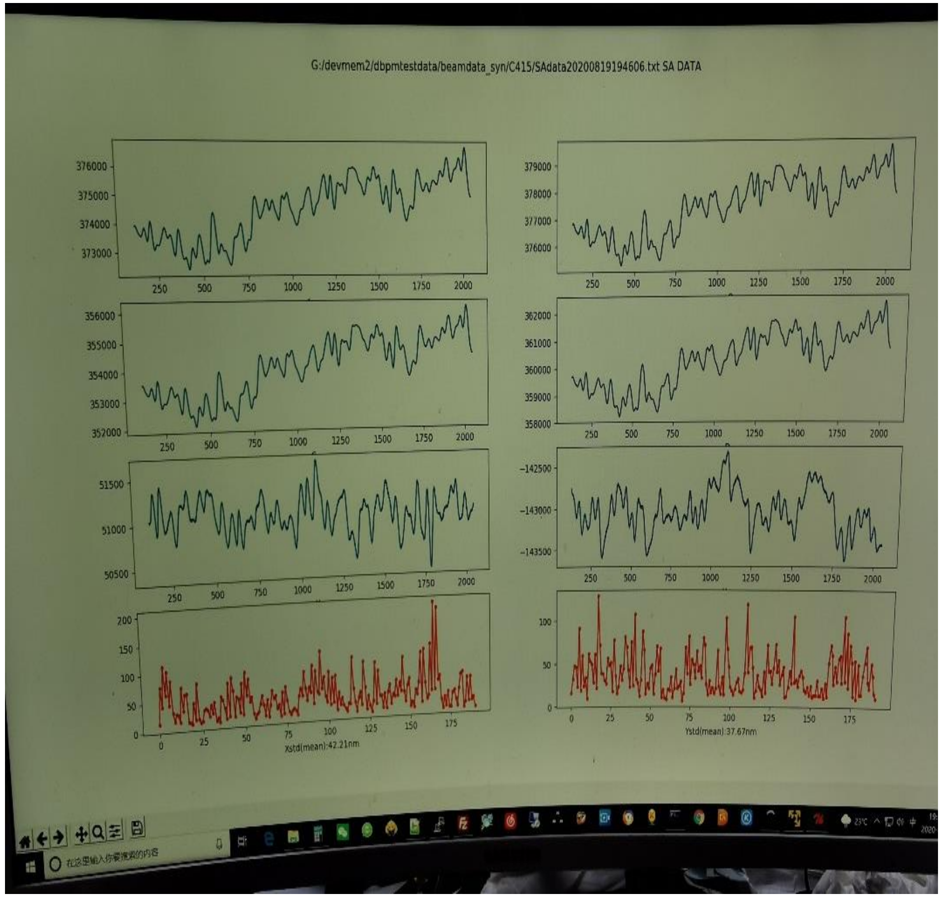


Prototype of BPMs are manufacturing by the companies

# DBPM electronics development



50 sets house-development DBPM electronics have been installed on BEPCII ring. They perform well.




The resolution of SA data of DBPM is **21nm in lab**

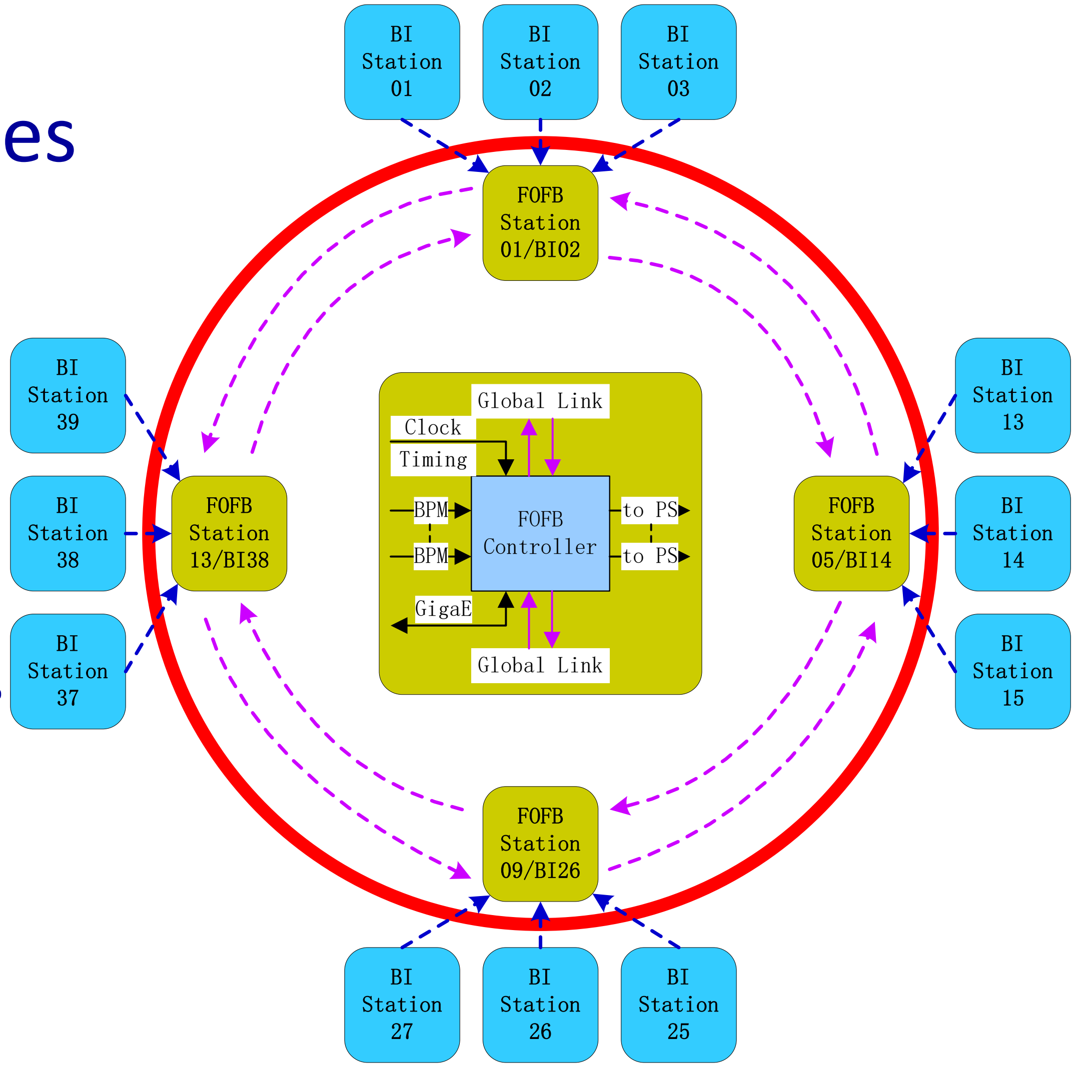
House-development water-cooled cabinet performs well. The temperature change inside the cabinet is **about 0.2°C（PP value）** in 8 days.

# Beamline Control System

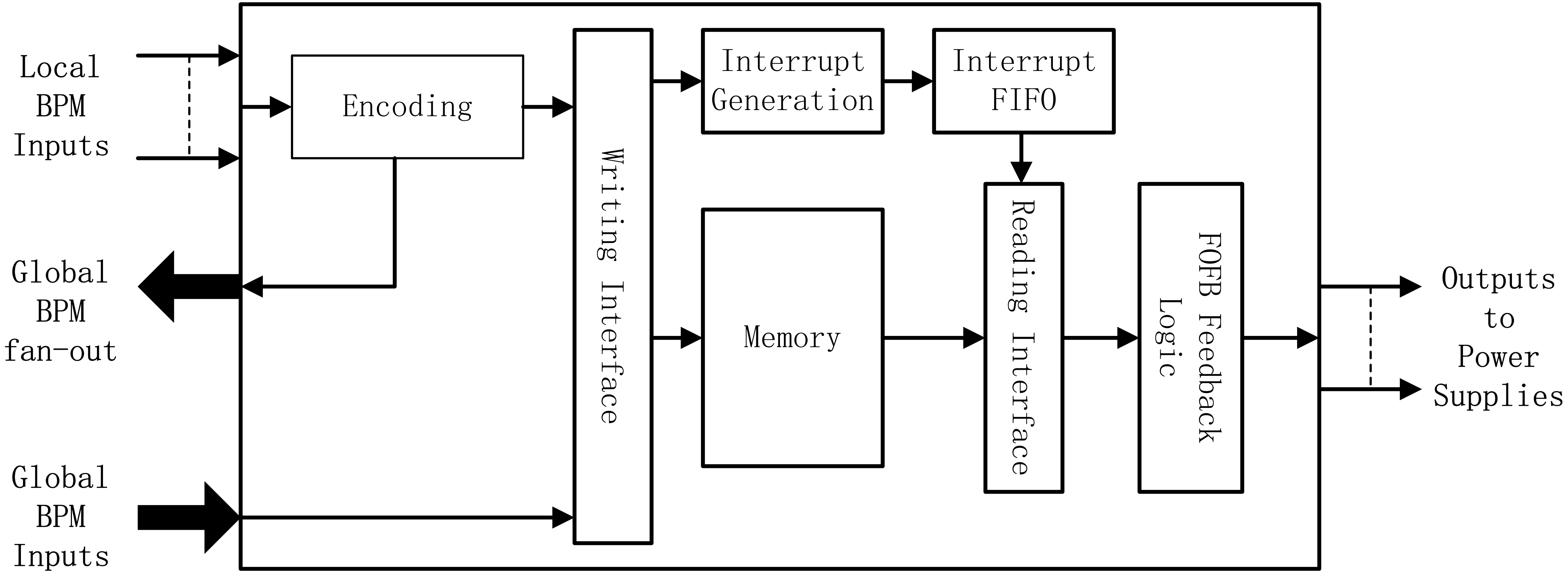
- Scope of beamline control system
  - Motion control system
  - Beam Position Monitoring system
  - Vacuum control system
  - Cryo-cooling and water-cooling system
  - Data Acquisition
  - Equipment Protection System(EPS)
  - Personal Protection System(PPS)
  - Timing and Synchronization(Cooperation with Timing System)
  - Etc.

