HB 2023

Status & challenges of HIAF and brief introduction of CiADS

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Outline

1. General information of the HIAF

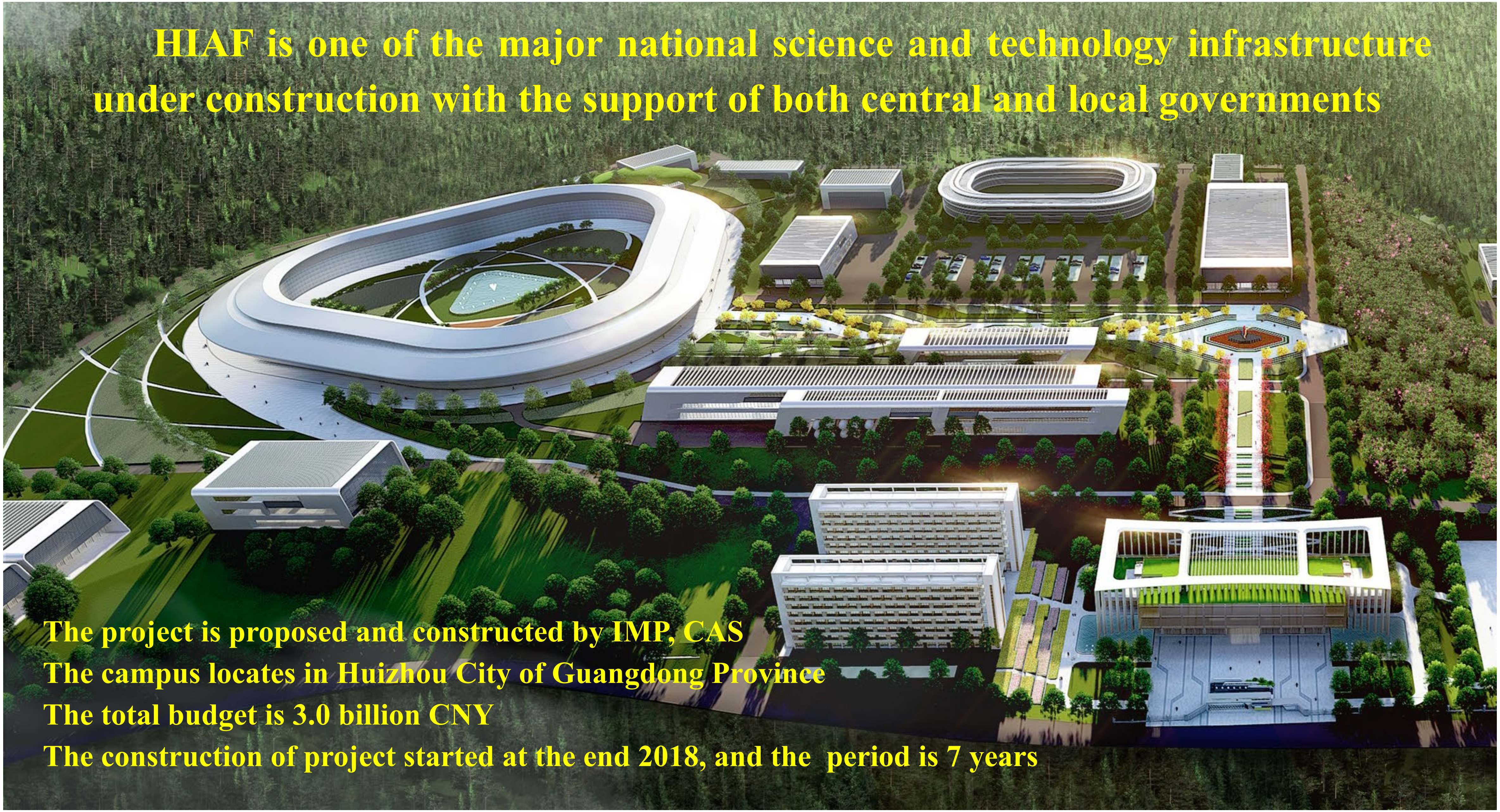
2. High intensity beam dynamics studies

3. Key technical challenges and R&D

4. Project progress and status

5. Brief introduction of the CiADS

High-Intensity Heavy Ion Accelerator Facility-HIAF

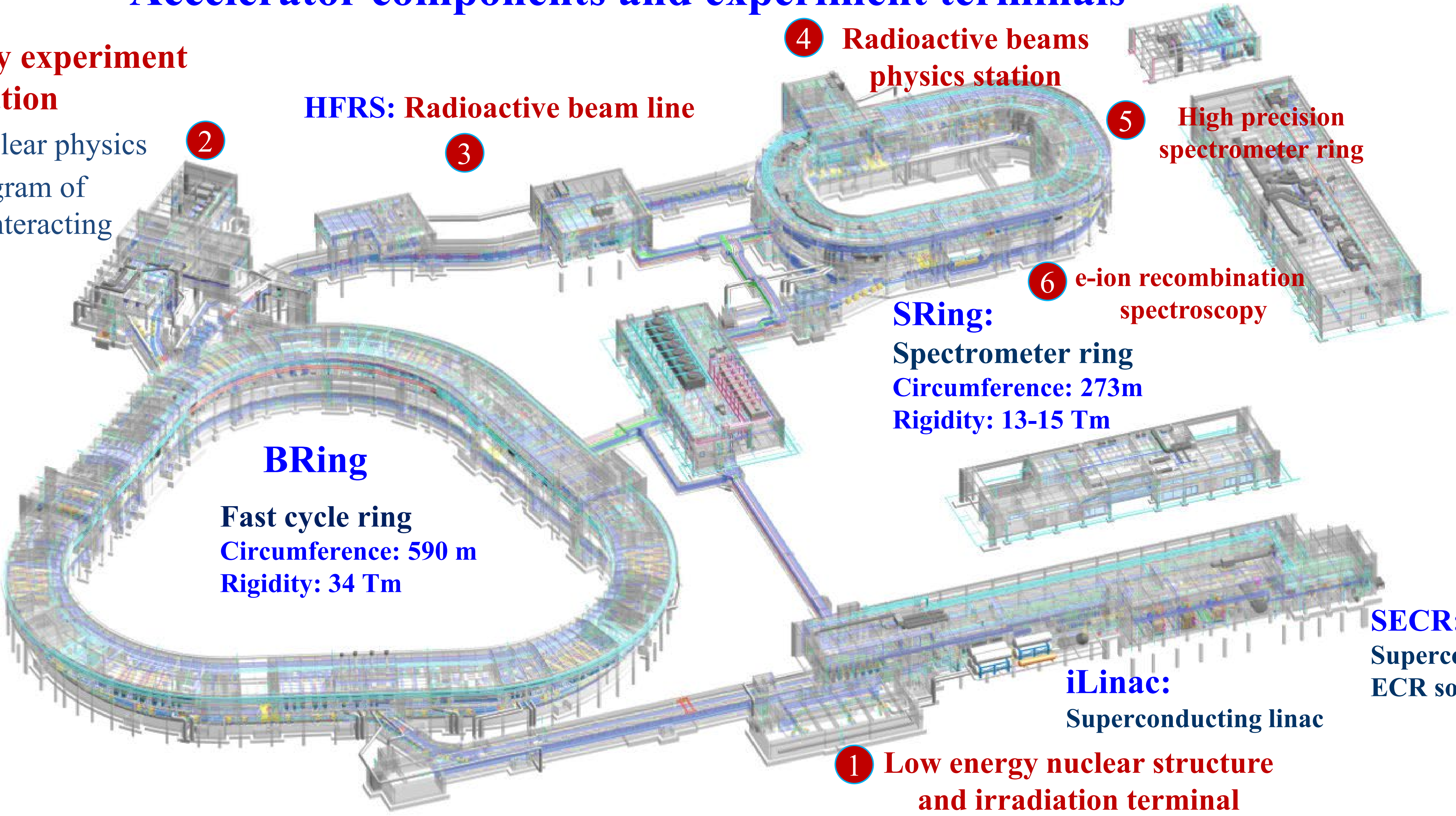


HIAF is one of the major national science and technology infrastructure under construction with the support of both central and local governments

The project is proposed and constructed by IMP, CAS
The campus locates in Huizhou City of Guangdong Province
The total budget is 3.0 billion CNY
The construction of project started at the end 2018, and the period is 7 years

High-Intensity Heavy Ion Accelerator Facility-HIAF

Accelerator components and experiment terminals



BIM (Building information model) of HIAF facility

High-Intensity Heavy Ion Accelerator Facility-HIAF

- **HIAF main parameters**

To provide very high intensity heavy ion beam

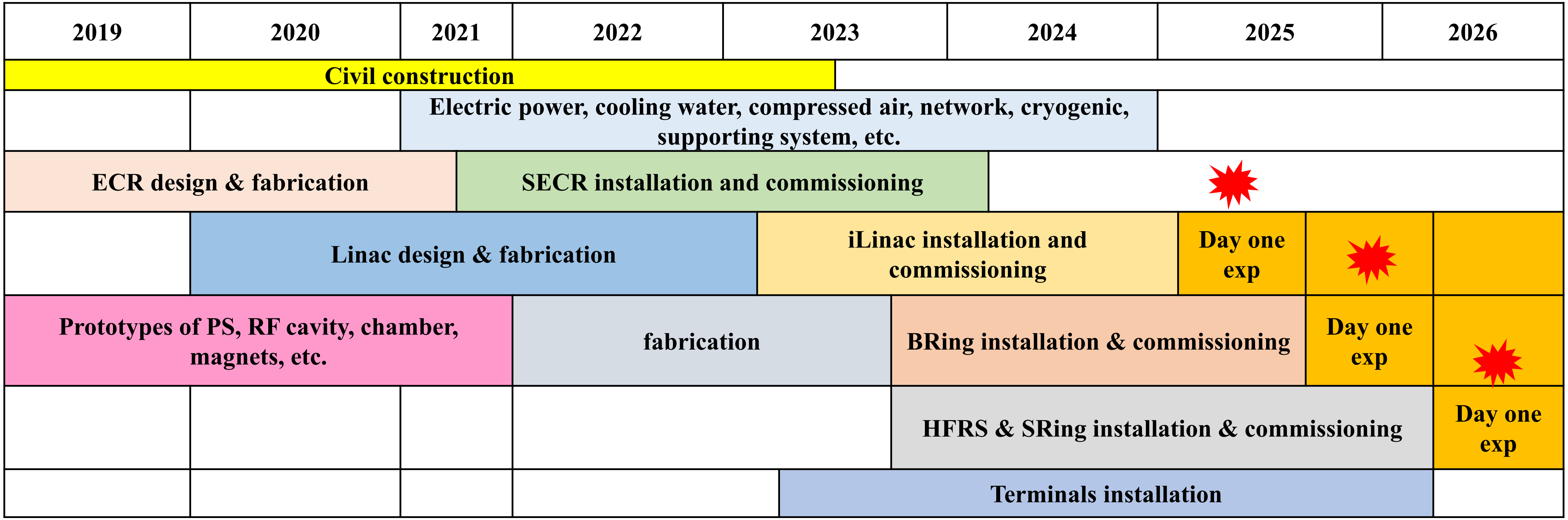
	SECR	iLinac	BRing	HFRS	SRing
Length / circumference (m)	---	114	569	192	277
Final energy of U (MeV/u)	0.014 (U^{35+})	17 (U^{35+})	835 (U^{35+})	800 (U^{92+})	800 (U^{92+})
Max. magnetic rigidity (Tm)	---	---	34	25	15
Max. beam intensity of U	50 pμA (U^{35+})	28 pμA (U^{35+})	2×10^{11}ppp (U^{35+}) 6×10^{11}pps (U^{35+})	-------	(0.5-1) $\times10^{12}$ppp (U^{92+})
Operation mode	DC	CW or pulse	fast ramping (12T/s, 3Hz)	Momentum-resolution 1100	DC, deceleration
Emittance or Acceptance (H/V, π·mm·mrad, dp/p)		5 / 5	200/100, 0.5%	±30mrad(H)/±15 mrad(V), ±2%	40/40, 1.5% (normal mode)

HIAF: for advances in nuclear physics and related research fields

- **Questions of nuclear physics:**
  - To explore the limit of nucleus existence
  - To study exotic nuclear structure
  - Understand the origin of the elements
- **High charge state ions for a series of atomic physics programs.**
- **Slow extraction beam with wide energy range for applied science**
- **High energy and intensity ultra-short bunched ion beams for high energy and density matter research**

High-Intensity Heavy Ion Accelerator Facility-HIAF

■ HIAF construction time schedule

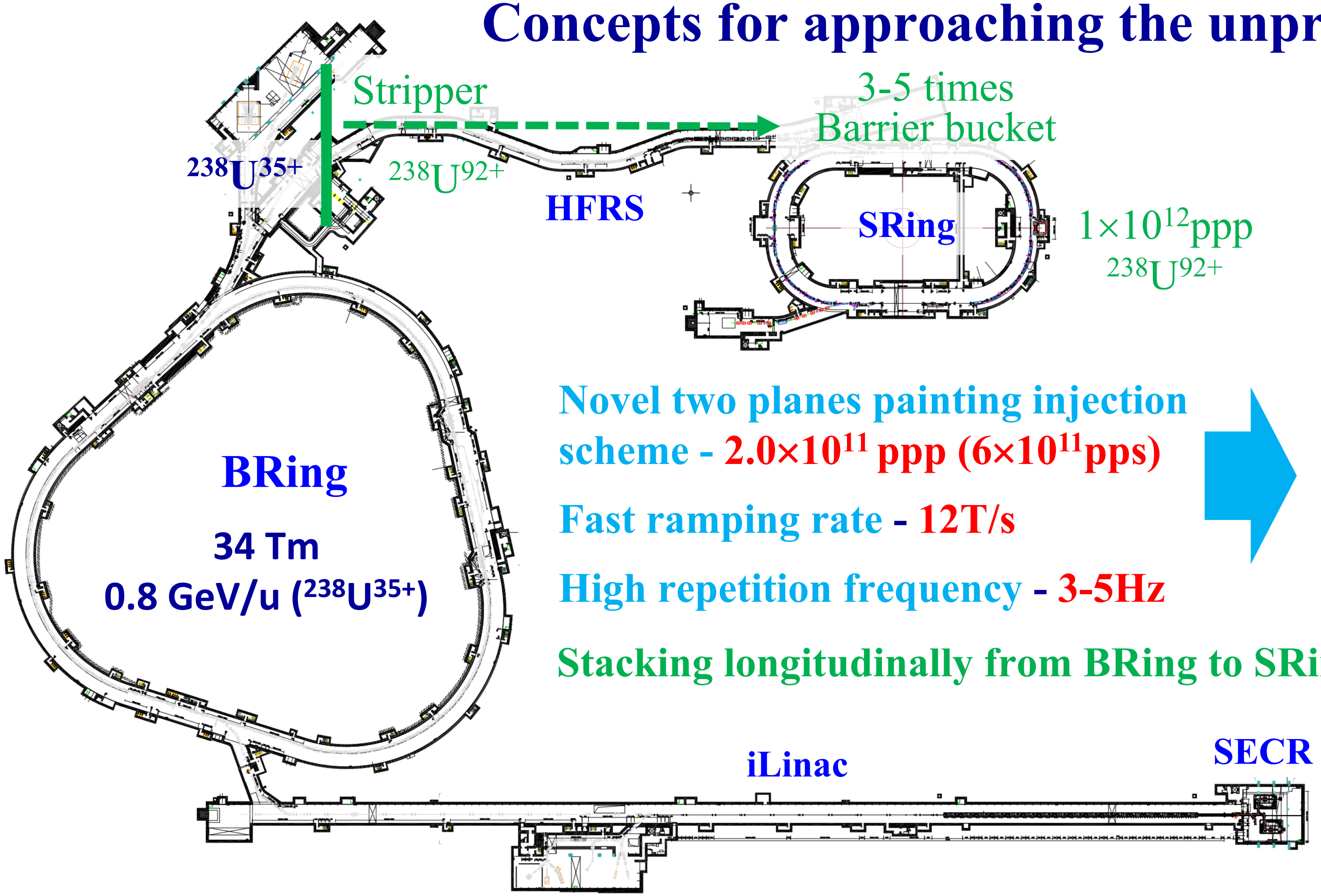


- The ion source **SECR** will provide first beam early next year
- The low energy CW ion beam of **iLinac** is expected at the end of 2024
- The high energy pulse ion beam from **BRing** is in September of 2025
- The Day One Experiment in **SRing** will be in April of 2026

