Progress and status of HIAF project

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Institute of Modern Physics (IMP) , Chinese Academy of Sciences (CAS)

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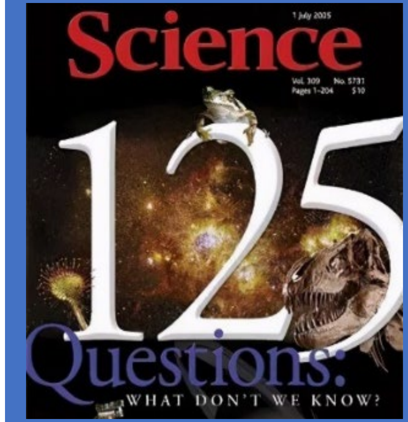
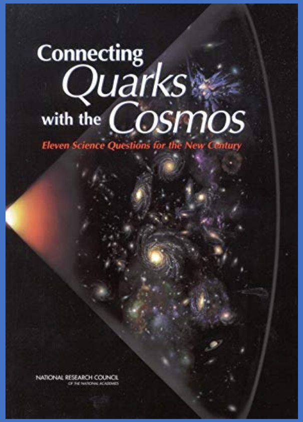
Outline

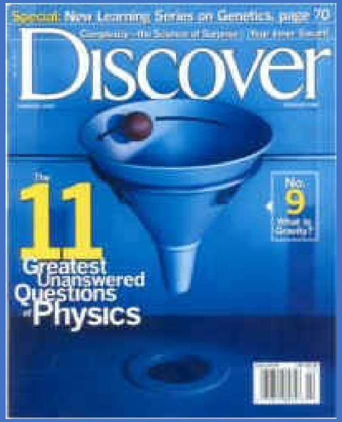
1. General introduction
2. Accelerator challenges and innovations
3. Construction and commissioning
4. Conclusion and future perspectives

General introduction

Nuclear physics frontier:

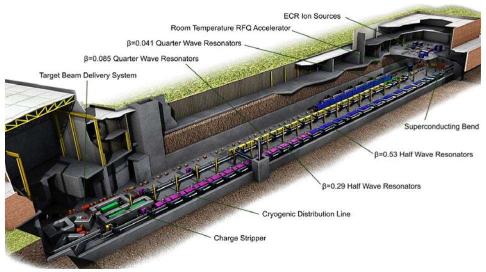






- Explore the limit of nuclear existence
- Study exotic nuclear structure
- Understand the origin of the elements
- Study the properties of High Energy and Density Matter

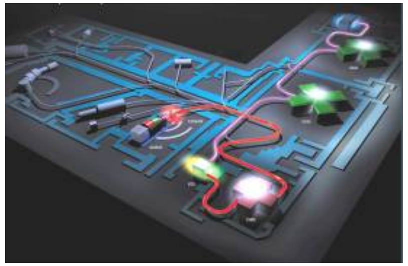
Accelerators and use of high intensity heavy-ion beams will be key to solving those questions