# FOFB system

- System structure and key techniques study finished.
- One set of firmware for all 16 stations.
- Global logic diagram under design.



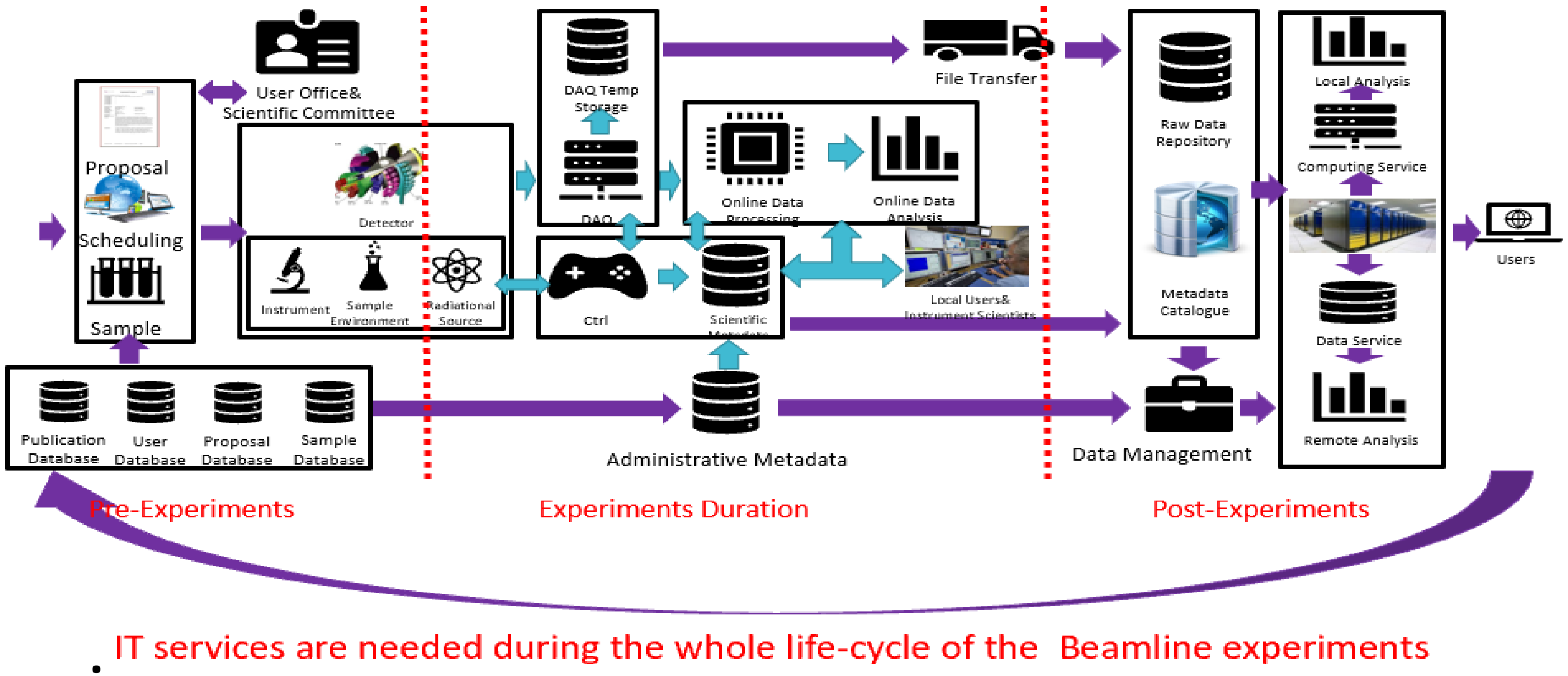
# FOFB system




Preliminary logic diagram of the FOFB sub-station

# HEPSCC - Missions

- Provision of scientific data and user services for HEPS
  - Infrastructure
  - Network
  - Computing
  - Storage
  - Data Management
  - Scientific Software
  - Public Software and Services

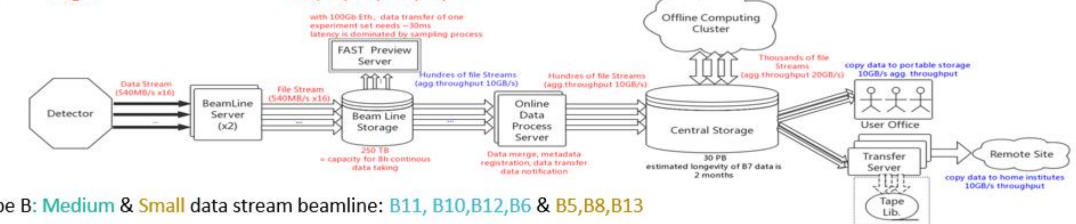



- Research on open IT technologies related to HEPS

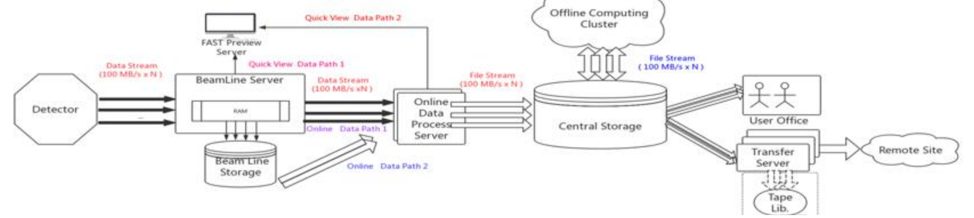
# HEPSCC - Progress

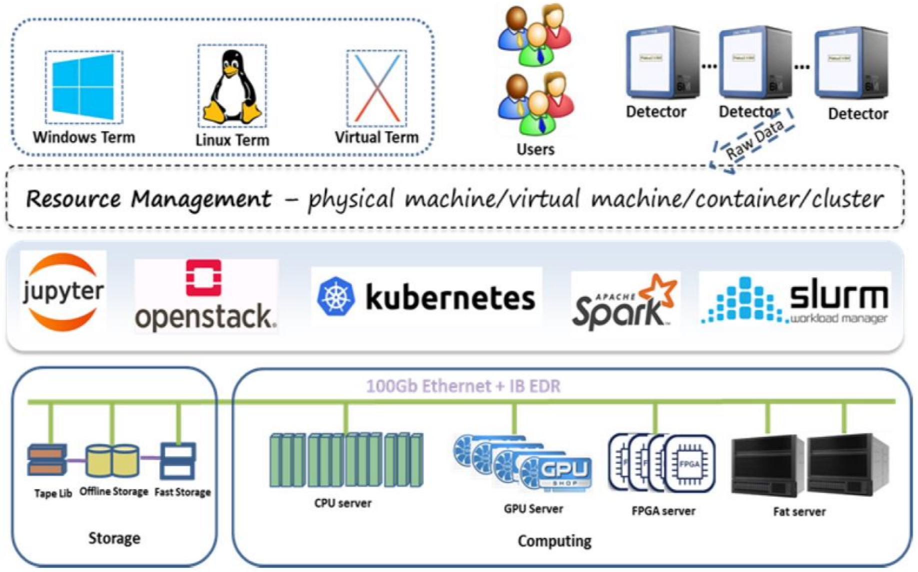
- Finished the detailed design of HEPSCC system
  - network, computing, storage, data management, user service, software framework…
  - Different IT architectures for different beamlines
  - Scalable, modular , Easy-to-use
- The key technologies and workflows are being validated on test-bed

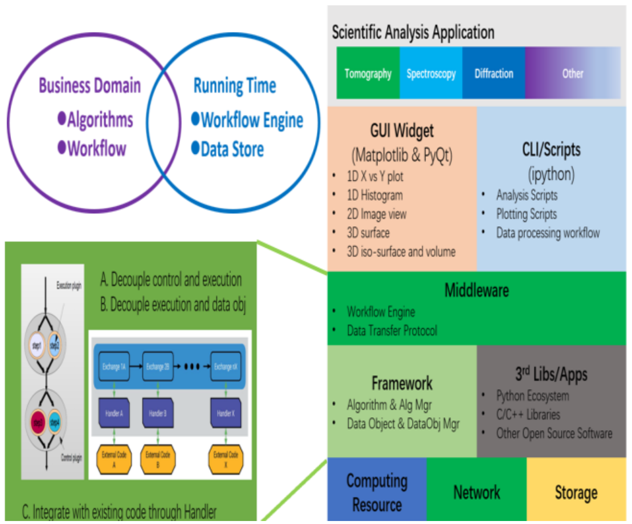
Type A: Large data stream beamline: B7,B3, B4,B14,B2,B1