High intensity beam dynamics studies

High intensity beam dynamics studies

Concepts for approaching the unprecedented heavy ion intensity

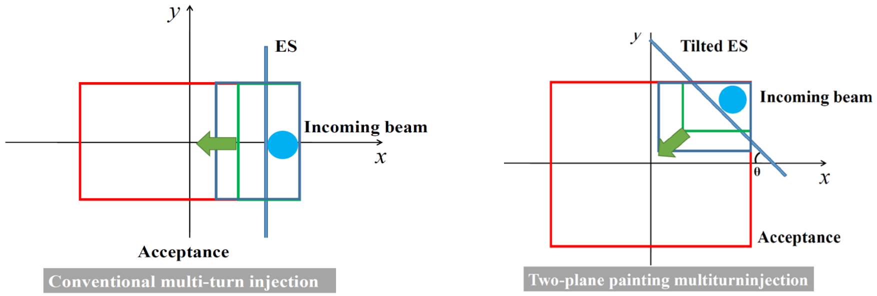


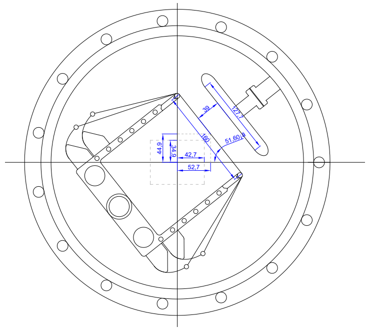
Novel two planes painting injection scheme - 2.0×10^{11} ppp (6×10^{11}pps)

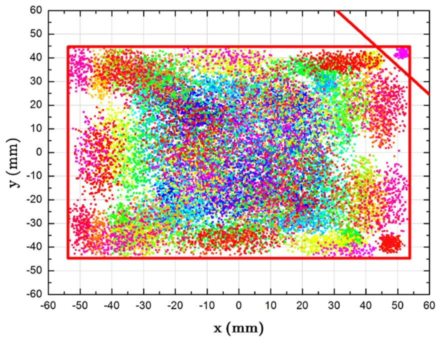
Fast ramping rate - 12T/s

High repetition frequency - 3-5Hz

Stacking longitudinally from BRing to SRing







Ions	Plane	Injection Turns	Single injection
$^{238}U^{35+}$	H	33	3.3×10^{10}
	V	16	1.6×10^{10}
	H+V	**150**	**2.0×10^{11}**

High current superconducting linac

- Pulsed 28 pμA U^{35+}, U^{4x+}
- CW 15 pμA U^{35+}
- 17 MeV/u

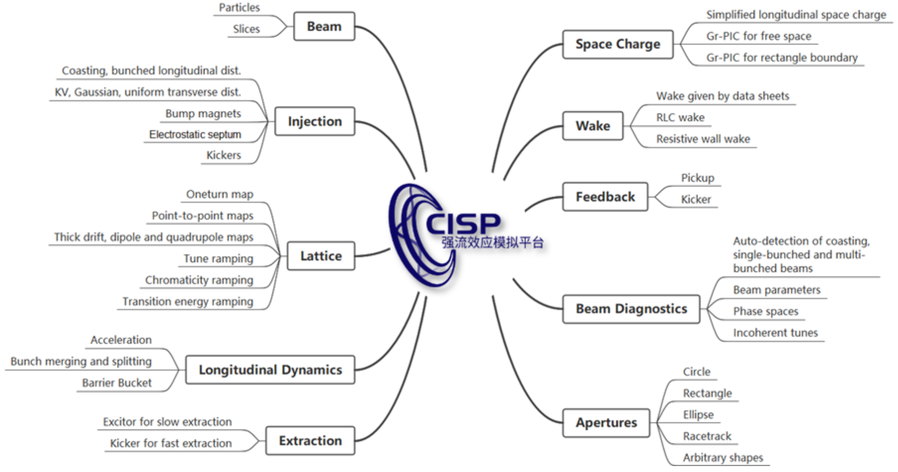
45 GHz superconducting ECR

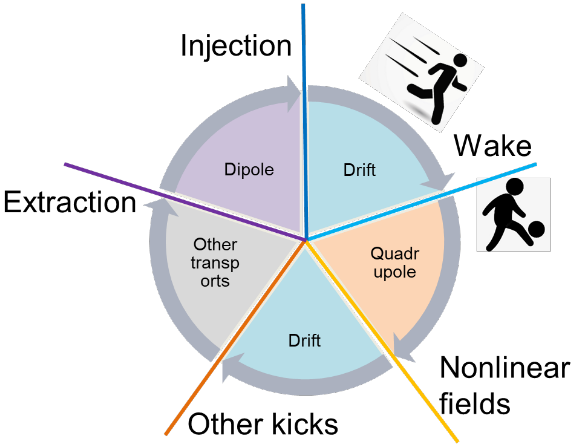
- Pulsed 50 pμA U^{35+}, U^{4x+}
- CW 20 pμA U^{35+}
- 14 KeV/u

2.0 ×10^{11} with two planes painting, **nearly 10 times over the conventional single-plane injection.**

Development of simulation code CISP-GPU

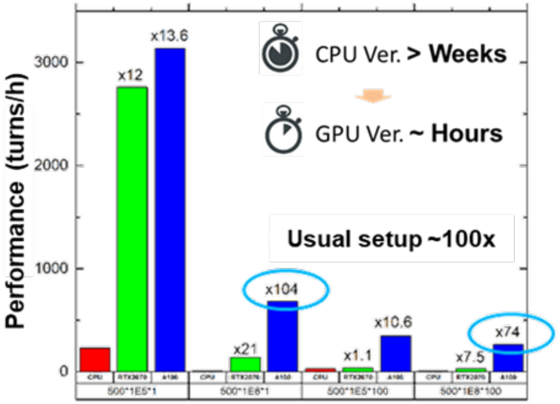
A simulation code **CISP (Simulation Platform for Collective Instabilities) and its GPU version** are developed to perform **1:1 end-to-end multi-dynamics coupling simulations** in high intensity ion accelerators

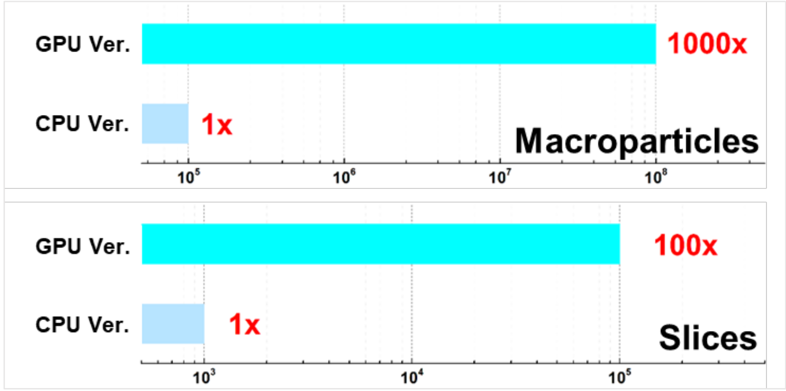


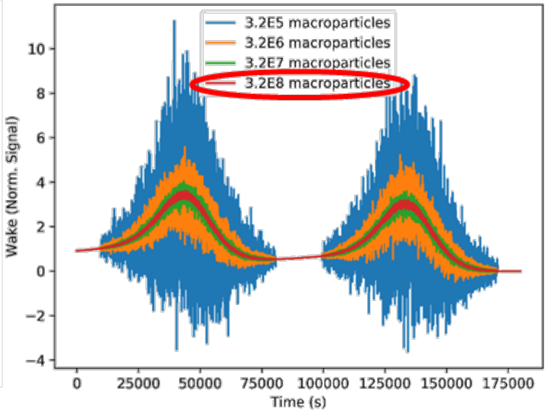


- **All important beam dynamics in high intensity ion accelerators** are implemented in the CISP
- Employ transport-kick model to **include all these beam dynamics in a single simulation to get closer to the actual accelerators**

GPU-accelerated parallel computing of all beam dynamics: **Higher performance → Much higher accuracy**





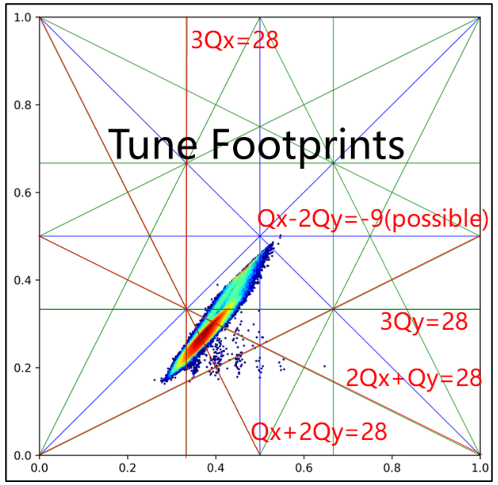


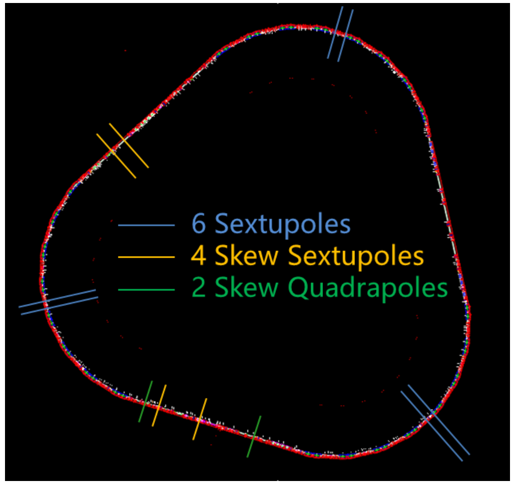
- ~ 10^8 macroparticles and 10^5 beam slices
- study **the interaction between ultra-short wakes and ultra-long bunches**, and many **other multi-dynamics coupling effects**

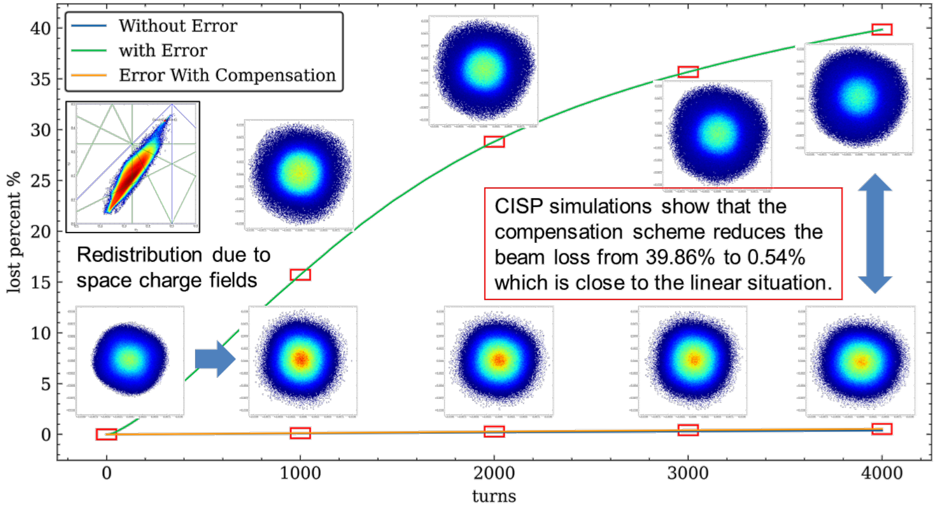
Nonlinearity and Space Charge

Key issues

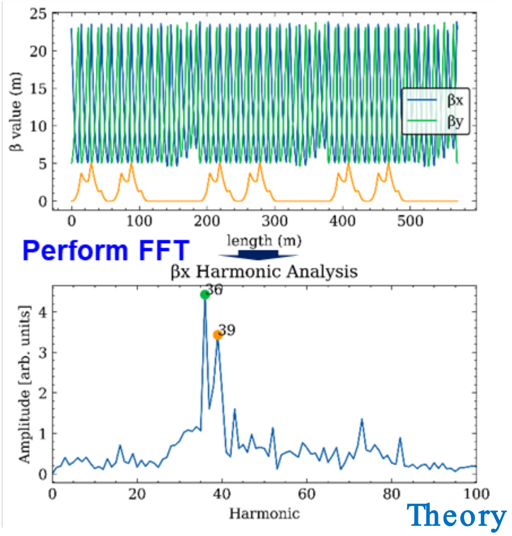
- Large magnet apertures and large beam sizes → **Strong nonlinear magnetic errors**
- Low and medium energy ion beams in all beam manipulations → **Strong space charge effects**

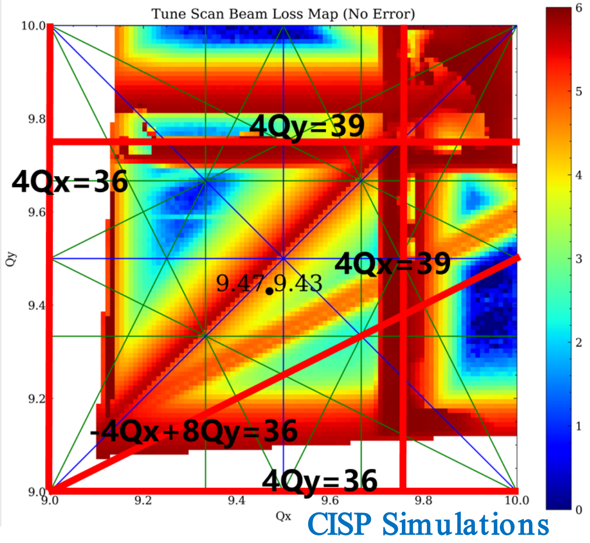






- **All 3rd order resonances** driven by field errors with space charge could be **compensated by correctors!**

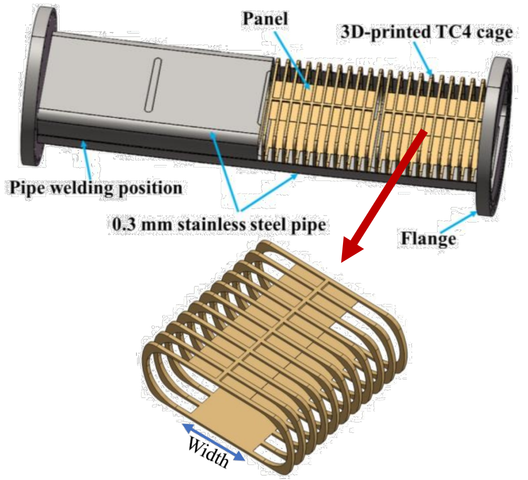


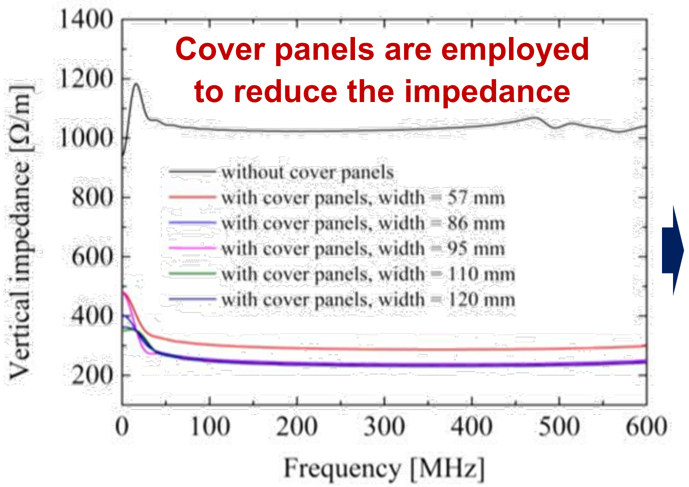


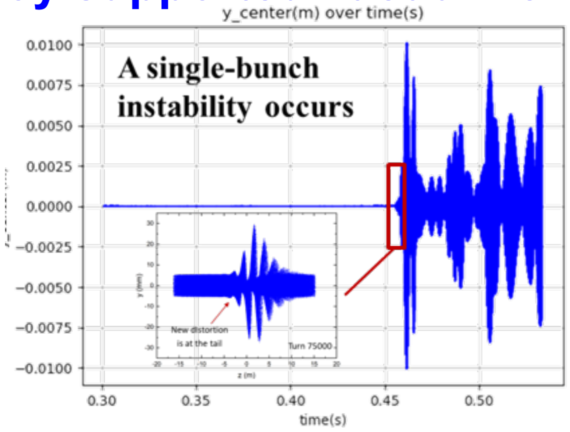
- **Structural resonances mQ_x+nQ_y = 36 or 39** could be driven by space charge fields in the HIAF given by the theory, which is completely verified by the CISP-GPU simulations.
- Work point **stay away from the red area;** correction scheme **is under investigation**