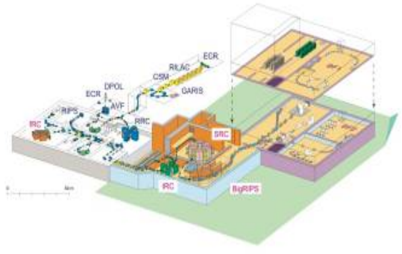
FRIB

FAIR

NICA



SPIRAL2



RIBF

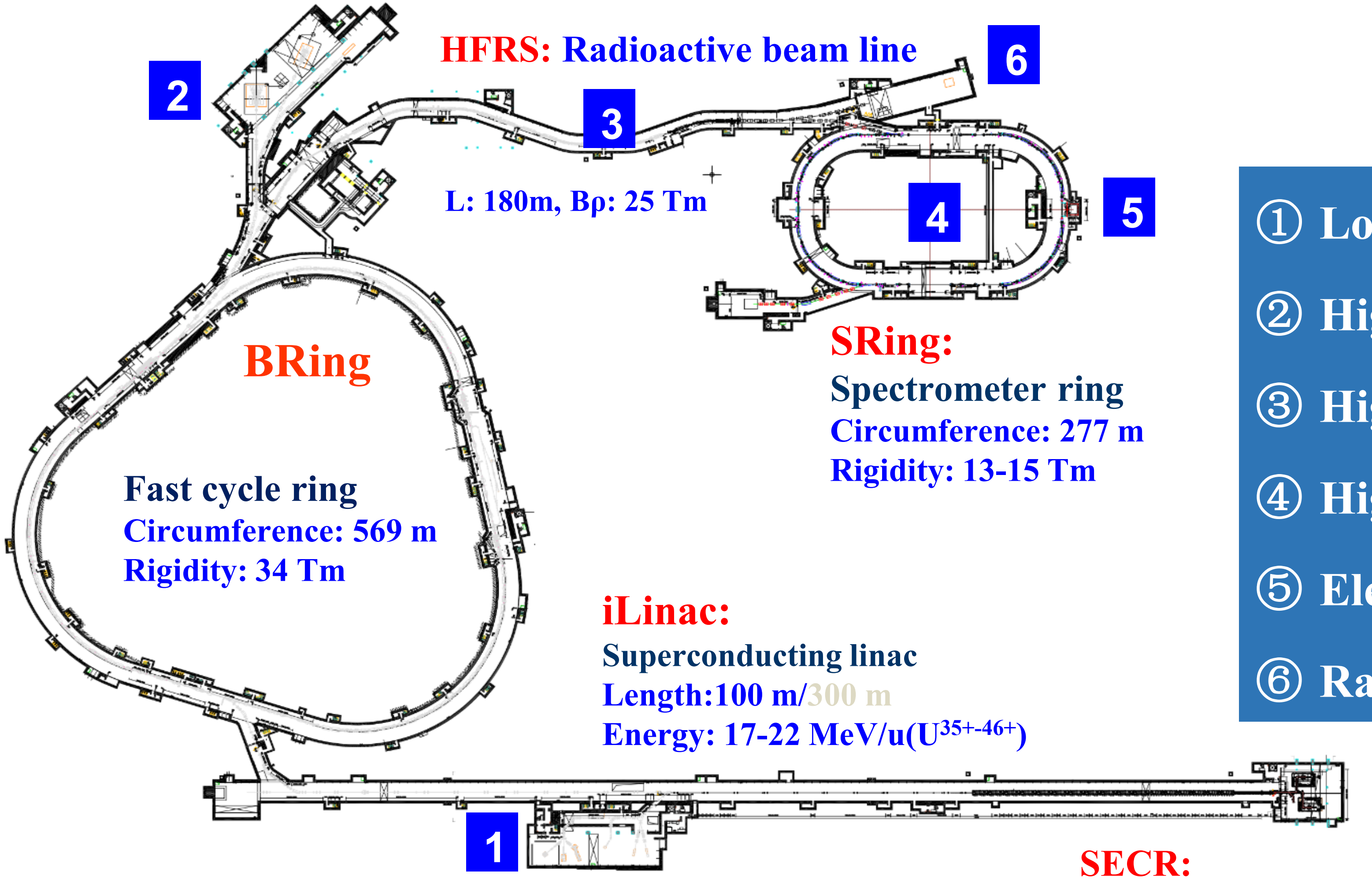
High-Intensity Heavy Ion Accelerator Facility - HIAF

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

The project was proposed and constructed by IMP, CAS
The total budget is 3.0 billion CNY

General introduction

The whole layout: accelerator components and experimental terminals



Experimental terminals

① Low energy nuclear structure terminal

② High energy experimental terminal

③ High energy fragment separator HFRS

④ High precision spectrometer ring SRing

⑤ Electron ion recombination terminal

⑥ Radioactive ion beam physics terminal

General introduction

Features:

High current low energy CW and the highest intensity high energy pulse

	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+})	1100 (U^{92+})
Magnetic rigidity(Tm)	---	---	34	25	15
Beam intensity of U	**1.7 emA (U^{35+})**	**1.0 emA (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)

General introduction

Where is HIAF?

HIRFL
Lanzhou, since 1957

IMP/Huizhou Branch

HIAF, CiADS Facilities

the Greater Bay Area (GBA)

Located in Huizhou of Guangdong Province, strategically positioned near Shenzhen, Hong Kong, and Guangzhou