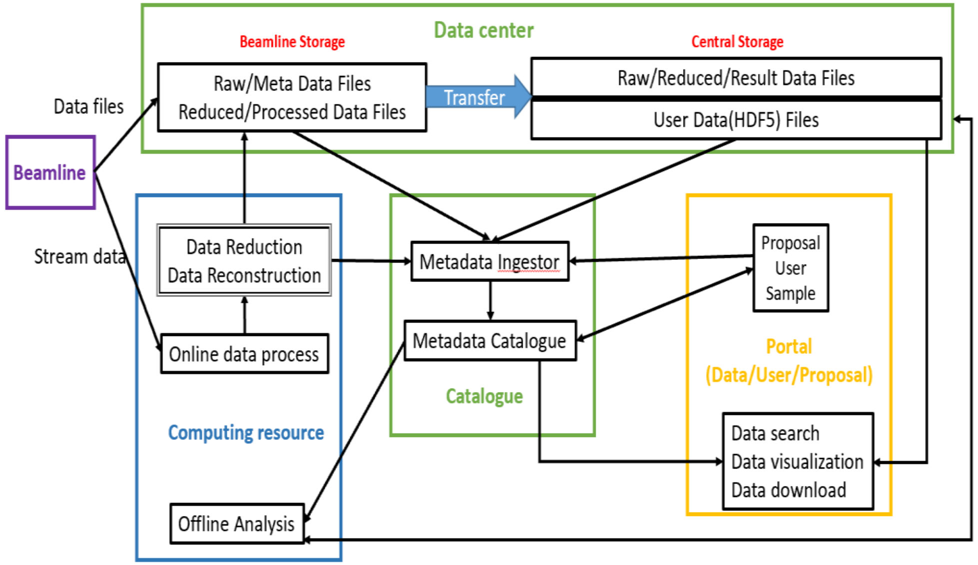



Type B: Medium & Small data stream beamline: B11, B10,B12,B6 & B5,B8,B13



# HEPSCC - Capability

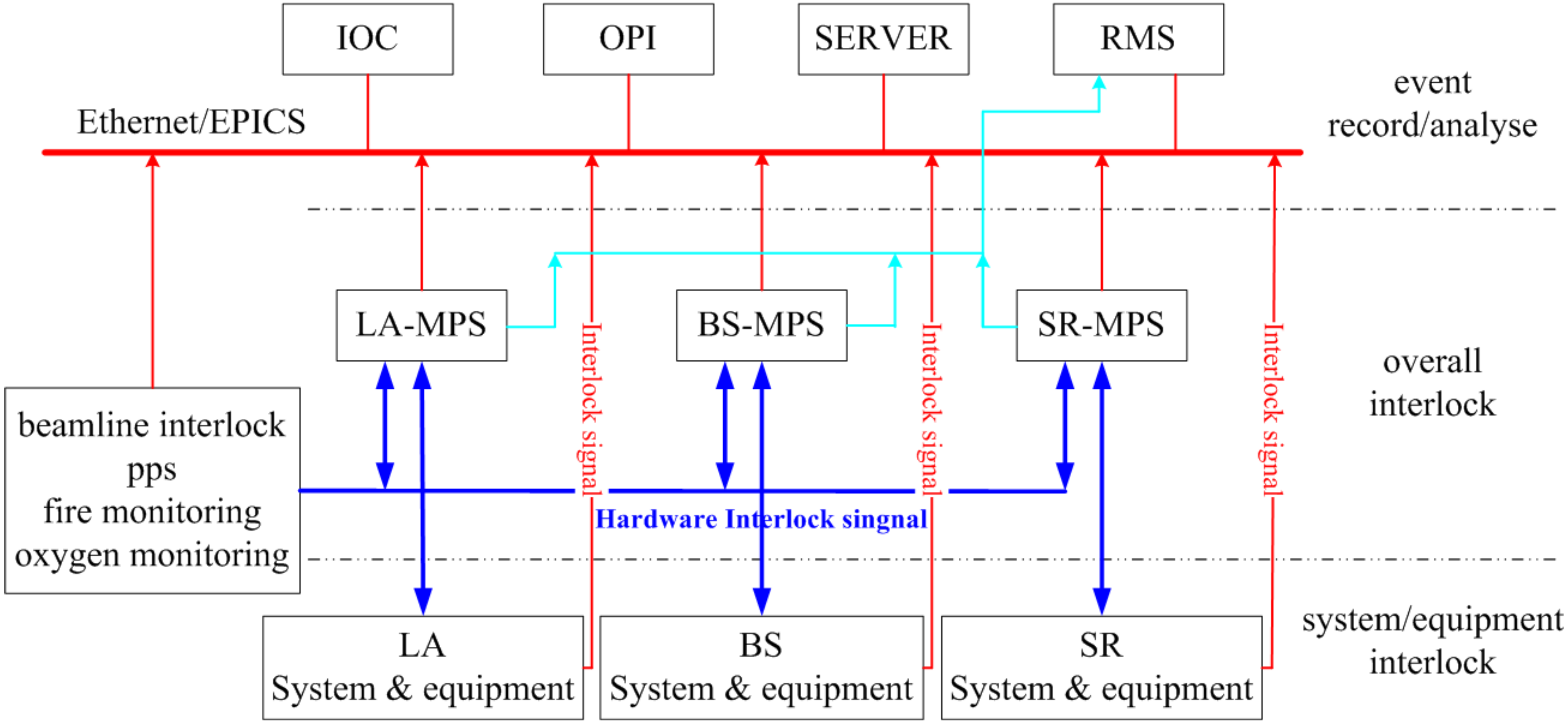
| Items | Performance | |
|---|---|---|
| Machine Room | Floor Space: 600 ㎡<br>Racks: 30 for phase I (totally 100) | 14 beamlines phase I<br>>90 beamlines phase II |
| General Network | 1Gbps/10Gbps | |
| Data Center Network | 10Gbps/100Gbps | |
| Storage Resource | 30 PB Disk<br>XXPB Tape | Tape storage will be provided according to the funding |
| Computing Resource | CPU: 90 TFLOPS(2500 CPU Cores)<br>GPU:365 TFLOPS (48GPU NVIDIA Tesla V100) | |
| Big gap.....between the capability and the missions / requirements for the funding reason<br>But the system is scalable..... | | |

# MPS System

- The HEPS (High Energy Photon Source) operate with large amount of power and energy stored in beams and superconducting magnets. In order to prevent damage to accelerator components in case of failure, highly reliable Machine Protection System(MPS) is indispensable.

- The MPS consist of Slow Protection System(SPS), Fast Protection System(FPS) and Run Management System(RMS). The SPS is Programmable Logic Controller(PLC)  based system which can deliver less than 20 msec reaction time. The FPS is Field Programmable Gate Array(FPGA) based system which can deliver less than 20 μsec reaction time. The RMS guarantee HEPS running safely and easy to operate, together with Personnel Protection System(PPS), it can set the accelerator modes by mechanical key switch.

# MPS System




MPS architecture

# Database and its Application

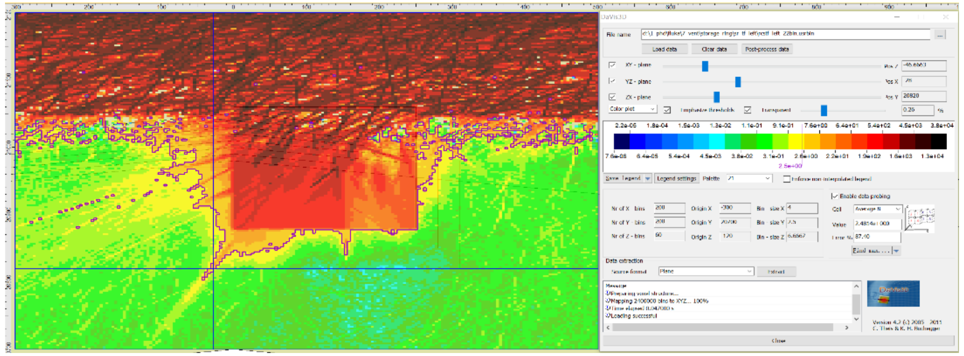
- The overall coverage of the HEPS database is very large, 16 working modules based on relational database are planned according to functions, including:
  - Project Management/Documentation; Parameter List; Naming Convention; Magnet Measurement Data; Device Information; Survey/Alignment; Cable; Authentication and authorization; Lattice/Model; Device/Configuration; Physics/Save/Restore; Operation/Maintenance; Alarm; Machine Protection System/ Interlock; MPS Postmortem Analysis

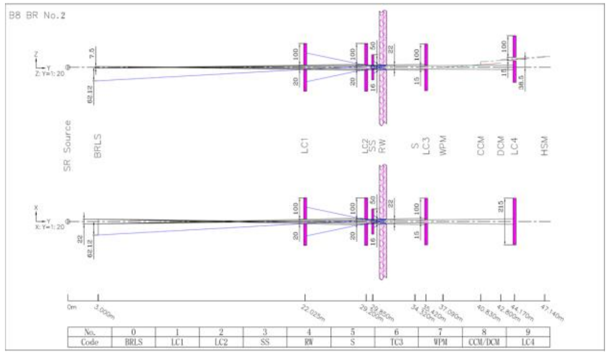
# Database and its Application

- **Parameter List**：Table design and data entry are completed and operational
- Naming Convention：6 systems have been input and are in progress
- Magnet Measurement Data：Cooperate with the magnet system, complete the design of the table related to magnetic measurement report, software programming function test and Web interface development
- **Device Information**：Docking with the asset management system

# Radiation Protection and Safety System

- **Radiation shielding design verification according to engineering design modification.**
  - **Accelerator shielding** work includes local shield design for Linac collimator, dose rate assessment for reserved cable holes, maze and ducts.
  - **Beamline shielding** work includes verification of tracing results of bremsstrahlung, optimization of shielding thickness under more strict dose constraint.
  - **Heat/Absorbed dose evaluation:** evaluate the impact of heat deposition and absorbed dose caused by ring collimator to magnets, insert devices and electronics