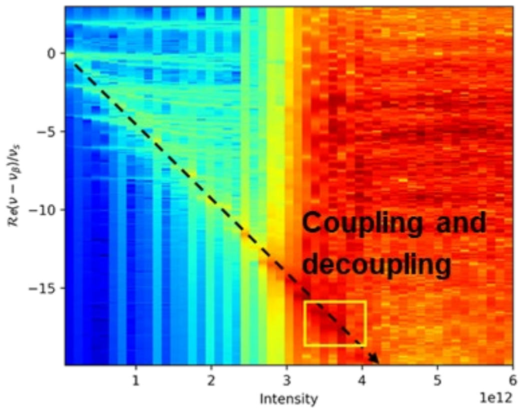
Collective Instabilities

- With CISP-GPU simulations, **it is the first time to study collective instability stimulated by the extra broadband impedances from 3D-printed titanium alloy supported vacuum chamber in the BRing**





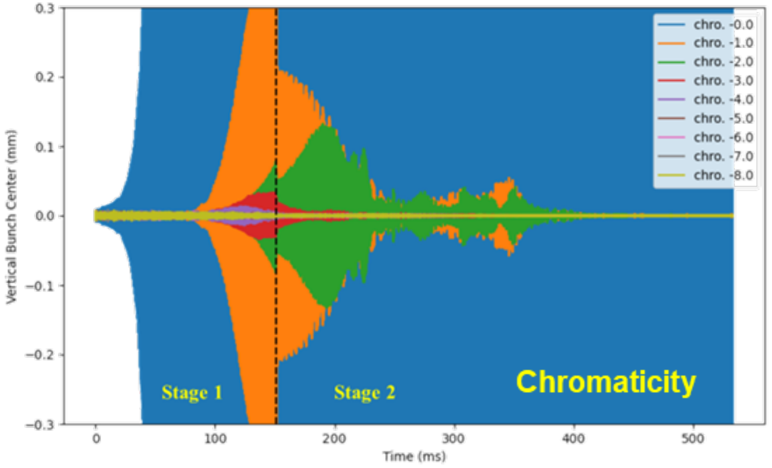


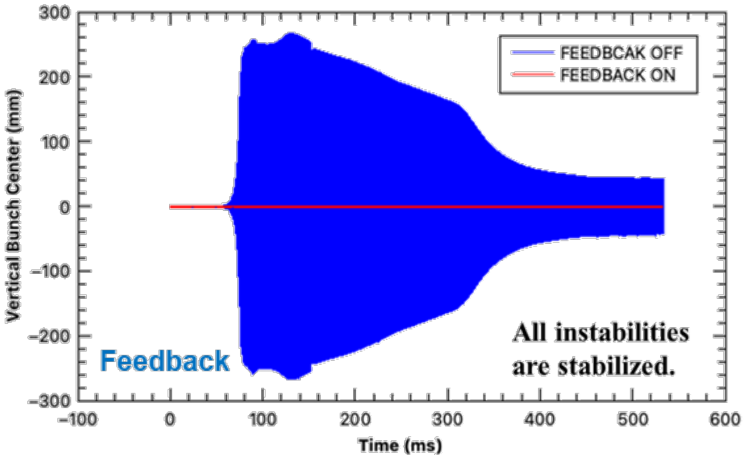


In the proton beams, high order transverse mode coupling instability is stimulated as the bunch σ_z is about 5 m while the peak of wake is at 0.1 m.

- Instability stimulated by the broadband impedances from rings is stabilized by:

1. **Chromaticity** of a relatively large value ~ -5
2. **Wideband feedback system** with a band-width > 500 MHz





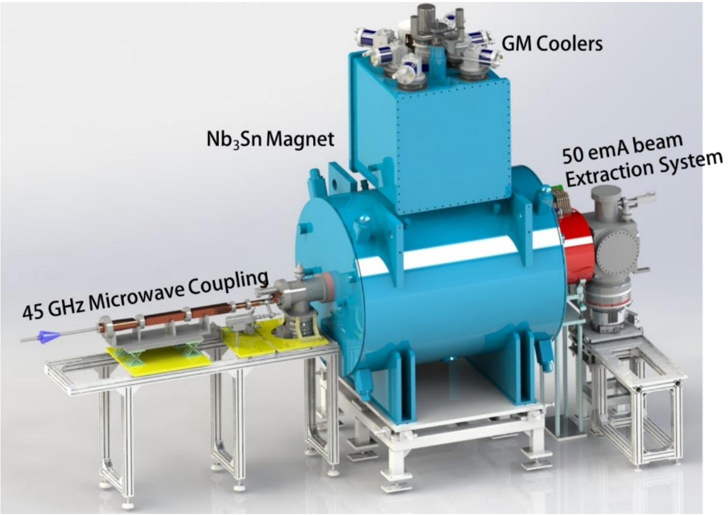
"Development and Application of High-Performance CISP-GPU Code for High Intensity Effects in HIAF by Jie Liu

Key technical challenges and R&D

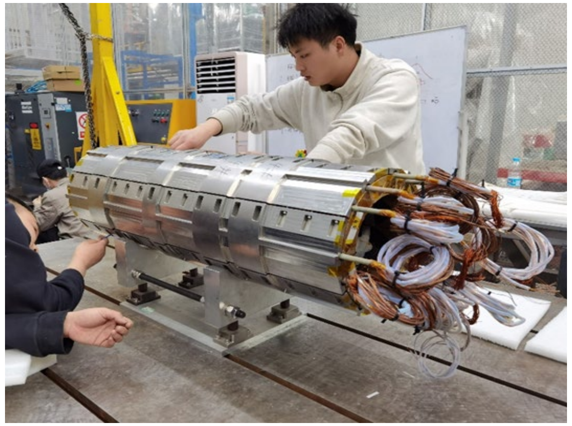
45 GHz superconducting ECR ion source

The first 45GHz superconducting ECR in the world: 50 pμA (U^{35+})

- The critical one is to fabricate a fully Nb_3Sn superconducting magnet



Sextupole Coils

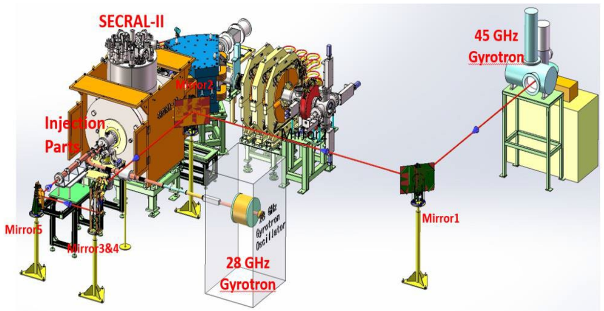


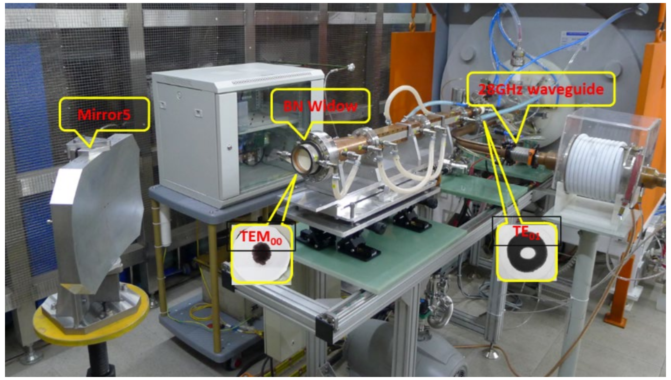
Coils integration

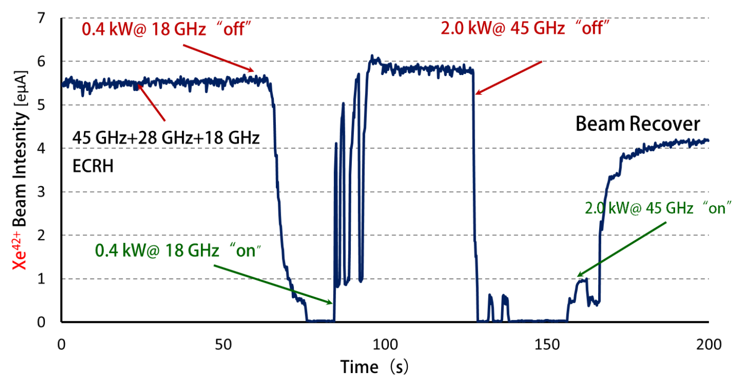
Full-sized cold mass

Most technical challenges have been verified, system integration is under progress

- 45 GHz microwave coupling



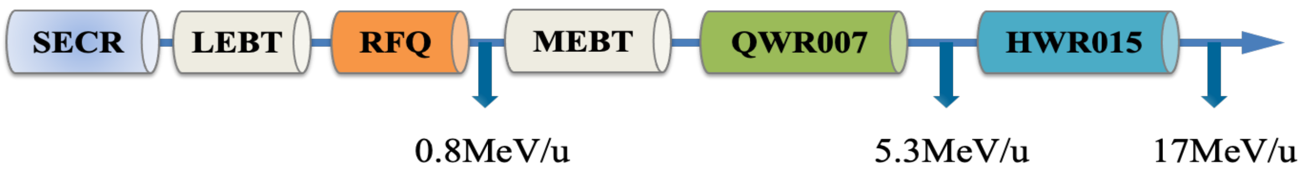




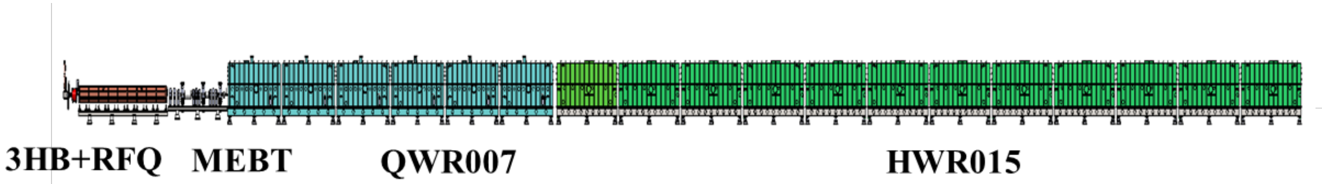
45GHz/20kW microware transmission system based on the quasi-optical design, ECR plasma with 45GHz microwave has been tested with exiting SECRAL2 ion source. The first beam at 45 GHz is expected in 2024

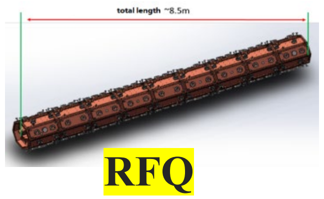
High current superconducting ion linac - iLinac

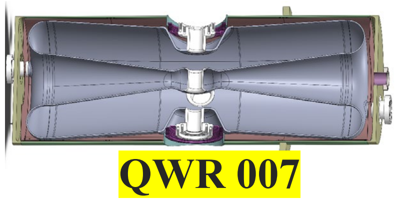
➢ iLinac

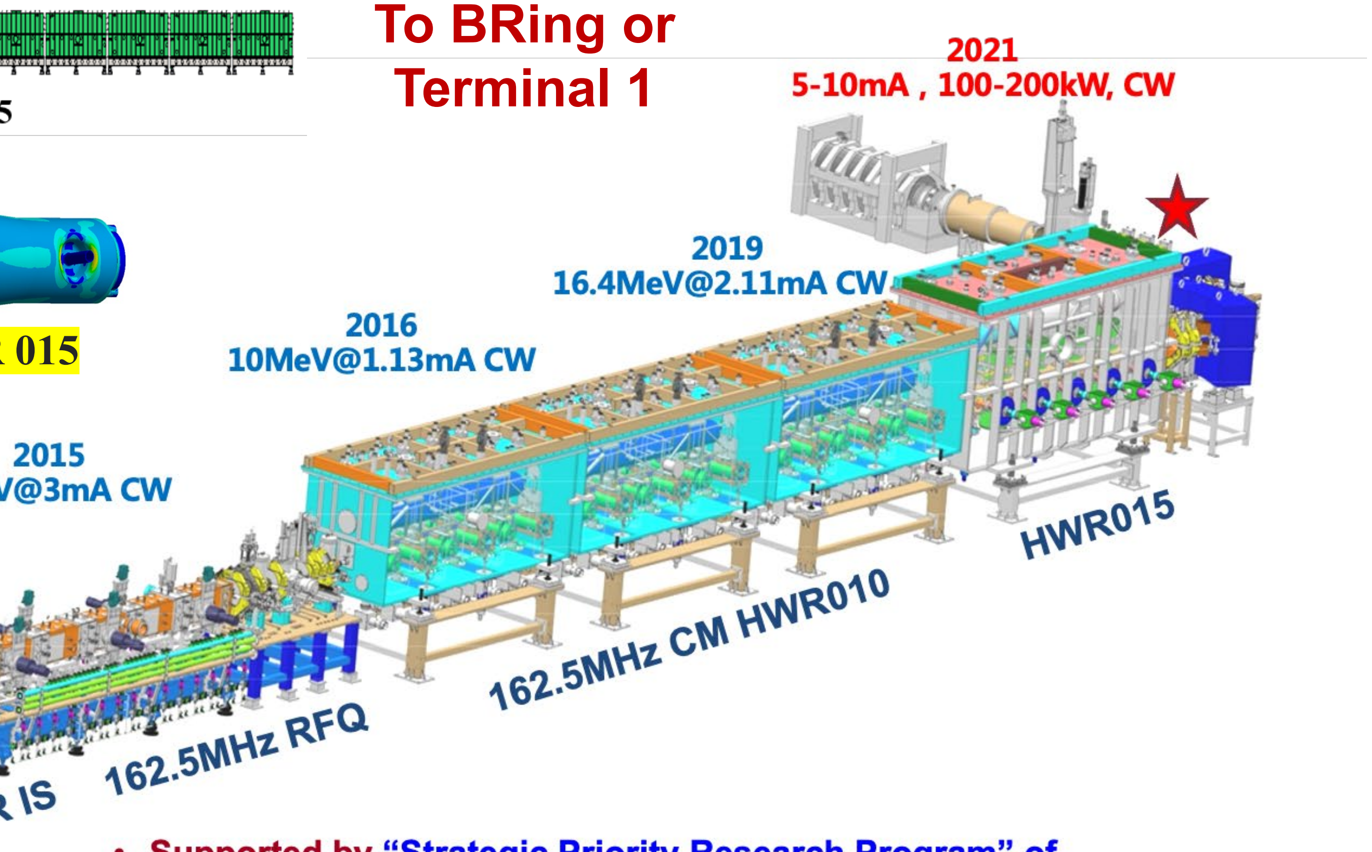


- Pulsed, 28 pμA U^{35+}
- CW, 15 pμA U^{35+}









- In order to demonstrate the SRF technologies, a 25MeV SC linac has been built
- Several types of SC cavities have been developed
- The CW beam power reached 200kW in 2021

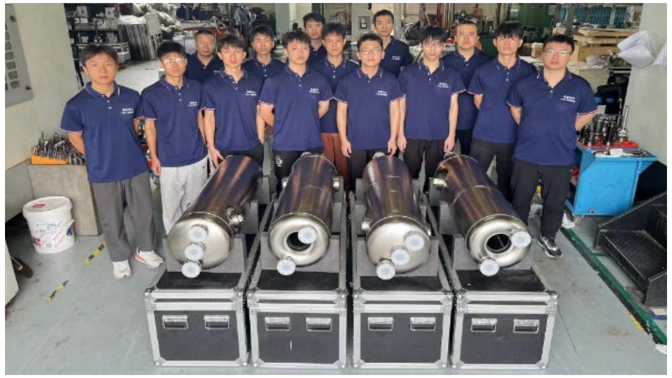
- Supported by "Strategic Priority Research Program" of the Chinese Academy of Sciences.