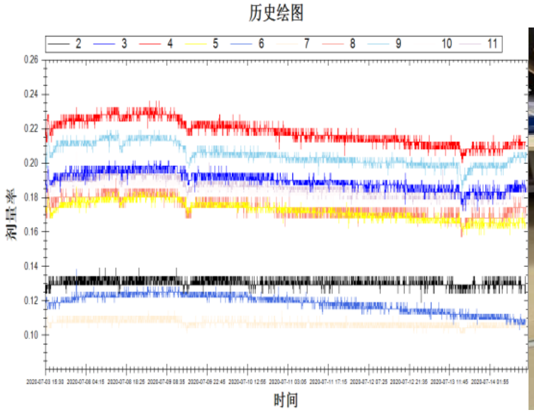


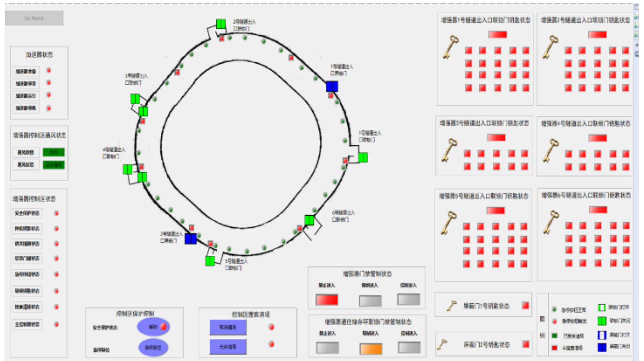


| | 不带 kicker | 带垂直 kicker |
|---|---|---|
| 铜 | 830.7 ± 1.7 | 16.3 ± 0.2 |
| 碳 | 216.1 ± 0.4 | 4.1 ± 0.08 |
| 铝 | 279.0 ± 0.5 | 5.2 ± 0.09 |
| 铍 | 179.4 ± 0.4 | 3.4 ± 0.4 |
| 钛 | 437.2 ± 1.0 | 8.2 ± 0.5 |

# Radiation Protection and Safety System

- Complete the technical design review for radiation dose monitoring system and safety interlock system.
- Continue the research development for the both systems
  - Amplifier circuit modified design
  - Microcontroller prototype test
  - Environmental monitor investigation
  - PLC monitoring interface development based on EPICS
  - PPS test platform was completed and key interlock logic design was vivificated



# UTILITY

# Utilities--Key requirements

- Electrical power (operational demand): 35.4 MW
- Total cooling tower water (CTW) flow rate: 7200 t/hr
- Total low-conductivity water (LCW) flow rate: 4162 t/hr
- Total heat load for cooling water: 17.7 MW
- Total cooling load for HVAC: 16.5 MW
- Total heating load for buildings: 10MW
- The vibration criterion for the storage ring: 25 nm (RMS displacement all frequencies 1-100Hz)

# Utilities--Recent Accomplishments

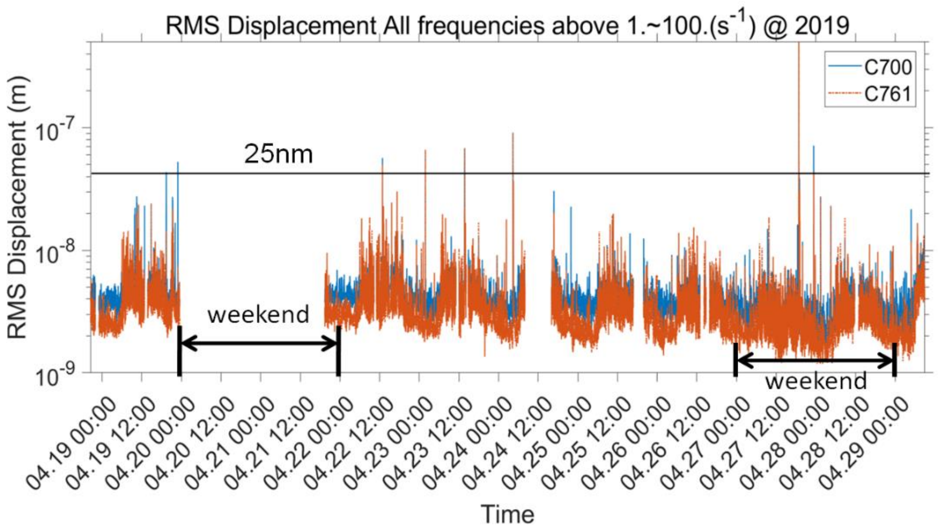
- The key requirements and schematic diagram for utilities have been defined, and optimized with participation from scientific teams and  external experts, engineers etc.
- The detail design of utilities was completed.
- Bids and  award for mechanical and electrical equipment were mostly completed.
- The ground motion was surveyed, and the vibration of ring and experiment hall foundation  have been simulated.

# Ground vibration

Detailed by Fang Yan

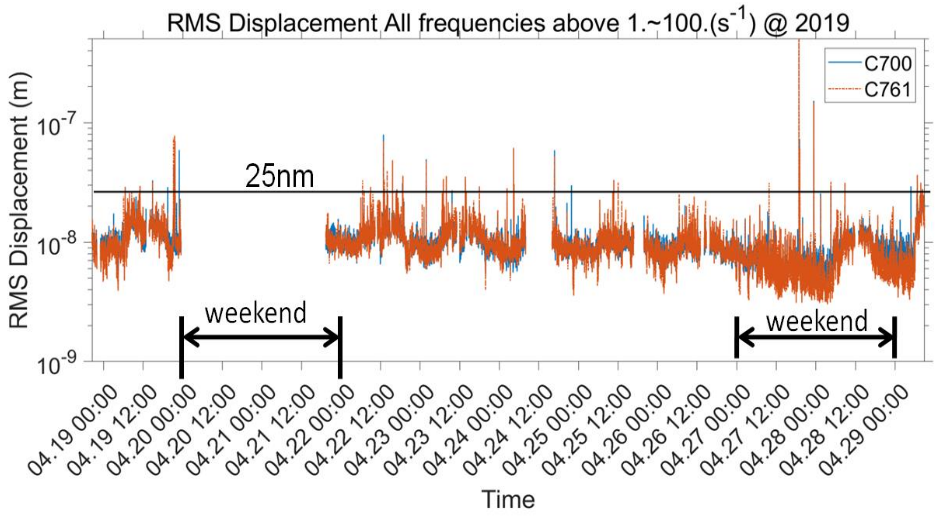
## •Vibration measurement

- Variation of ground motion level
  - Location:
    - ring
    - testing area nearby cryogenics bldg.
  - Time: one week


On the ground (close to slab4) : C761 On ground (@main ring) : C700

Vertical

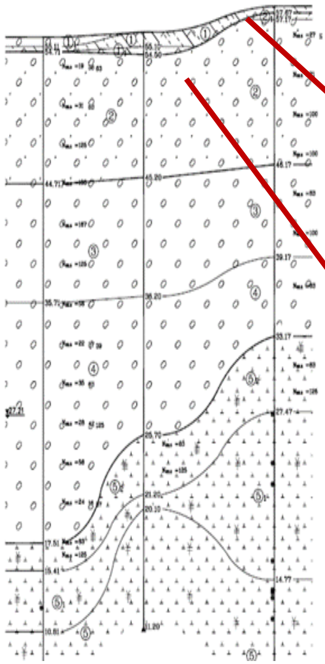



Horizontal (east/west)

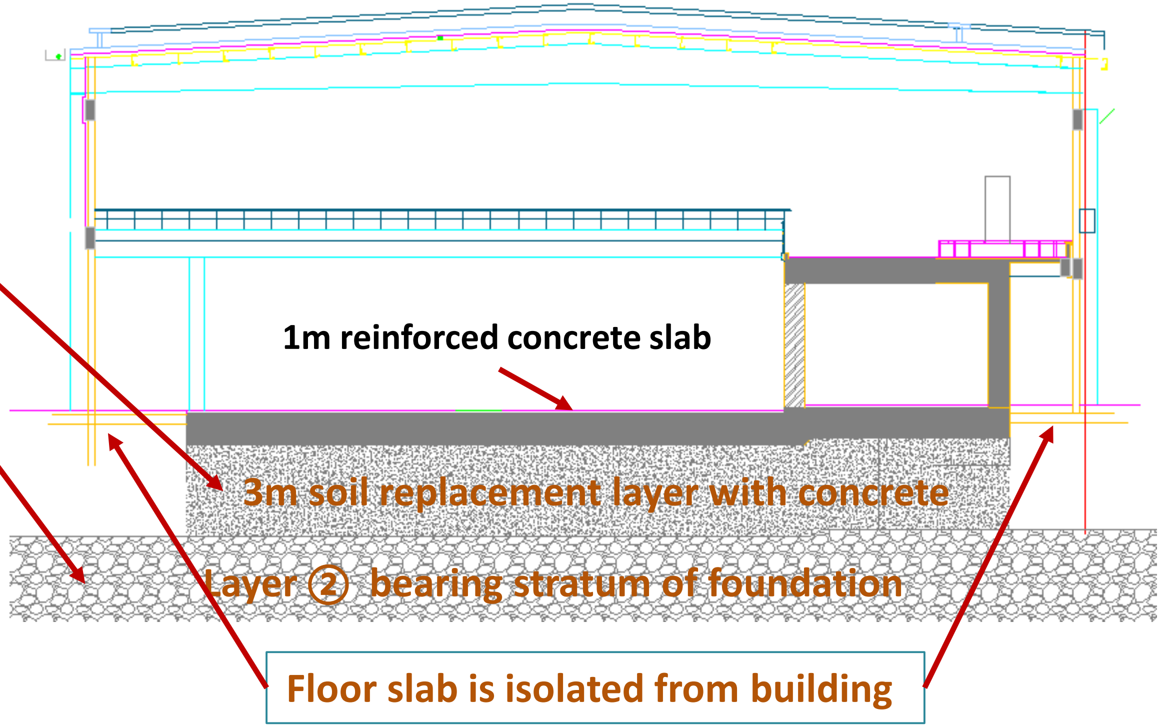
# Ground vibration

- Ring foundation

- ①Artificial deposited clay silt fill and ①$_1$ Pebble layer:
  - 0.50-2.80m
- ② Newly deposited pebble layer
- ③Quaternary deposited pebble layer
- ④Pebble layer
- ⑤$_1$ Strongly weathered and ⑤$_2$ Completely weathered granodiorite
  - 36.10-45.00m
- ⑤Middle weathered granodiorite



Geotechnical survey




- Detailed design of foundation for ring tunnel and experiment hall
  - It is verified by simulation that soil replacement with concrete is equivalent to the grouting scheme upon vibration.