High current superconducting ion linac

■ RFQ and SRF cavities fabrication

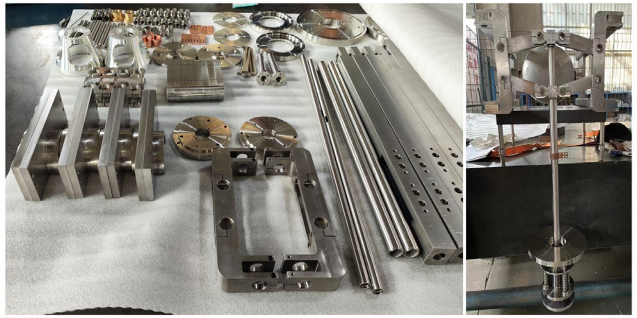
RFQ cavity

HWR015 type cavity



QWR007 type cavity

SFR cavity coupler



SFR cavity tuner

superconducting solenoid

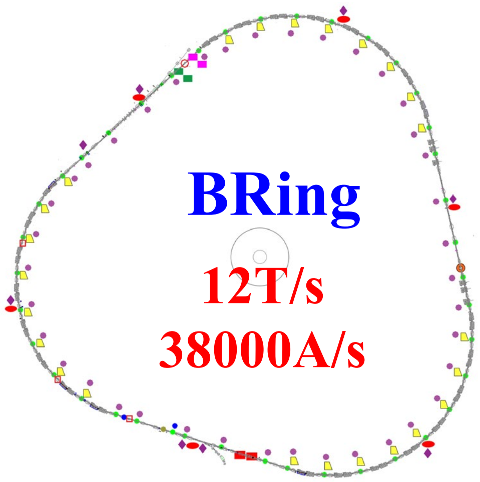
solid state amplifiers

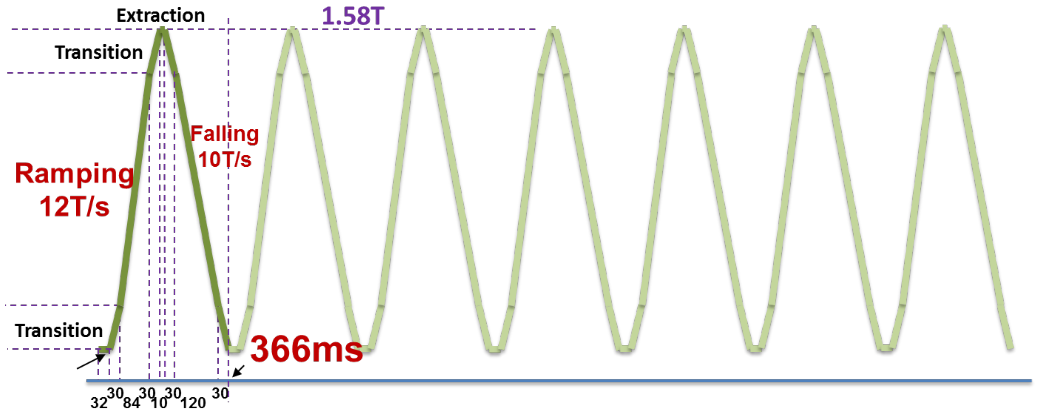
Fast cycle booster synchrotron BRing

➢ **Fast ramping rate mode**

Why?

Due to **space charge** and **dynamic vacuum** effect, beam should be launched to the high energy as soon as possible.





Repetition rate: 3-5 Hz, 5-10Hz

The highest ramping rate for heavy ion synchrotron, challenges for key system, such as power supply, RF and vacuum chamber

A major breakthrough through innovative technologies:

1. Fast ramping rate full energy storage power supply

2. Magnetic alloy core loaded RF system

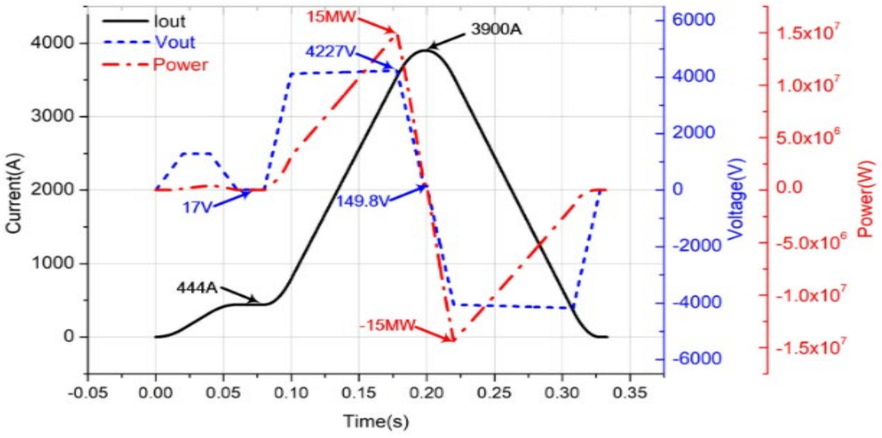
3. Ceramic-lined thin wall vacuum chamber

Fast ramping full energy storage power supply

- **Load specification and performance requirement of magnet power converters featured by fast ramping rate: 12T/s, ±38000A/s, the peak power reaches ± 230MW totally at full load**

Items	
Excitation current/voltage	3900A/4300V
load inductance	116mH
Load Resistance	36.4mΩ
Current changing rate	≤±38000A/s
Flat bottom error	≤±0.2A
tracking error	≤±0.2A
Flat top error	≤±0.2A

Parameters of BRing bending magnet power supply

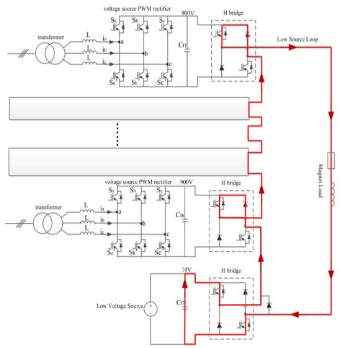


Parameters of BRing bending magnet power supply

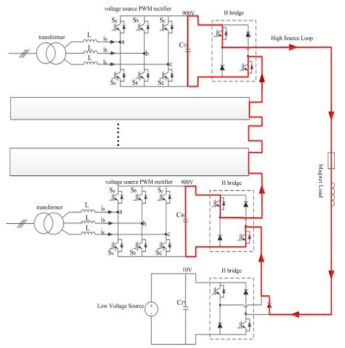
Challenges:

High tracking precision and low current ripple, especially strong un-allowable line voltage fluctuation due to very large cyclic variation of reactive power

- **A innovative power supply topology are proposed for HIAF BRing (variable forward excitation, full energy storage, PWM rectification technology)**



Energy from capacitor tank to magnet load



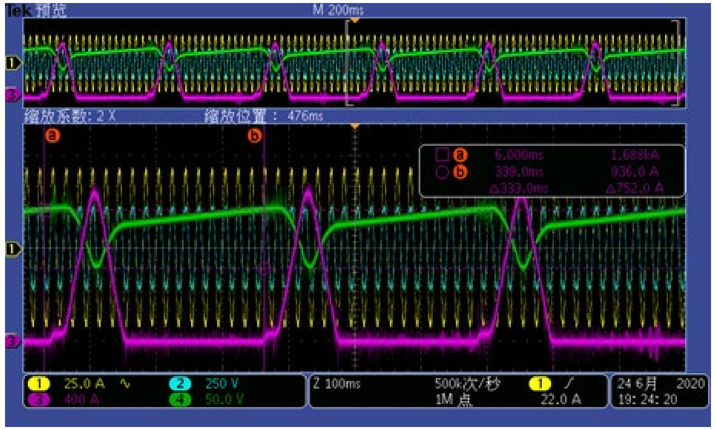
Energy from magnet load to capacitor tank

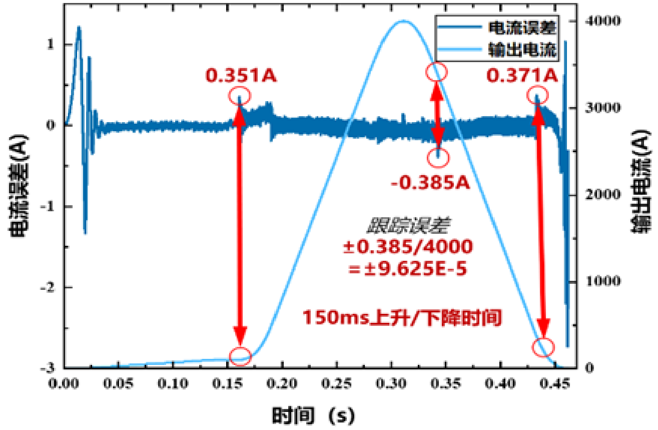
Circuit diagram of bending magnet power supply

- Energy capacitor will be used to store energy during the falling, and provide the energy for next fast ramping
- The energy can be controlled by PWM rectification technology, only active power will be taken from the grid!

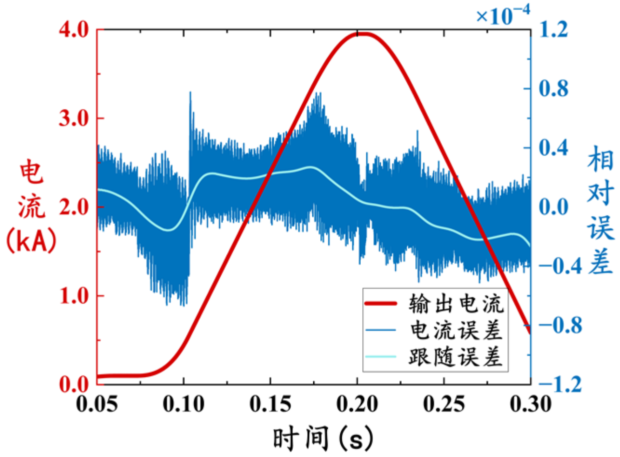
Key technical challenges and R&D

- A full size prototype has been developed, the key technology and design of the power supply have been verified





- First actual power supply of mass production, leading level performance has been achieved



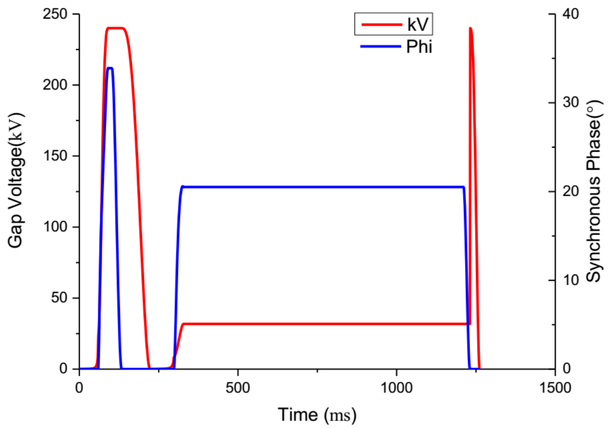
Power requirement (MVA)	Conventional	Energy storage
BRing bendng magnet	180	15
BRing quadruple magnet	50	6
Total of BRing	250	41
Total of HIAF	297	88

Test results on the real magnet loads:

Current 4000A, ramping rate > 40000A/s, tracking error< ±9.625e-5, power requirement of power convertors for bending and quadrupole magnets will reduce from 230MVA to 21MVA

Magnetic alloy core loaded RF system

- ❑ High voltage: 240kV
- ❑ Short rise time(≤10μs) for beam compression



Voltage and phase waveform of BRing RF system

MA RF system:

Compared with ferrite, MA cores have the characteristics of **high gradient, wide band, and fast response**

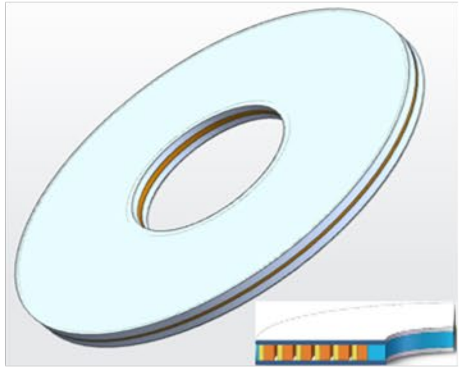
Not well established yet:

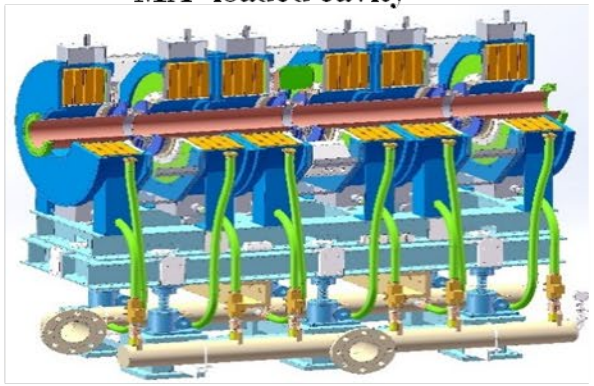
Fabrication of MA core module

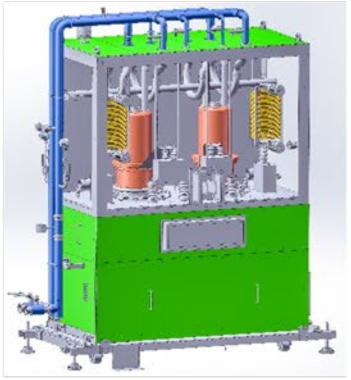
Cooling of MA-loaded cavities operating at intense power dissipation

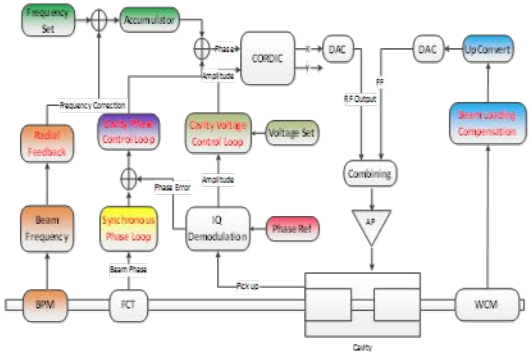
System Components

- Large size oil cooled MA core
- High gradient direct cooling MA- loaded cavity
- Broadband push-pull tetrode amplifier
- Multi harmonic digital LLRF





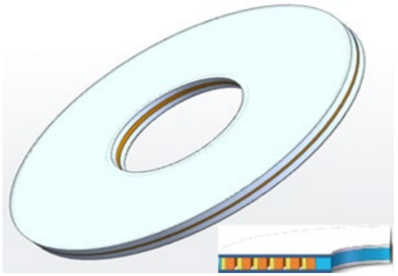




Magnetic alloy core loaded RF system

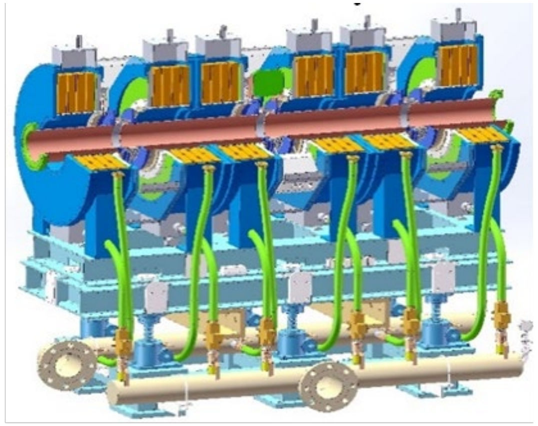
➢ Independent research and development of magnetic alloy □ MA□ core

- Over ten years exploration from small(φ90), medium (φ460), to large (φ780) MA core.
- The thickness of ribbon is getting thinner from 18 to 14um, and the performance of MA cores are getting better.
- Q value: 0.65 ~ 0.3@0.1~20MHz; μ'pQf :5.3GHz@0.3MHz, higher than Hitachi's products.



product bans

technological blockade

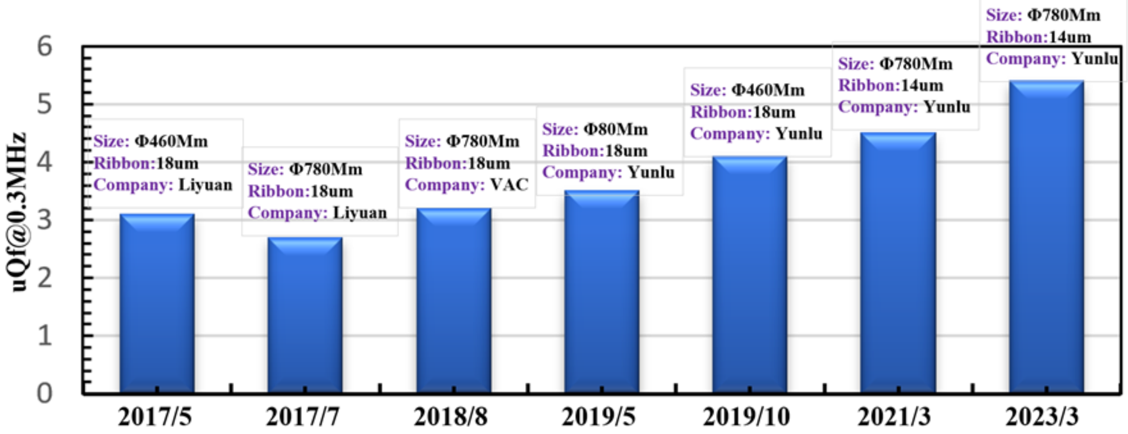


MA loaded cavity

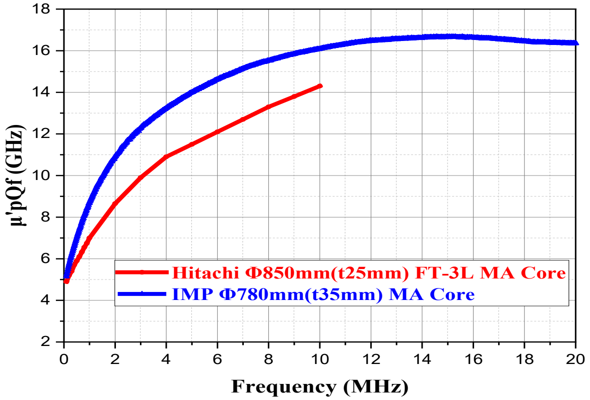
95× 65× 25mm

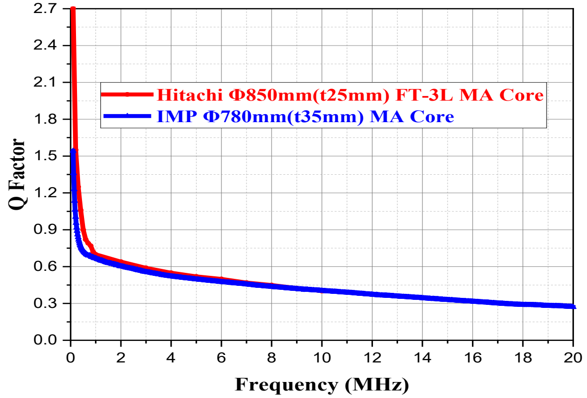
460× 230× 25mm

780× 360× 35mm



Development history of MA core

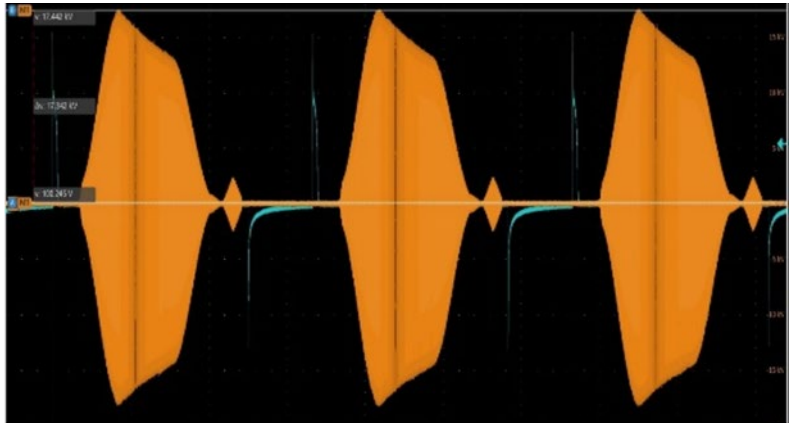




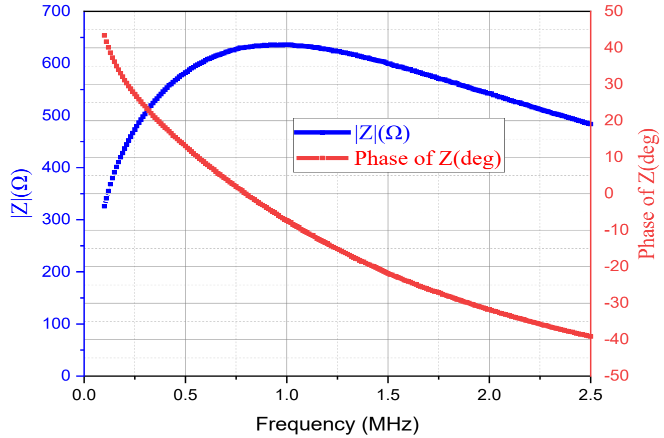
Parameters of MA core

Magnetic alloy core loaded RF system

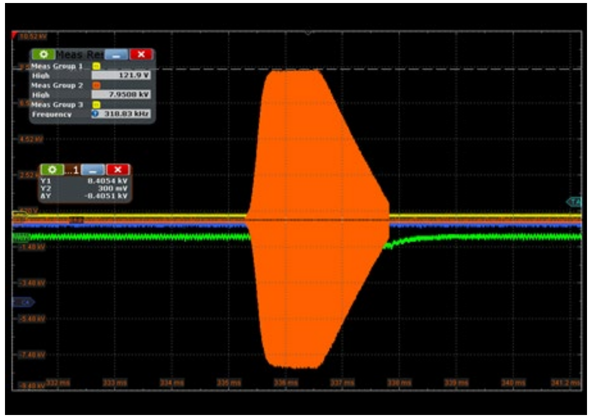
- **MA RF system with oil cooling has been constructed and power test show the good performance**
  - **The cavity RF voltage can reach 66kV@0.3~2.1MHz, with 3Hz and 70% duty cycle operating mode**



Cavity pick (3Hz operating mode)



Impedance of MA cavity



High voltage pulse (50kV/10us)

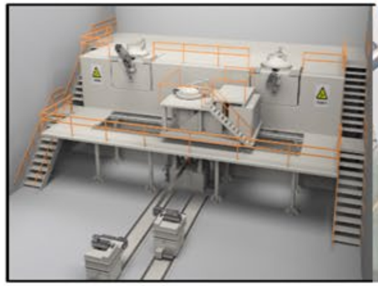
MA loaded RF system prototype

MA loaded cavity

LLRF VPX hardware

Magnetic alloy core loaded RF system

➢ The advanced MA cores automated production line in China






14um ribbon production | Ribbon shearing | 1~2μm silica coating | Constant tension winding | Water proof coating | Atmosphere annealing

➢ The manufacture of MA loaded RF systems (6 sets)

- ☐ 170 high-performance MA cores have been produced. The manufacture of amplifiers and cavities are in progress
- ☐ The online installation and debug of the MA loaded RF systems will be carried out in May 2024

Tetrode TH558

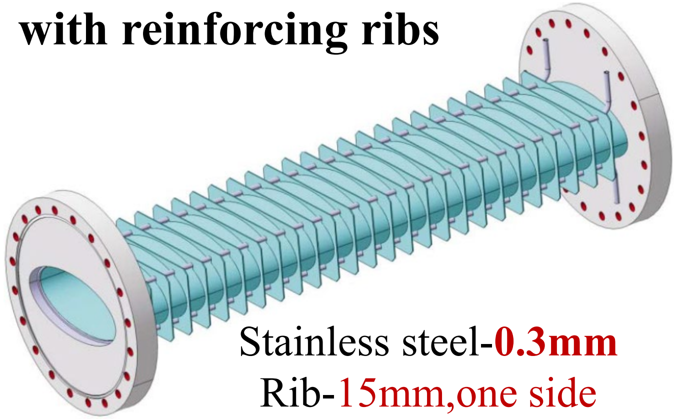
MA cores


500kW Push-pull tetrode Amplifiers

Titanium alloy lined thin-wall vacuum chamber

Due to high ramping rates, thin wall vacuum chambers are needed for all magnets to keep eddy currents at a tolerable level.

■ Thin-wall vacuum chamber with reinforcing ribs

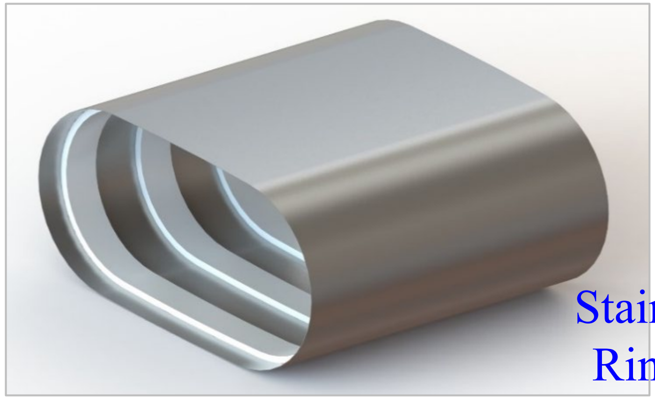


Stainless steel-**0.3mm**
Rib-15mm,one side

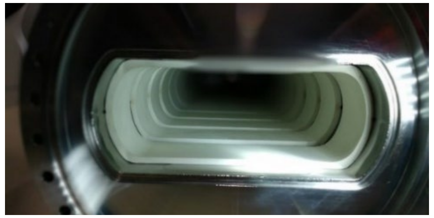
- **Complicated fabrication process**
- **Special material with high cost**
- **Low finished production rate**
- **Large gap of the magnet**

■ New scheme:

Thin-wall chamber supported by ceramic rings

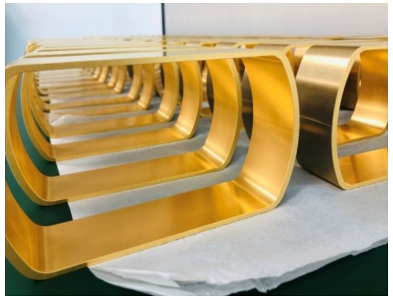


Stainless steel-**0.3mm**
Ring-4 mm,one side

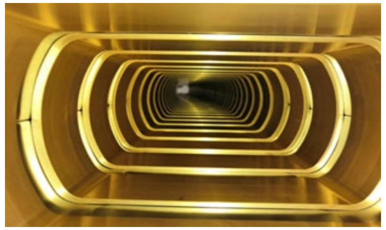


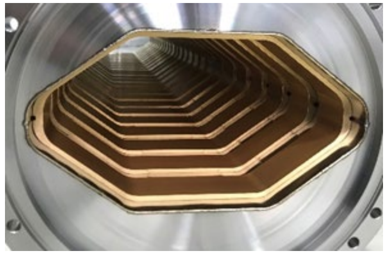
Thickness :5mm

Ceramic ring with golden coating



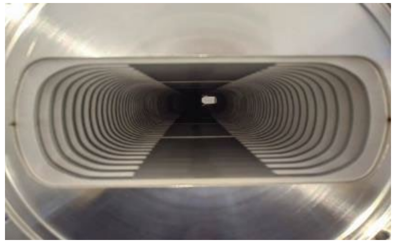
Thickness :4mm

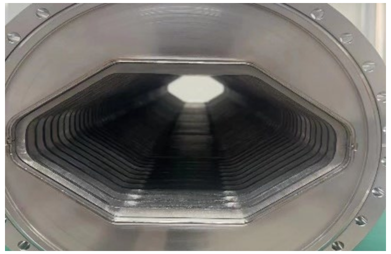




Titanium alloy-CT4 cage

Thickness :4mm

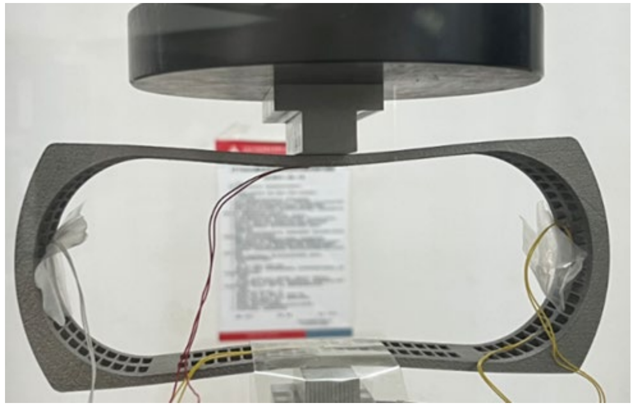


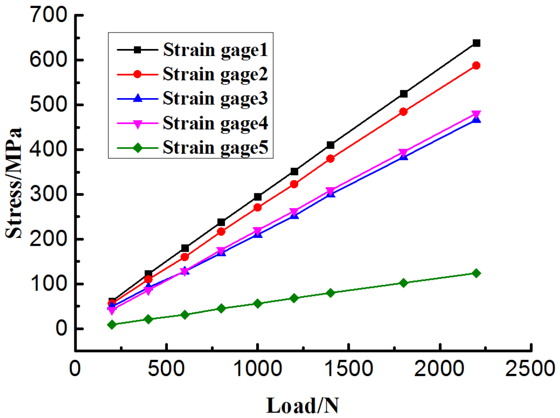


Titanium alloy lined thin-wall vacuum chamber

Advantages for TC4 cages manufactured by 3D-SLM(Selective Laser Melting):

- Occupied a less magnetic gas gap; A higher yield strength with 912 MPa; A lower outgassing rate with 1.12×10^{-13} mbar.l/s.cm^{-2} ; In addition, high reliability, easy to manufacture, and low cost……