# Electric power distribution

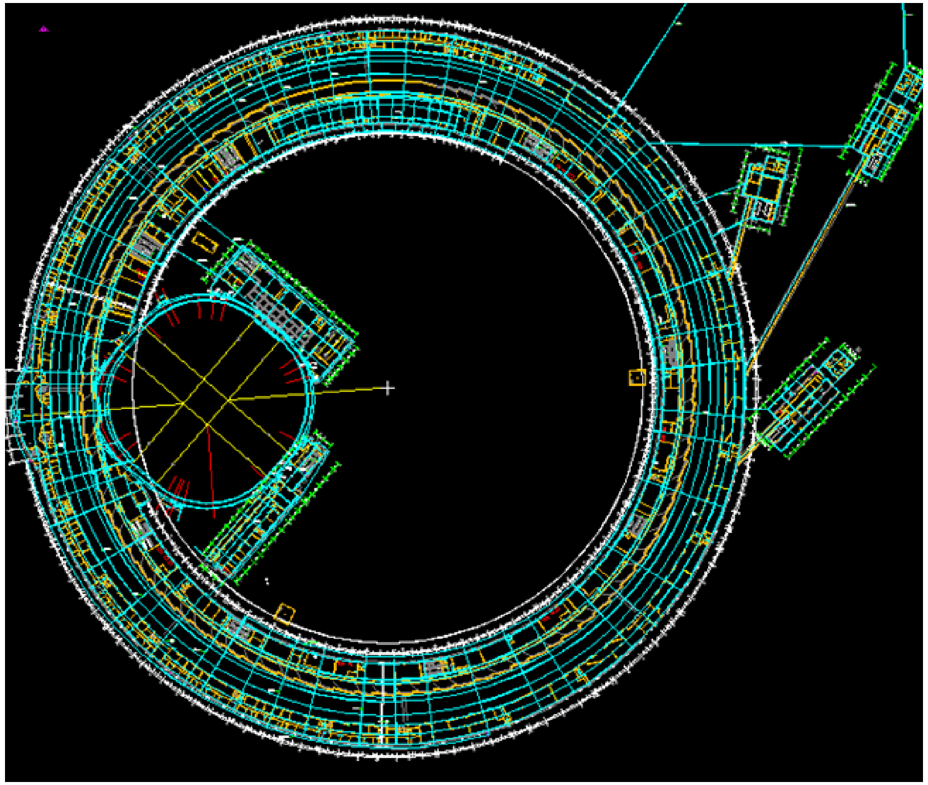
- Electric power demand for HEPS

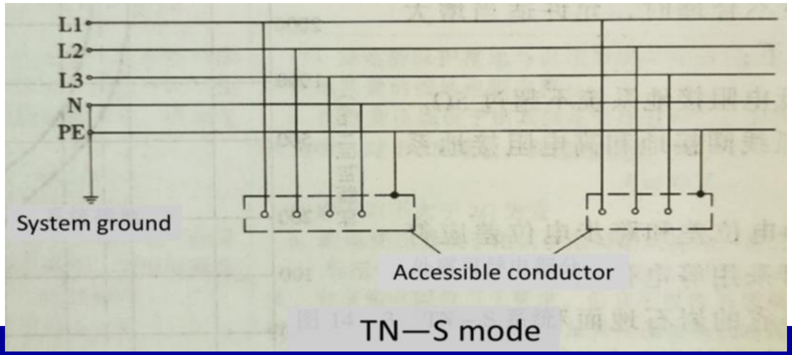
| Location | Electrical loads (kW) | Loads connected (kW) |
|---|---|---|
| Storage ring | 13669 | 18329 |
| Booster and BTR&RTB | 5300 | 6820 |
| LINAC and LTB | 963 | 1725 |
| Beamline | 2841 | 6188 |
| Ring building | 4406 | 20255 |
| Central utility and cryogenic bldg. | 8220 | 15202 |
| Total | **35399** | 68519 |

- Voltage levels on-site
  - 10kV power distribution system, for HV power equipment and step-down substation incomer
  - 0.4kV power distribution system, for dedicated services and general services
- Power factor ≥ 0.96
- Voltage drop will be limited to 5%.

# Grounding

- Grounding Electrode System
  - Utilize the building steel which is melded together by ϕ10 steel bar to make up natural grounding grid.
  - Its ground resistance will be less than 0.5 Ω.
  - Integrated for lightning protection grounding, safety protection grounding and instrument reference grounding .
- The ground bus
  - To be connected directly to the grounding grid where needed respectively.
- Power distribution system (LV)
  - TN-S AC grounding connection mode
- Equipotential bonding
  - Connect all accessible metalwork to the system earth.





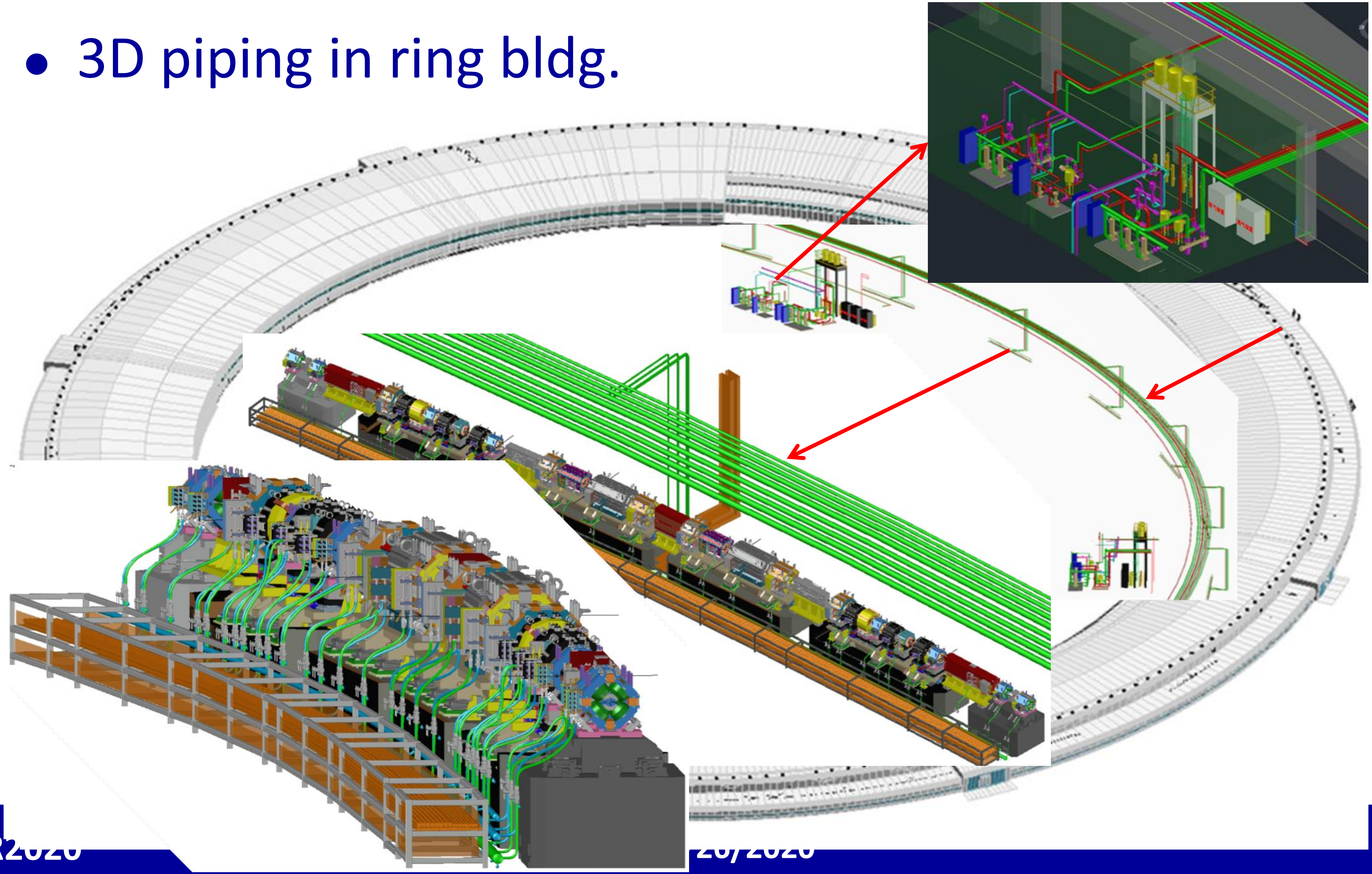
# Cooling water system

- The heat load dissipated by HEPS machine
  - The major heat sources of the facility are:
    - RF power sources, magnets, vacuum chambers, cryogenic compressors, power converters, pump, heater, etc.

| Location | Heat loads (kW) |
|---|---|
| LINAC and LTB | 297 |
| Booster and BTR, RTB | 4592 |
| Storage ring | 10217 |
| Beamline | 546 |
| Cryogenic | 1200 |
| pump | 831 |
| Total | **17683** |

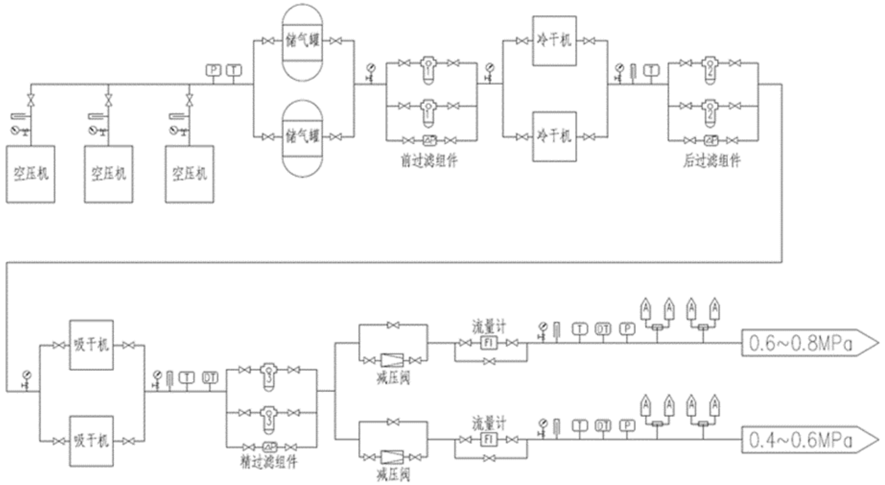
# Cooling water system

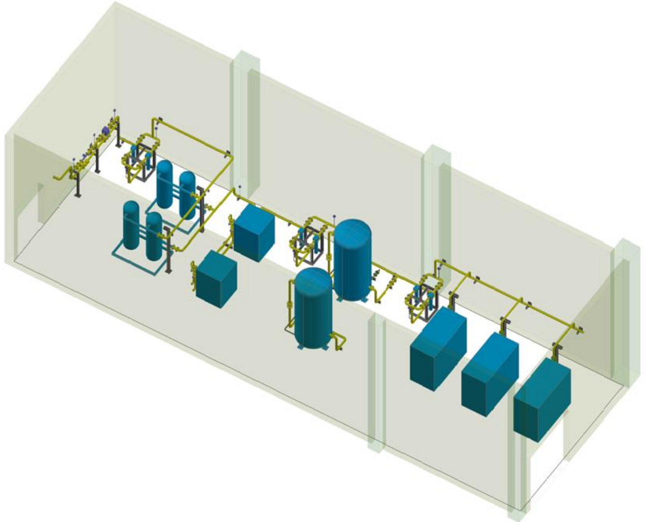
- 3D piping in ring bldg.



# Compressed air

- Air supply for pneumatic components on site
- Design requirements
  - Capacity: 22.1 $m^3$/min
  - Operating pressure
    - 0.6 MPa
    - 0.8 MPa
  - Air quality
    - Pressure dew point temp.: -40℃
    - Particle removal efficiency: ≥99.97%
    - Maximum oil content: ≤0.01ppm
- Compressor plant in utilities bldg.
- Distribution piping around machine area



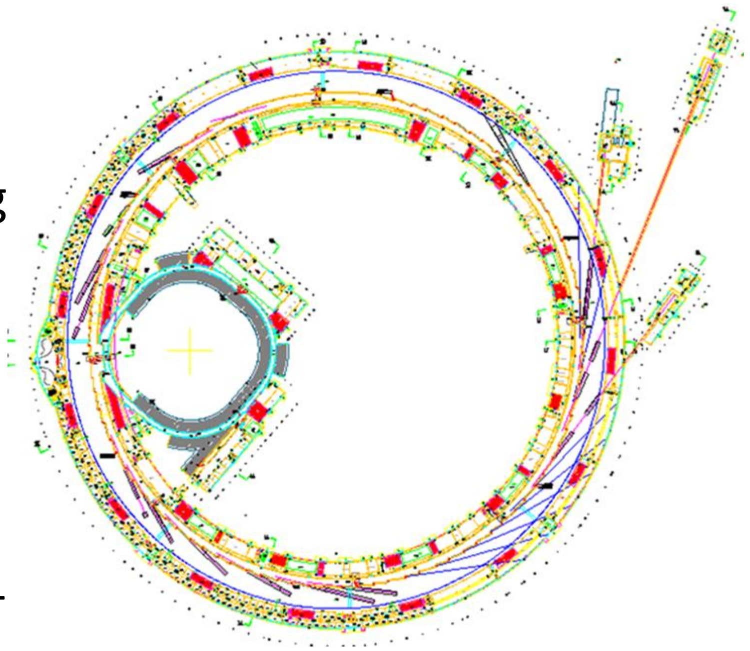
# HVAC

- Expected cooling and heating loads of HVAC

| Location | Summer cooling load (kW) | Winter heating load (kW) |
|---|---|---|
| Experiment hall | 4081 | 3436 |
| Ring tunnel | 870 | 0 |
| Booster tunnel | 517 | 75 |
| LINAC tunnel | 35 | 9 |
| Ring tunnel mezzanine | 2360 | 2718 |
| User building | 1900 | 1043 |
| Ring service bldg. | 2980 | 1349 |
| Booster service bldg. | 406 | 107 |
| LINAC service bldg. | 168 | 65 |
| Long beamline | 450 | 200 |
| Central utilities bldg. | 800 | 690 |
| Cooling water for cryogenics | 1200 | 0 |
| Total | 15767 | 9692 |

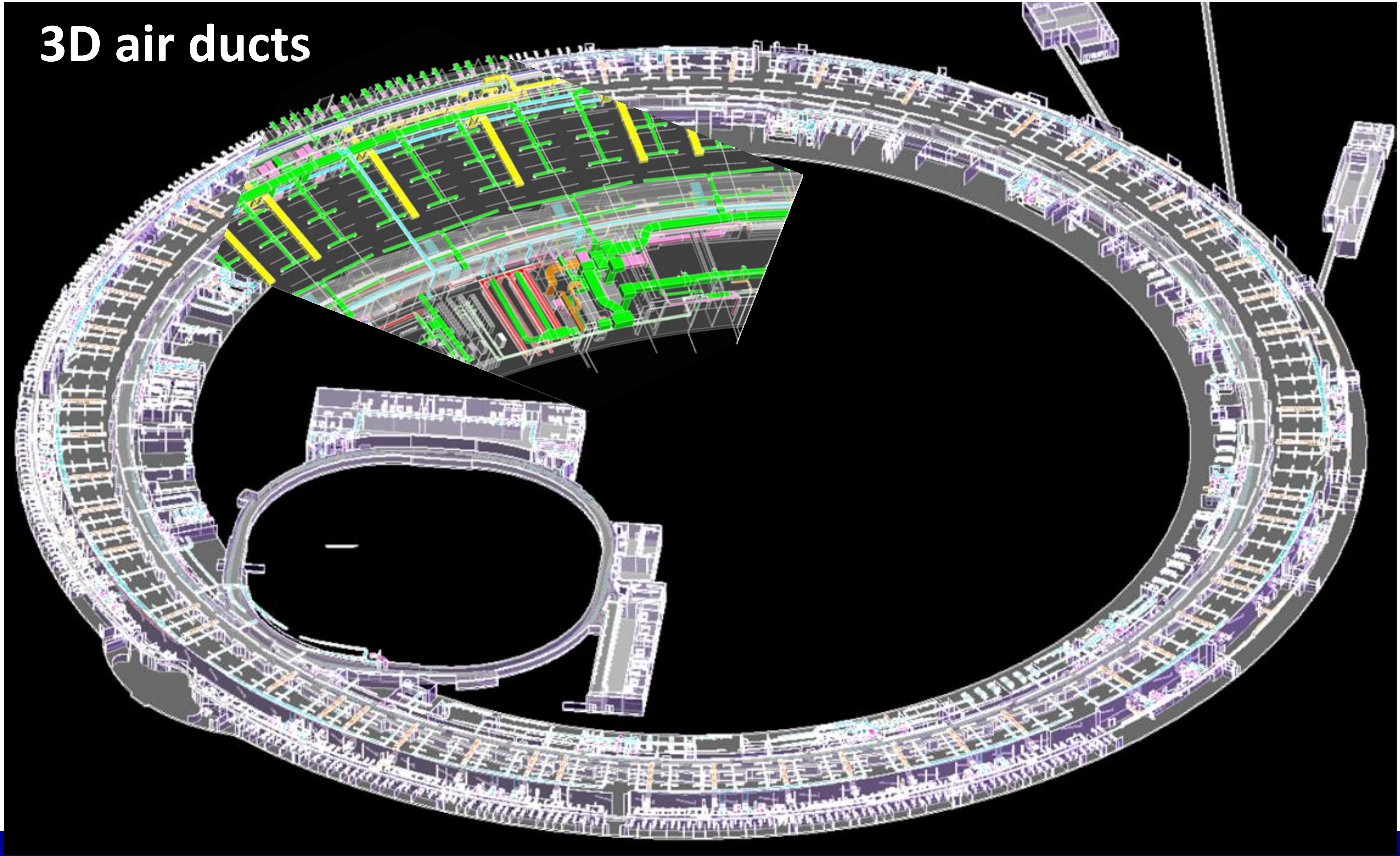
# HVAC

- Layout of HVAC
  - 16 air handling rooms around user bldg. for experiment hall air conditioning.
  - 12 air handling rooms around ring service bldg for ring tunnel air conditioning.
  - 1 air handling room in Linac
  - 2 air handling rooms in booster service bldg.