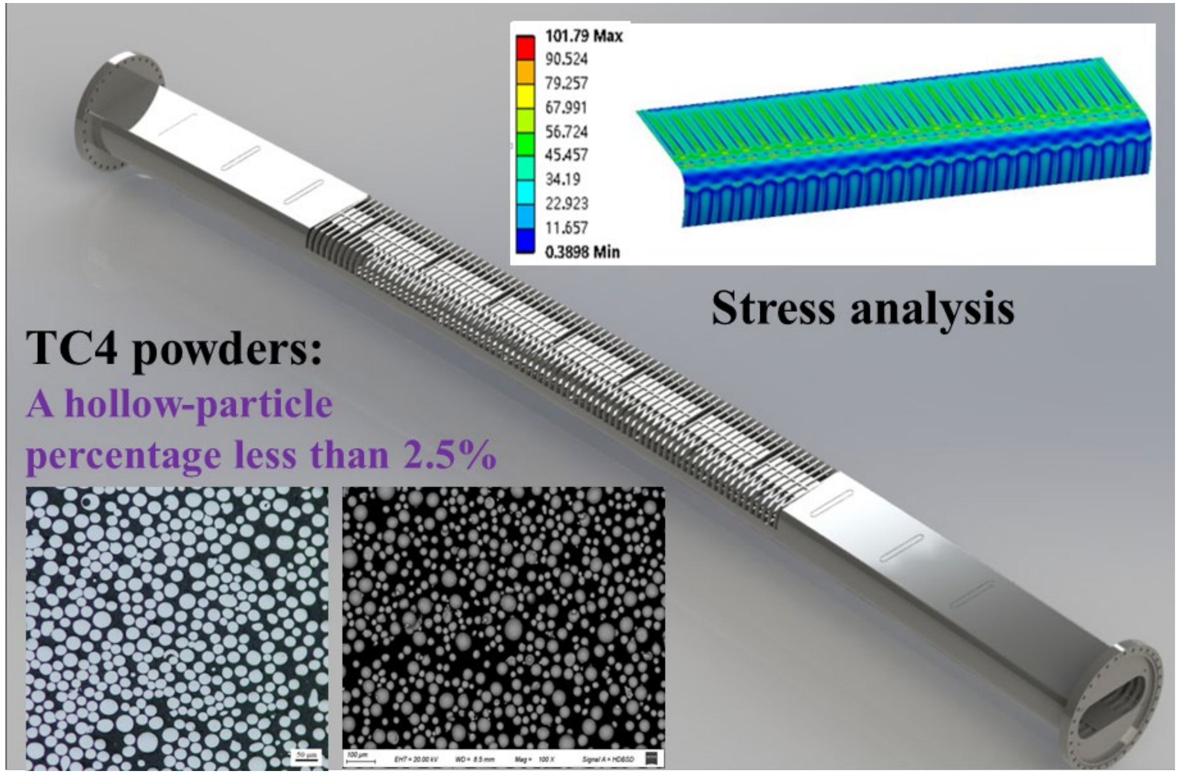




Mechanical loading test of titanium alloy ring

Comparison of Mechanical Properties of Materials

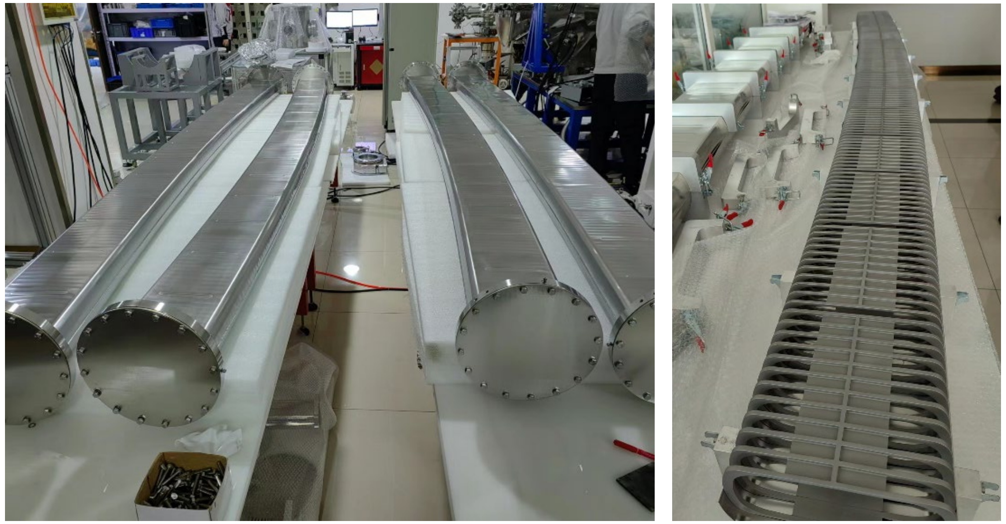
	Outgassing rate mbar·l/s·cm²	Yield strength MPa	Density kg/m³
Titanium alloy	1.12×10^{-13}	910-960	4510
Zirconia ceramic	2.1×10^{-13}	380□ Anti-bending □	6050
stainless steel	5×10^{-13}	202	7900



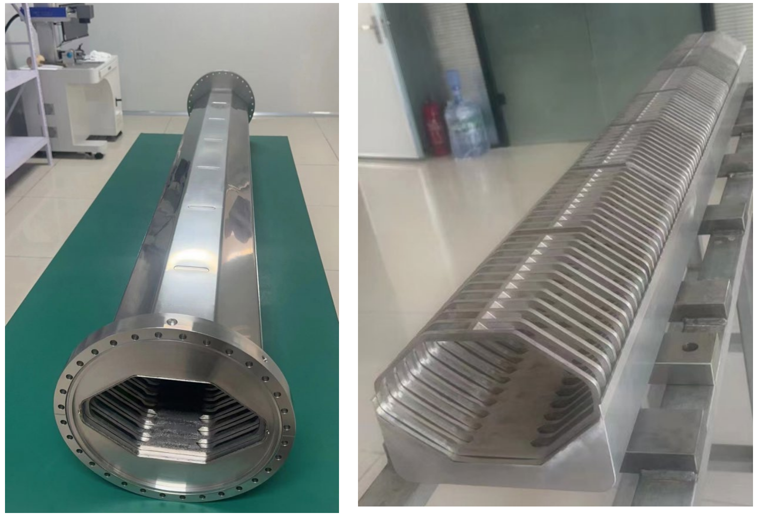
The titanium alloy-lined thin-wall vacuum chamber

Titanium alloy lined thin-wall vacuum chamber

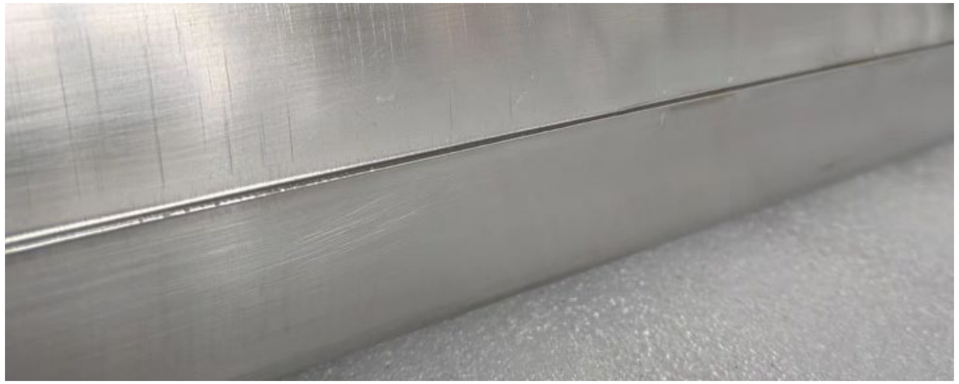
Progress: The thin-walled vacuum chambers with various cross-sectional specifications, such as octagon, circular, racetrack shape, and so on, have been developed by IMP.



The arc chambers for bending magnet of BRing



The chambers of quadrupole magnets

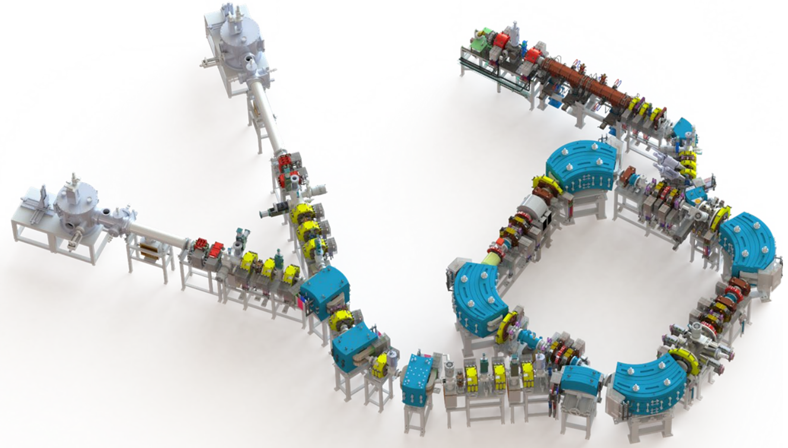
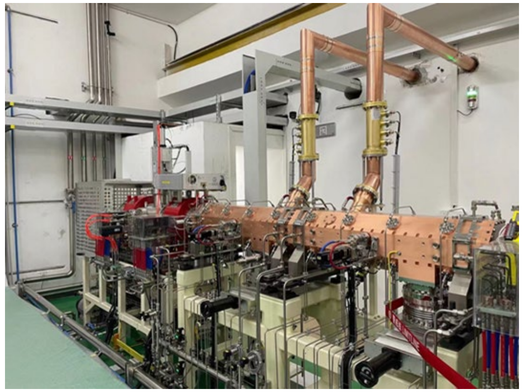
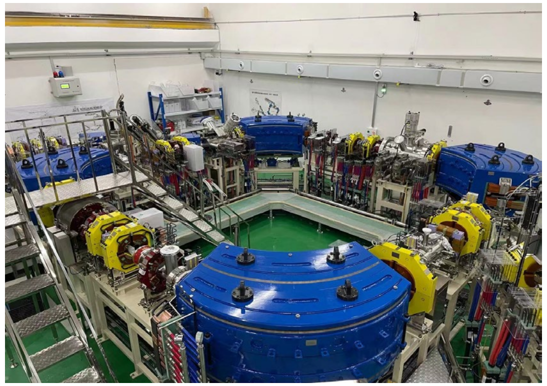
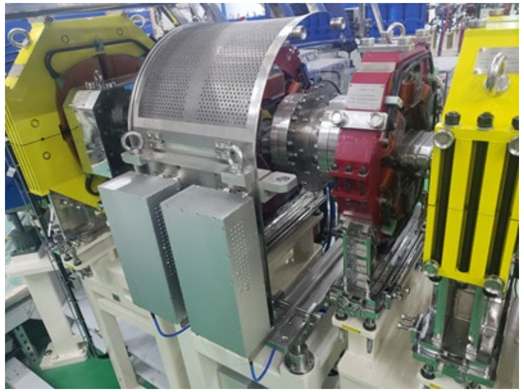


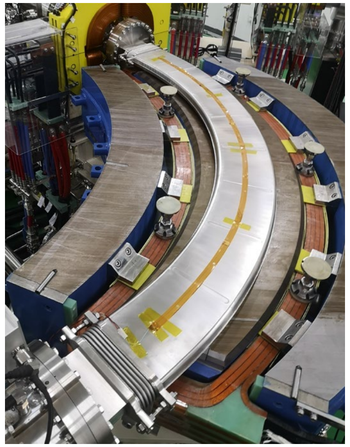
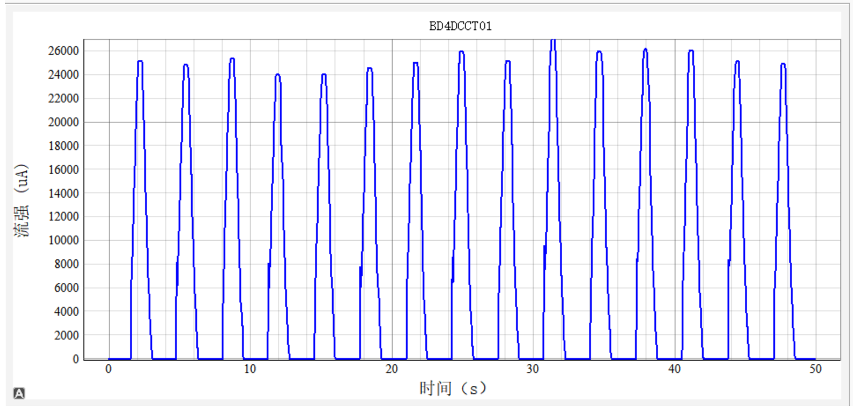
Welding quality

- Currently，48 sets of bending magnet chambers and over 80 sets of quadrupole magnet chambers are under fabrication and are expected to be completed by December 2023.

Beam test run of the key technologies

Proton Radiation Effects Facility (PREF)

2.87E+10ppp@60MeV

- **Applied in PREF facility and have been verified with proton beam. Two months beam test run show good performance and reliability**

Project progress and status

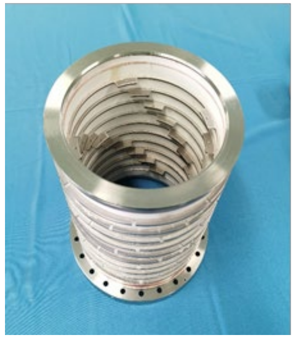
Hardware components

■ Mass production and fabrication

Solenoid of front-end

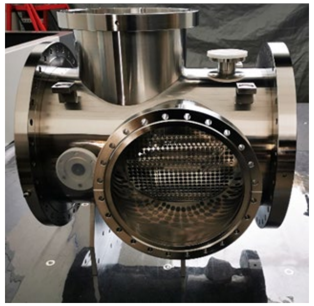

Fast ramping bending and quadrupole magnets of BRing

Superferric bending magnet with warm iron

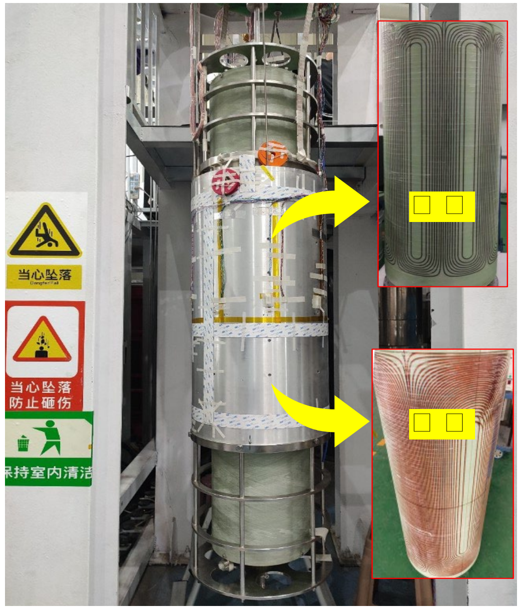



Electron cooling device

Sextupole magnets

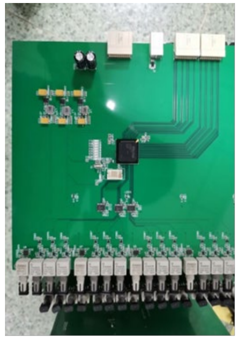
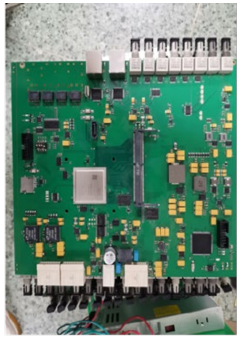