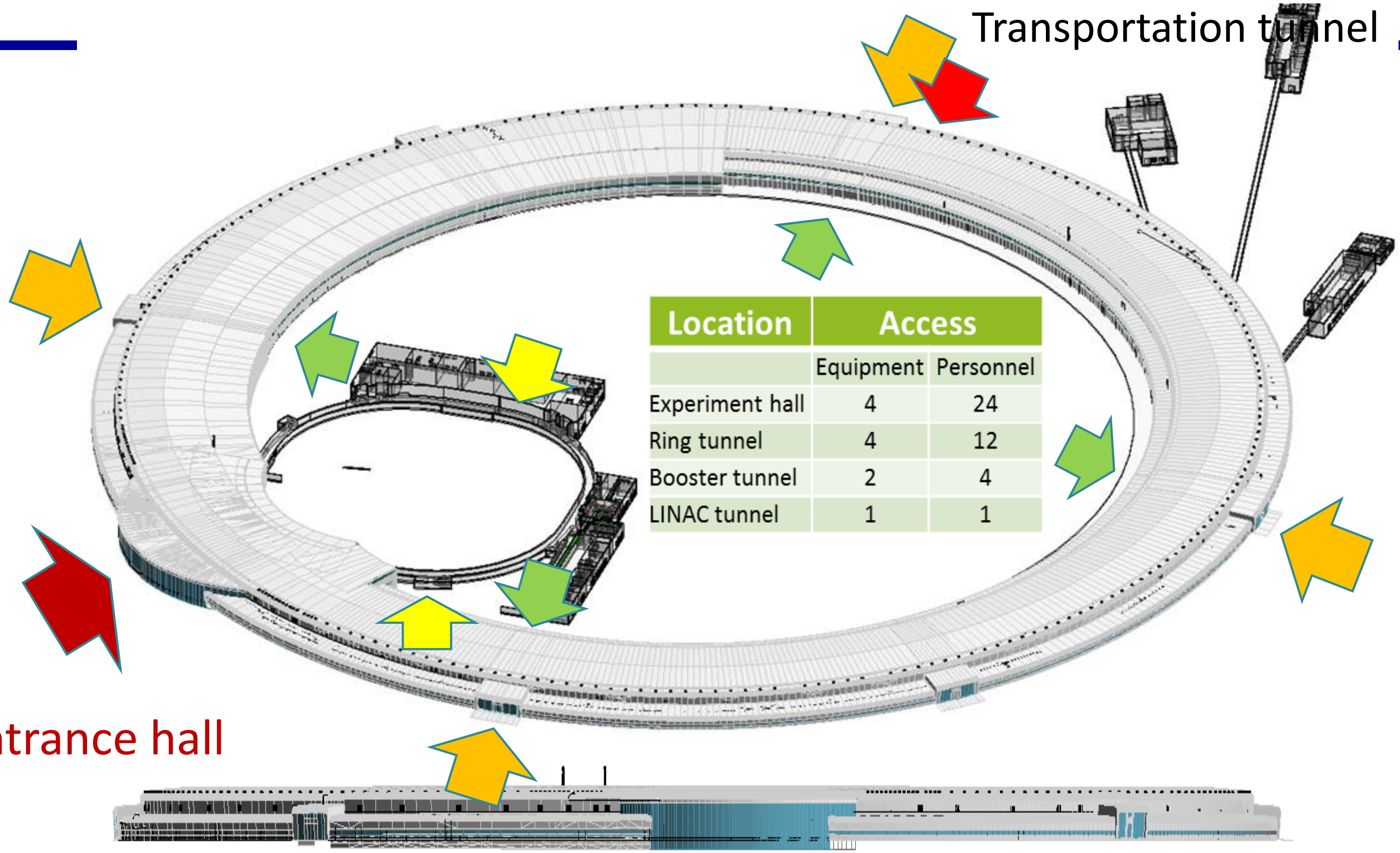


- Air pressure and air renewal
  - The ring tunnel must be kept at a slight under-pressure to prevent possibility of air contamination by air exhaust.
  - The air pressure of experience hall should be kept slightly higher than atmospheric pressure to keep dust away from the area by continuously introducing a certain amount of outside air.
  - Offices, conference rooms and other occupied areas will be provided with a minimum of 30m$^3$ /hr. persons.

# HVAC



# Equipment access and crane




| Location | Access | |
|---|---|---|
| | Equipment | Personnel |
| Experiment hall | 4 | 24 |
| Ring tunnel | 4 | 12 |
| Booster tunnel | 2 | 4 |
| LINAC tunnel | 1 | 1 |

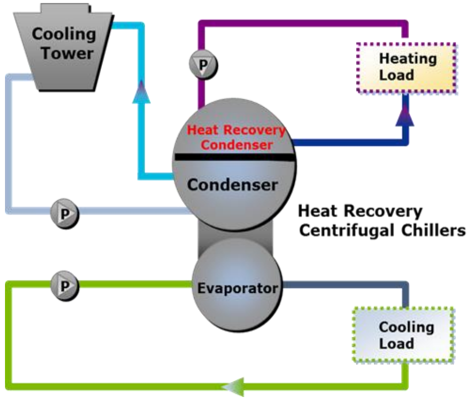
| Location | Crane |
|---|---|
| Experiment hall equipment access corridor | 5T |
| Ring tunnel equipment access corridor | 20T |
| Ring rf power source hall | 10T |
| Booster rf power source hall | 5T |
| Cryogenics hall | 20T |

**Front ends equipment access**

- Monorail crane overhead along beamline
- No doors on ratchet wall

# Energy conservation program

- Main measures:
  - Building energy conservation design
  - Waste heat recovery
  - Free cooling in winter
  - Use green energy
  - Reduce consumption
  - Increase efficiencies
  - Smarter energy management
- Heat recovery
  - Using waste heat of HEPS cooling water for heat source of the campus by heat recovery chillers
- Free cooling in winter
  - HVAC chilled water from heat exchange cooled by cooling tower water
- Green energy
  - Solar PV array on the roof of ring building
    - Reserved the load of roof structure for installing solar system
    - Electric company will Invests cost of solar energy system
- Building energy conservation design
  - Building envelope thermal insulation performance:
    - $K \leq 0.45 W/m^2.K$
    - Air tightness.
  - Efficient mechanical and electrical equipment

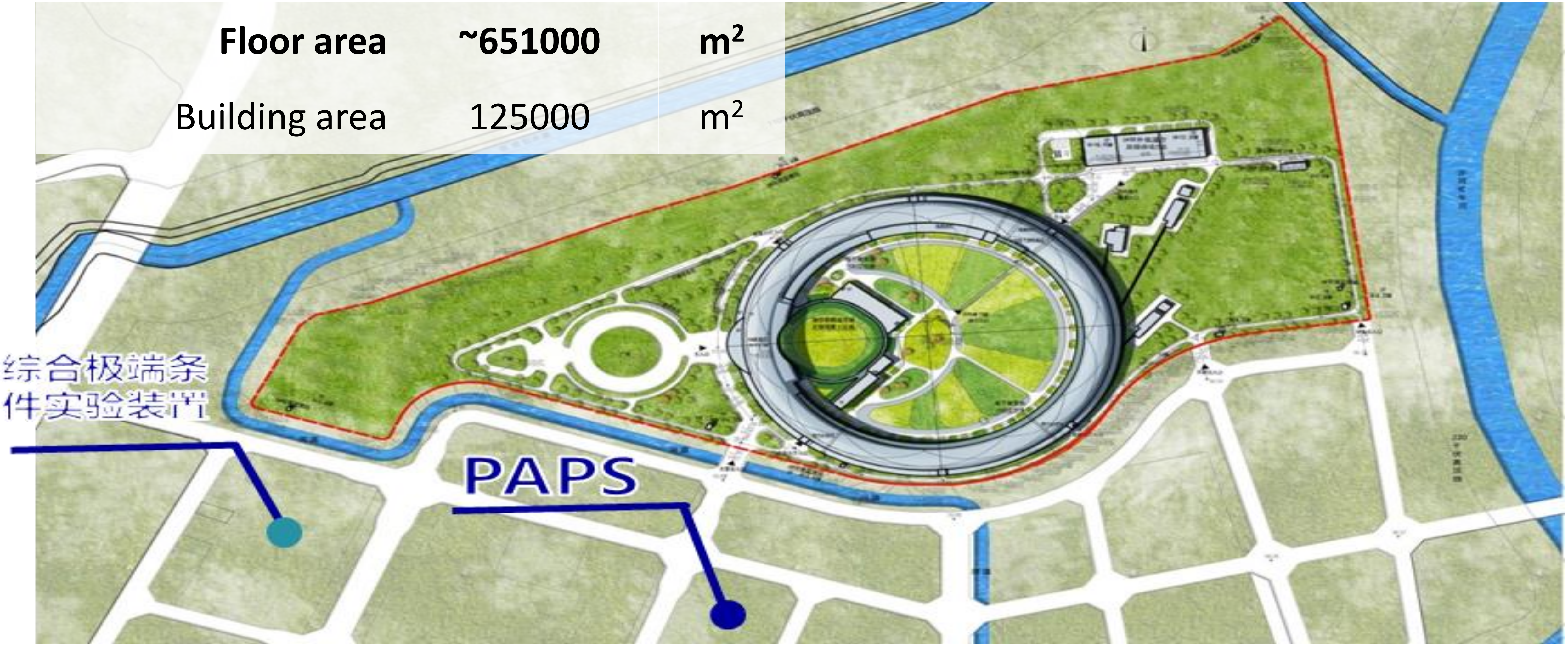



Energy conservation assessment was approved

# CIVIL CONSTRUCTION

# CIVIL CONSTRUCTION

| | | |
|---|---|---|
| **Floor area** | **~651000** | **$m^2$** |
| Building area | 125000 | $m^2$ |



# AERIAL PHOTO


# Construction progress

Up to Sep. 2020

- 80% of the total earthwork in the park area had been completed (about 210,000 cubic meters);
- Roof-topping works for the utility building and the Booster RF hall had been compeleted;
- Outdoor works had been under constructure;

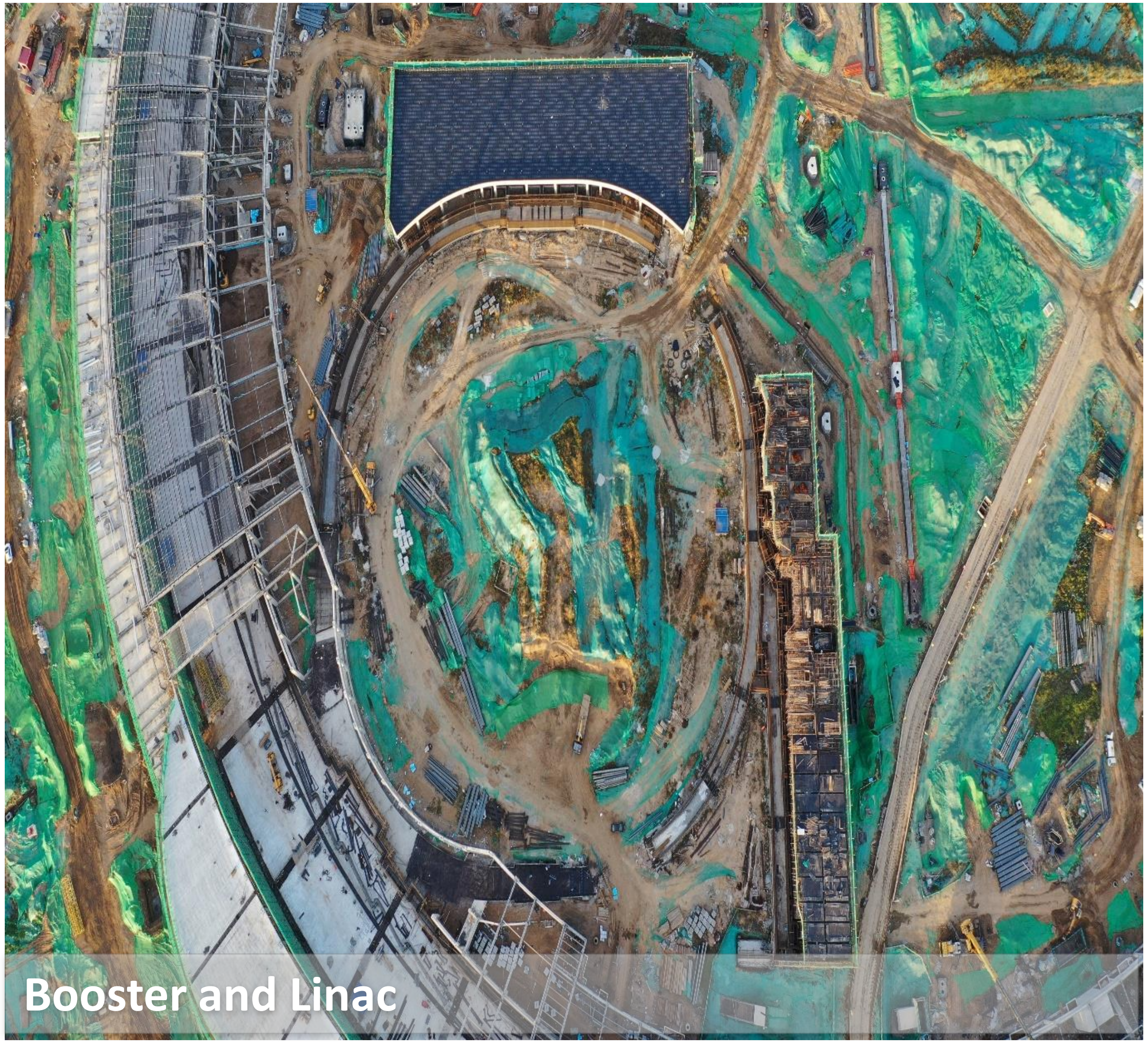
# Construction progress

Storage ring tunnel and Experiment Hall

Storage ring  tunnel

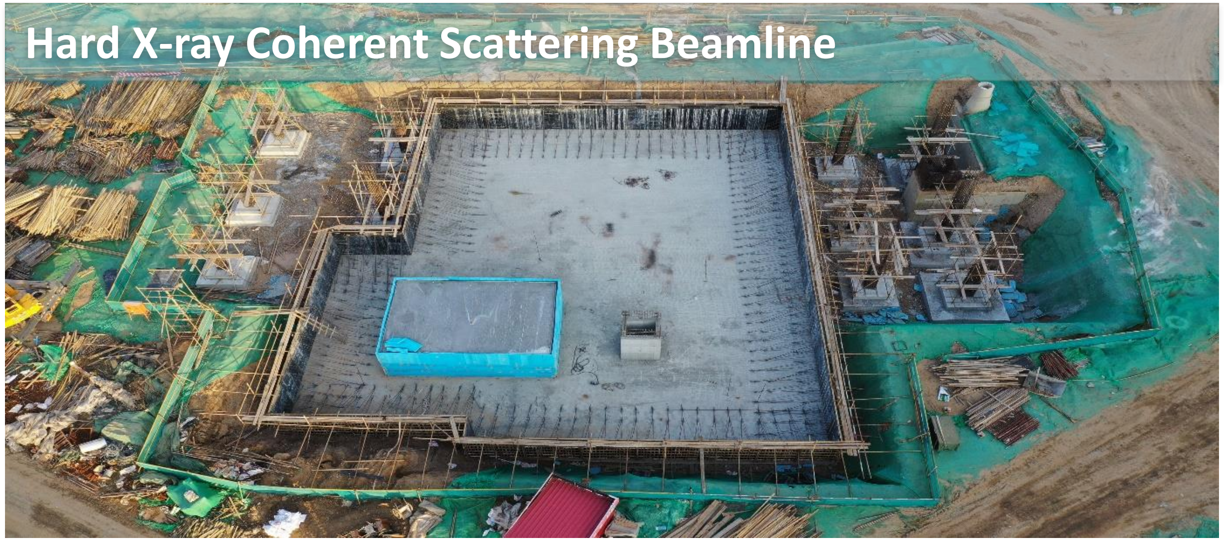
Large-span Foundation replacement (more than 30m)

# Construction progress





# Construction progress


# Risk and mitigation

- A Risk is an uncertain event or condition that, if it occurs, has an effect on at least one project objective, or the effect of uncertainty on the achievement of objectives.
- Sources of project cost and schedule risk:
  - **Estimate Uncertainty (EU)**
    - For activities in the baseline scope
    - Depend on the activity definition maturity
  - **Identified Risk Events**
    - Known events that may or may not happen
    - Not included in baseline scope activities
  - **Unidentified Risk Events**
    - Unknown events that may or may not happen (“unknown unknowns”)
    - Not captured in the AUP Risk Register
- We are trying to introduce the Risk Analysis Method in HEPS project
  - **Very preliminary now!**

# Risks and Risk Mitigation(R&D)

## Accelerator

| Risk Description | Risk Response |
| --- | --- |
| Magnet strength, field quality | Magnet prototypes |
| Support structure vibration, thermal effect | Simulations, environmental mea., prototype mea. |
| Vacuum SR heating, beam impedance | Simulation, prototype testing |
| Fast kicker system/on-axis swapout injection | Prototyping, pulser testing |
| Power supply accuracy, reproducibility | Prototyping, develop current calibration capability |
| Strong HOM-damped 166MHz SRF cavity, lack of beam demonstration | 500MHz HC used as main cavities as a backup solution |

**Long-lead procurement-** for instance, vacuum chamber material, magnet material, etc.

# Risk assessment

- Very little contingency of budget (3% included in the total budget)
  - Foreign currency rate increased compared to the approval time of the project
  - Unexpected inflation, especially the cost of some important materials
- No any contingency of schedule
  - Civil construction needs more time than expected
  - Some advanced hardware/devices maybe delayed during manufacture or import
  - COVID-19 cause 2~3 months delay
- Manpower
- Technical problems exist in all systems (work packages)
- Other unknown risks

# HEPS project Construction Video

# Thanks for your attention!