Beam diagnostic devices & instruments



Coil dominated Canted Cosine Theta multipoles magnets

Fast ramping full energy storage power supply

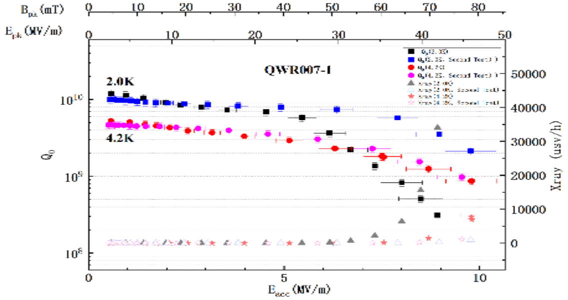




Electronics devices

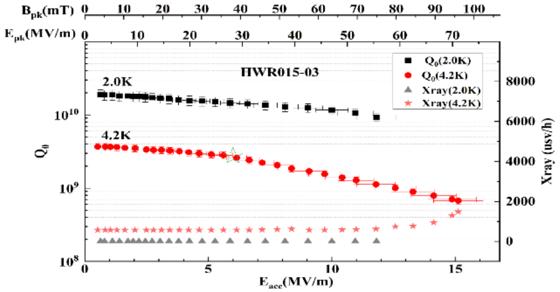
Hardware components

■ Test and measurement of key system and devices


QWR007

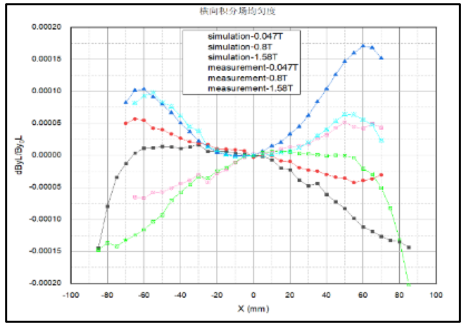



HWR015

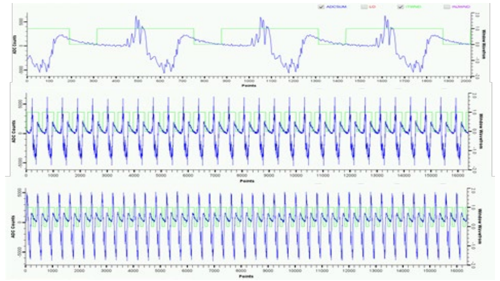


SRF cavity vertical test

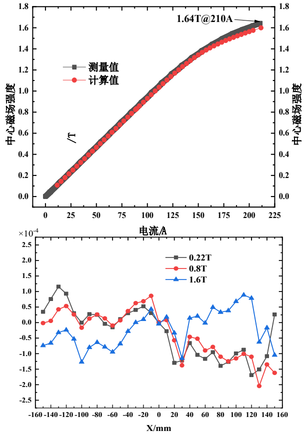
Cryomodule test



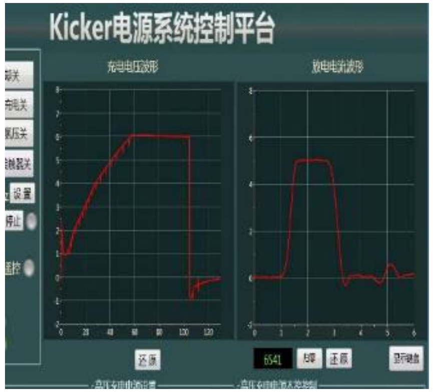
Field measurement of bending magnets



Online beam test of BPM electronics



Test and measurement of superferric magnet

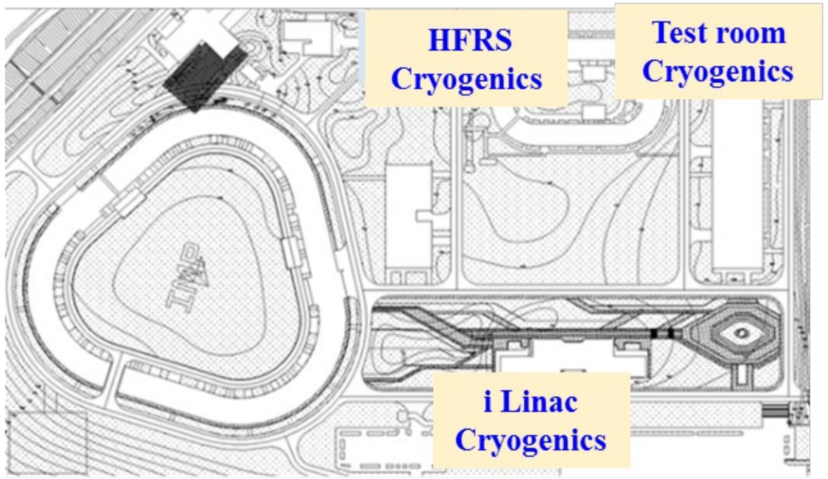


Kicker power supply test with real load

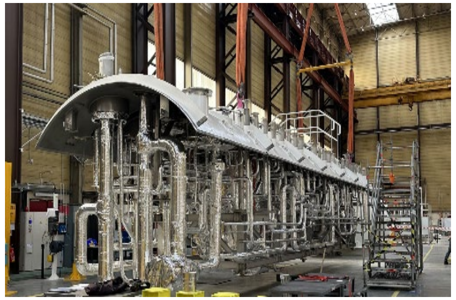
High power primary target test

Common Utility

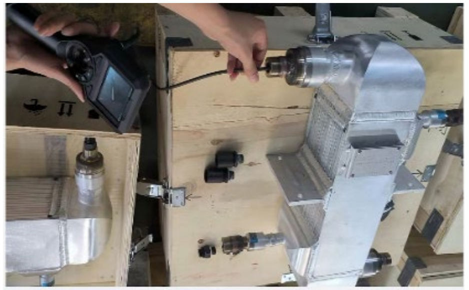
Cryogenics system



10kW@4.5K/2.0K for superconducting linac


The assembly of cold box

Tank processing


The test of negative pressure heat exchanger

Arriving November, 2023 → **Debugging August, 2024** → **Operating January, 2025**

2.5kW@4.5K for superferrit magnets


Components fabrication has completed and installation is expected in November 2023

500W@4.5K for test cryogenics station


Pipeline laying, equipment installation, and system integration are being carried out, will

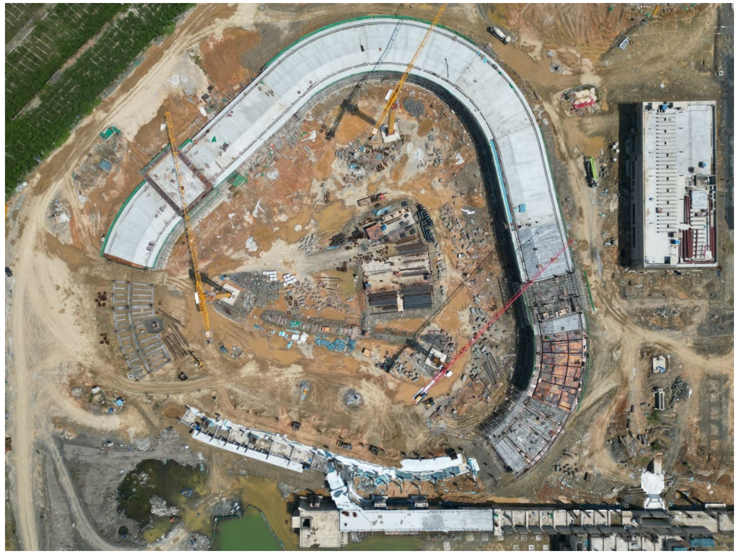
Civil construction

Civil construction

Civil construction

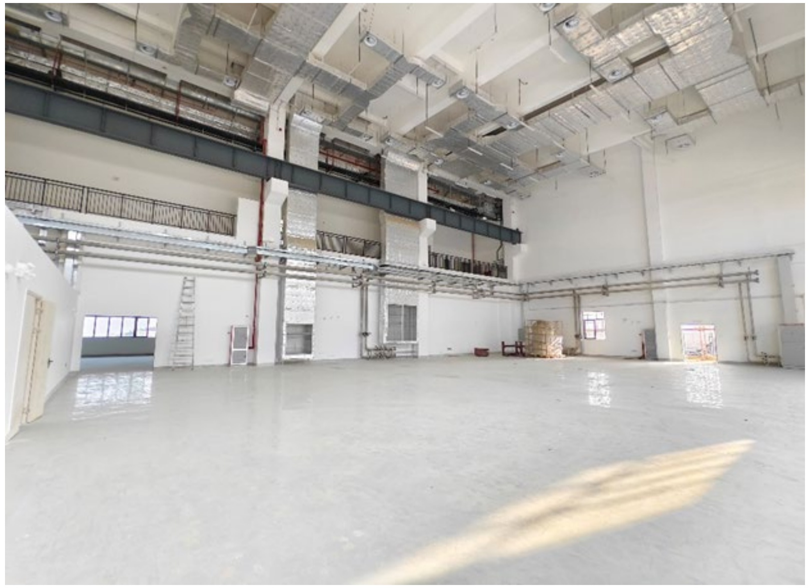
- Cooling water pipes, air conditioning ducts and cabling bridges are being installed in tunnel

Civil construction






Civil construction




Brief introduction of the CiADS

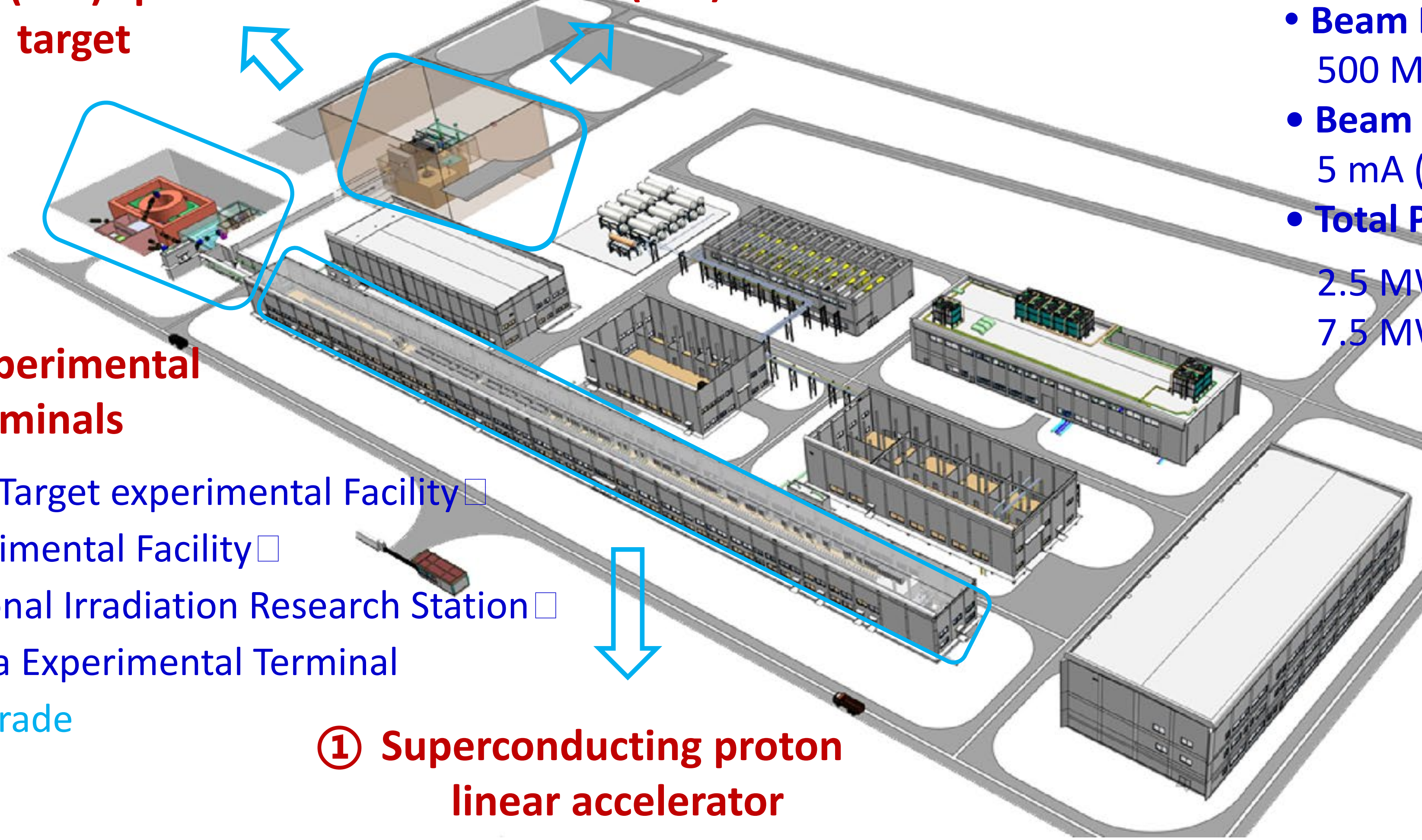
CiADS-China Initiative Accelerator Driven System

Accelerator-driven subcritical systems (ADS) is considered to be the most effective and promising method to solve the nuclear waste. CiADS will be the world's first prototype of ADS facility

- **High power lead-bismuth eutectic (LBE) spallation target**
- **Sub-critical lead-bismuth eutectic (LBE) fast reactor**

Megawatt level *to explore the safe and proper technology of nuclear waste disposal*

- **Beam Energy:**
  500 MeV (upgrade to 2.0 GeV)
- **Beam Current:**
  5 mA (upgrade to 10 mA)
- **Total Power: <10 MW**
  2.5 MW beam power,
  7.5 MWth reactor power



④ The experimental terminals

- High power Target experimental Facility
- Muon experimental Facility
- Multifunctional Irradiation Research Station
- Nuclear Data Experimental Terminal
- ISOL for upgrade

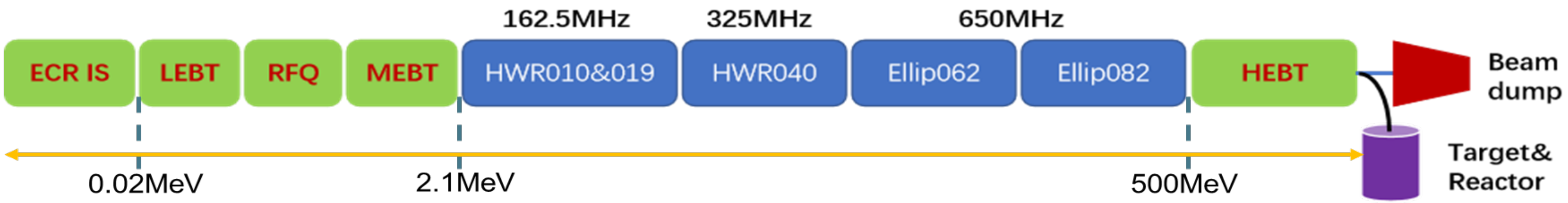
① Superconducting proton linear accelerator

The total budget is 4.0 billion CNY

Construction period: 2021-2027, 6 years

The same campus with HIAF

Superconducting proton linac



Research on the stability, reliability and long-term operations of the superconducting Lianc

The overview design consideration :

- **RAMI - oriented**
  - Redundancy design
  - Modular design
  - Fault-compensation scheme
  - Beam loss control
- **Economy**
  - High utility efficiency of Key components (cavity and SSA)
  - Well developed technology at IMP
  - More focus on the system integration and optimization (LLRF,ICS)
- **Upgradeability**
  - Energy ~2 GeV
  - Current ~ 10 mA

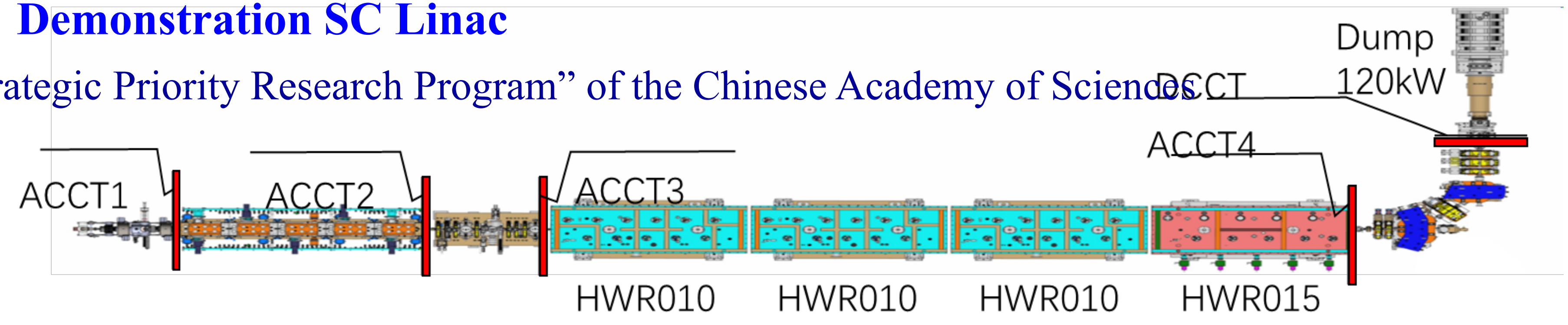
Particle	proton	
Energy	500	MeV
current	5/10	mA
Beam power	2.5	MW
RF freq	162.5/325/650	MHz
Epeak	26/28/29/29/29	MV/m
Num of CM	32	-
Num of cavity	151	-

"High availability oriented beam dynamics for CiADS proton linac"
by Shuihui Liu

Superconducting proton linac

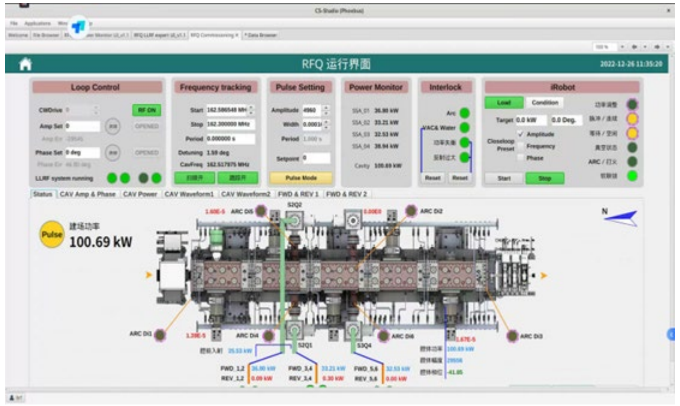
■ **Demonstration SC Linac**

Strategic Priority Research Program” of the Chinese Academy of Sciences



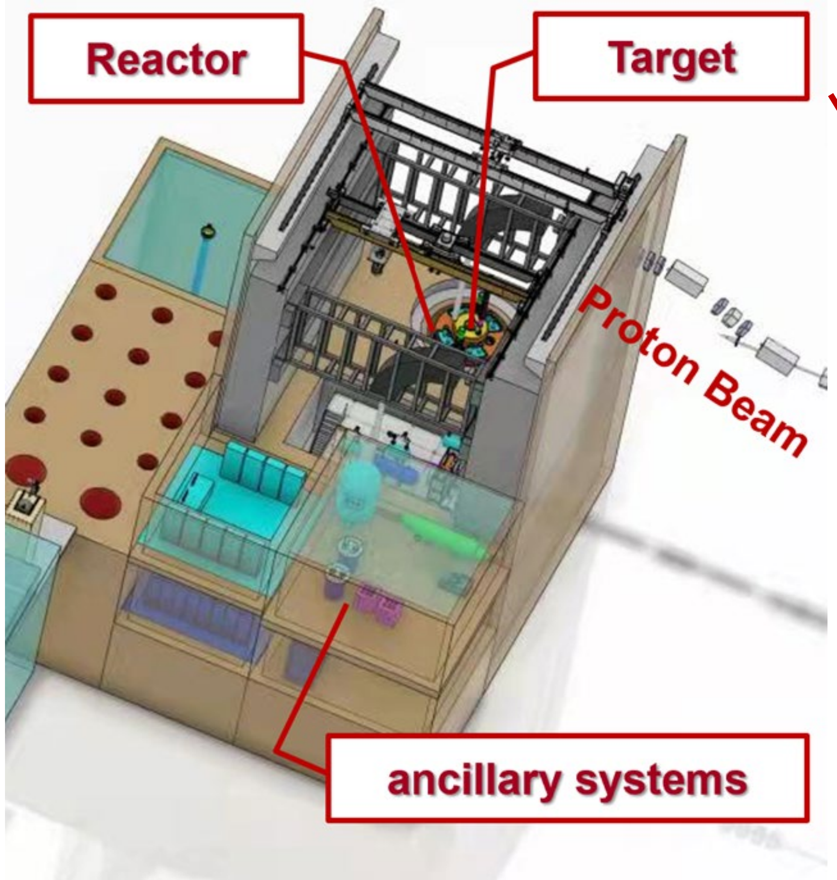
- **Proton, ~ 35 m**
- **25 MeV, 10 mA**
- **CW, 4.5 K operation**

■ **Front-end of RT section has been pre-installed and commissioned in 2022**



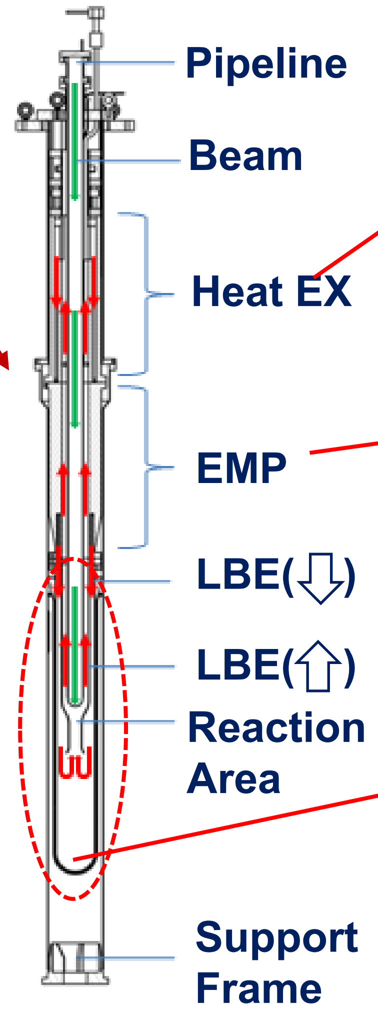
High power lead-bismuth eutectic spallation target

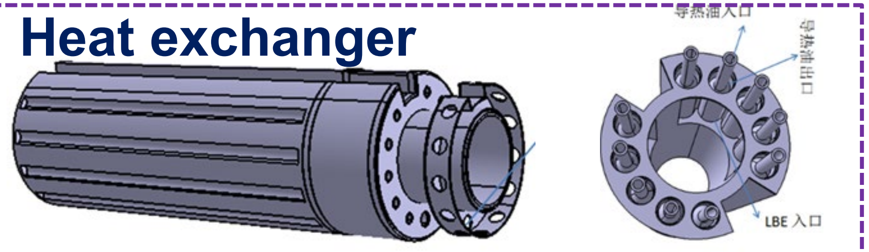
■ Verify the Accelerator-Target-Reactor Coupling Technology

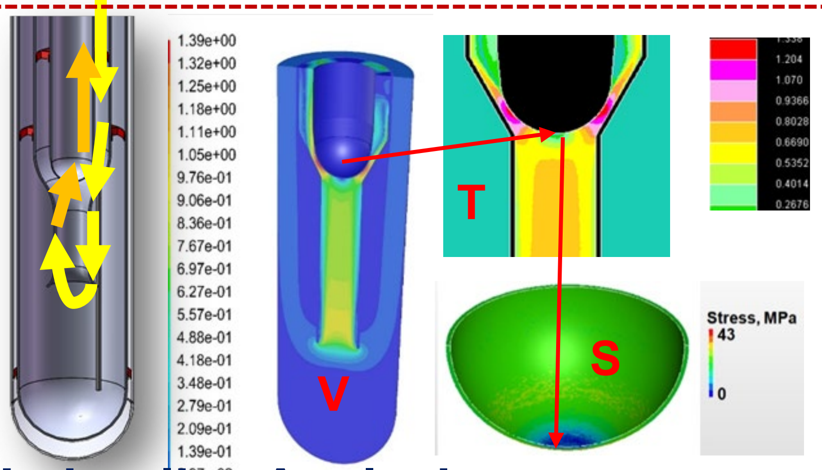


Beam Power: 250 kW - 2.5 MW
Thermal Output: 10 MW

Schematic view of Target System



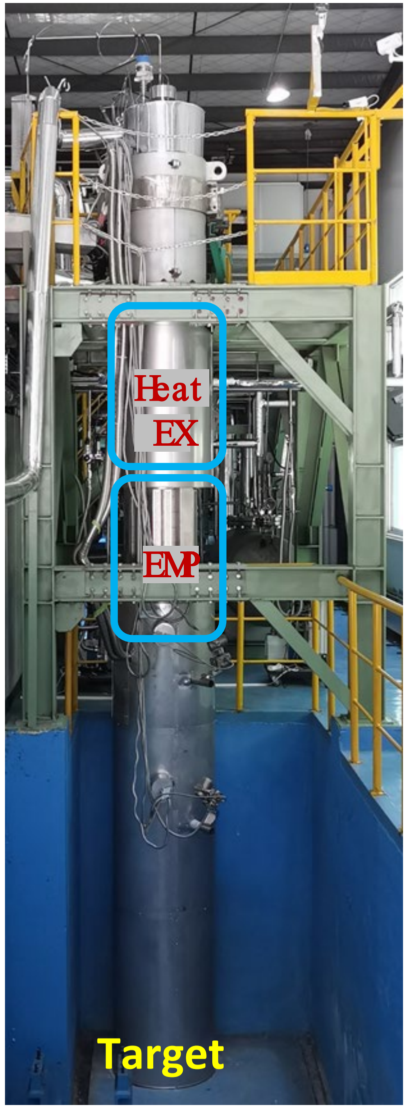




Hydraulics Analysis

High power lead-bismuth eutectic spallation target

■ The first prototype of LBE high-power target and its testing platform



- No in-beam test.
- Verify the reliabilities and performances of key components.

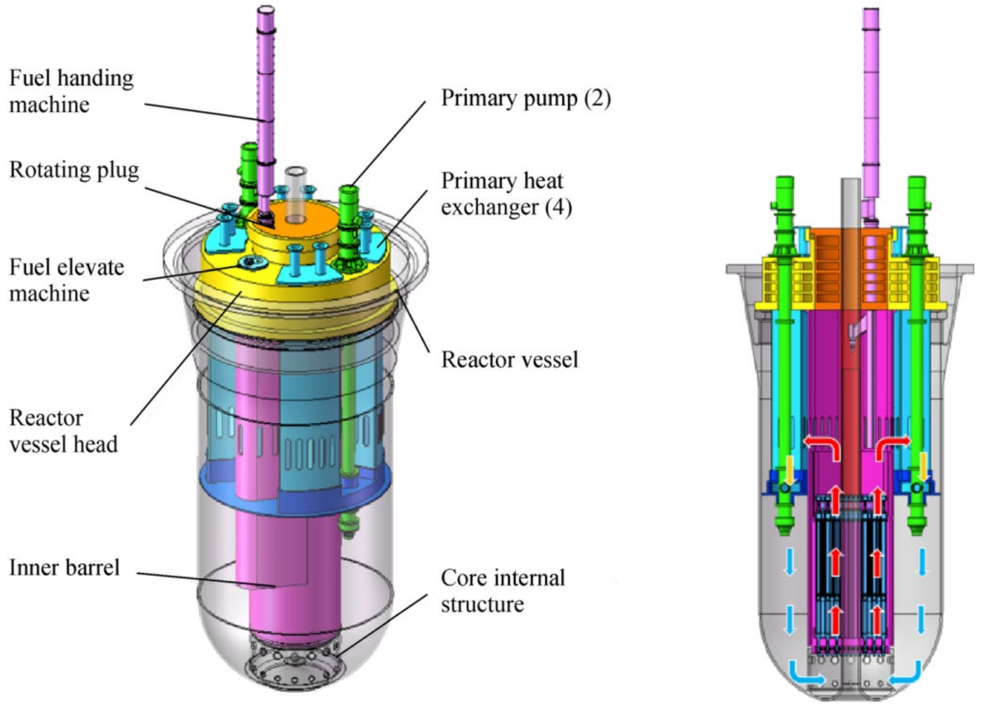
- The prototype has been installed in Oct. 2022.
- Experiments have been performed

  High precision measurement of pressure, temperature, liquid level of liquid LBE fluid, and the flowrate calibration

Subcritical LBE Fast Reactor

- **The conceptual design of the main process system of the subcritical reactor has been completed:** determined the **overall parameters** and **the primary and secondary loop coolant parameters**, confirmed the **list of system equipment**, and finished **the preparation various designing specifications and other related critical works**

	Top level spec.
type	LBE sub- FR
Power	10MWt (incl. beam)
fuel	UO_2 (19.75%)
K_{eff}	0.75~0.96
Main coolant Configuration	Pool-loop
Main coolant driven mode	Forced circulation
Coolant	LBE
Main coolant pressure	Normal
Main coolant temp	280-380°C
Main heat exchanger	Main exchanger× 4
Main pump	Mechanical pump× 2
Secondary Loop coolant	LBE
Secondary Loop pressure	Normal
Secondary Loop Temp	220-230°C



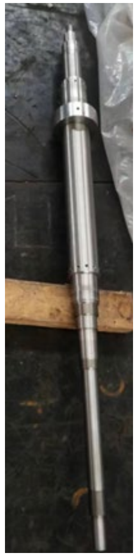
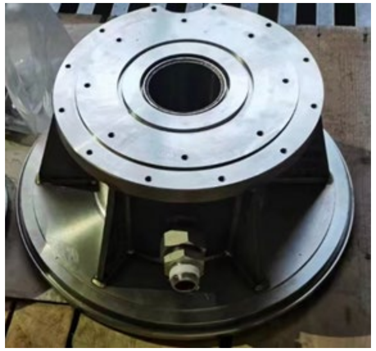
Lead-bismuth eutectic (LBE) as the coolant, a spallation target window reserved on the reactor roof and a pool-type design main container, can simultaneously achieve the coupling and physical isolation with the spallation target. A passive containment thermal conduction system will be used to ensure the safety of the sub-critical system in the accident conditions.

Subcritical LBE Fast Reactor

■ Progress of Thermal demo Reactor

- **Reactor Vessel**

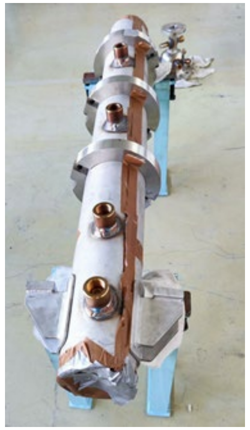

- **Pump**


- **Reactor internals**



- **Heat exchanger**




- **LBE container**

CiADS-China Initiative Accelerator Driven System

■ CiADS Research Plan (2025～2030)

2025～2026

Construction
Accelerator and Target

- Accelerator 25kW
- Target >25kW
- At HiTa

- ☐ Accelerator Commissioning
- ☐ Target thermal study
- ☐ **Beam-target coupling tech**
- ☐ **Reactor thermal study**
- ☐ Beam-target coupling

2026～2027

ADS Coupling
Early Fuel test

- Accelerator 250kW
- Target 250kW
- K_{eff}~0.5
- Reactor~30kW

- ☐ 3 Fuel Assemblies online
- ☐ Accelerator stability study
- ☐ Reactor stability study
- ☐ **Beam-target-reactor coupling**
- ☐ **Low power test for fuels**
- ☐ Low power exp for reactor

2027~2029

ADS/ADANES demonstration
10MW system coupling

- Accelerator 2.5MW
- Target 250kW
- K_{eff}=0.96
- Reactor ~9.75MW

- ☐ Full fuel online
- ☐ Neutronic study of Subcritical Reactor
- ☐ **Operation study of Subcritical Reactor**
- ☐ LBE cooling demonstration with power
- ☐ **ADS systematic study**
- ☐ **ADS operation key tech study**
- ☐ **2.5MW beam test for accelerator**
- ☐ ADANES design demonstration

2029~2030

ADS/ADANES
transmutation research

- Accelerator ~2.5MW
- Target ~2.5MW
- K_{eff}~0.75
- Reactor ~7.5MW

- ☐ **High power target demonstration**
- ☐ ADS operation with high power
- ☐ **Transmutation demonstration**
- ☐ Test fuels with deep burnup
- ☐ Fuel test with high power density
- ☐ ADANES preliminary design report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HIAF and CiADS welcome all of you !!!
Huizhou, 2025

Thanks for your attention!