General introduction

Time schedule

7-year construction period since 2019

Civil construction began

Key prototype

Equipment bidding

Testing

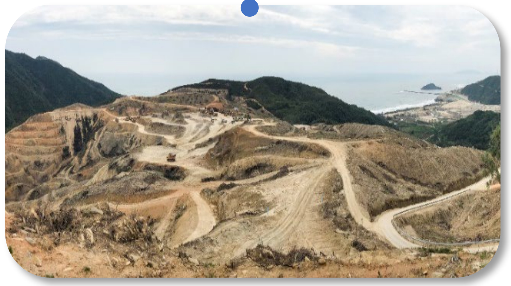
Auxiliary system

Beam commissioning

Equipment operation

2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025

First key equipment



Batch processing

Installation

Offline commissioning

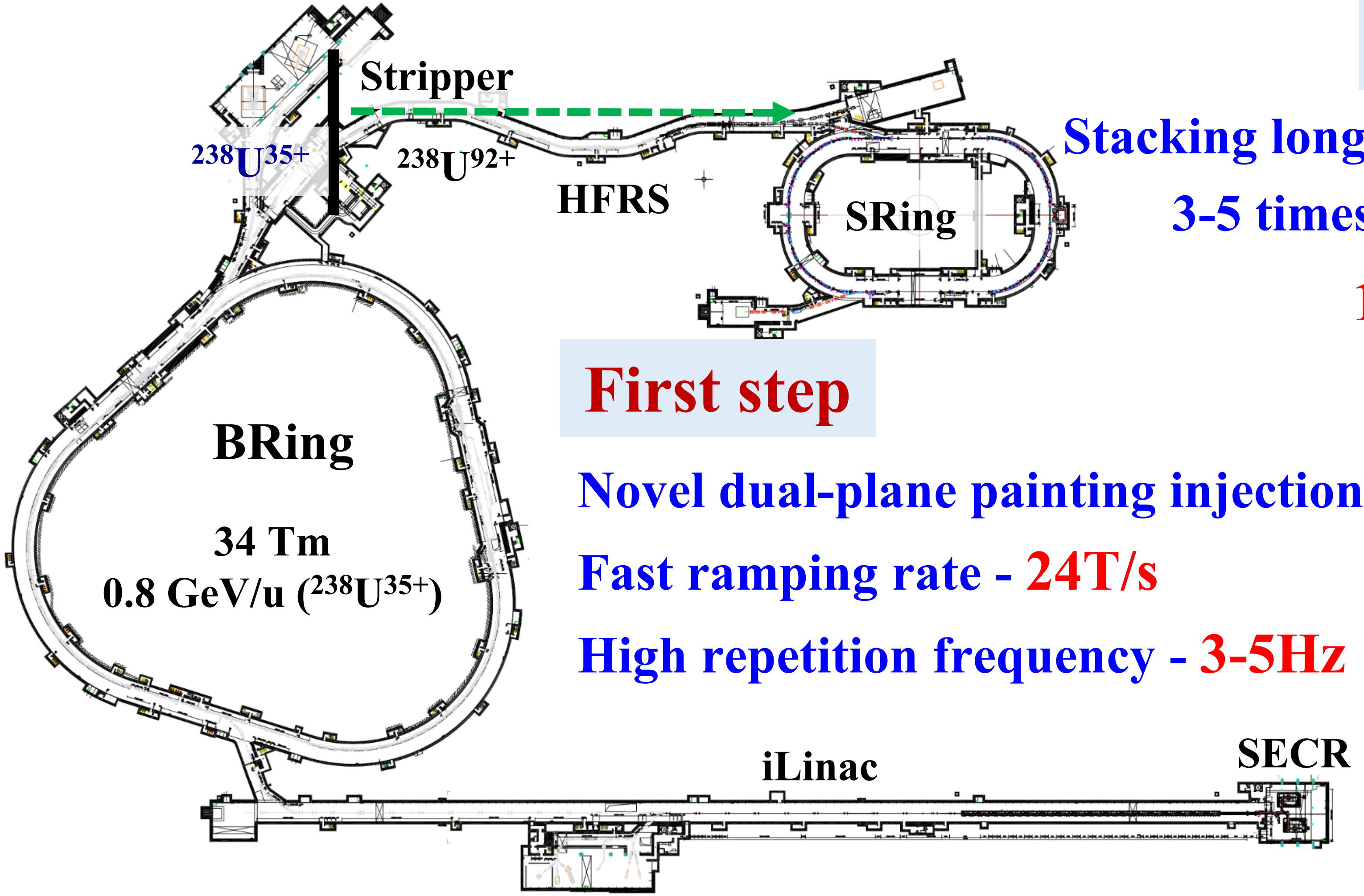
Achieve design parameters @2025.11

Outline

1. General introduction
2. **Accelerator challenges and innovations**
3. Construction and commissioning
4. Next step plan and future perspectives

High intensity ion beam

How to achieve the unprecedented heavy ion intensity



Second step

Stacking longitudinally from BRing to SRing

3-5 times barrier bucket technology

1×10^{12}ppp ($^{238}U^{92+}$)

First step

Novel dual-plane painting injection scheme - 2.0×10^{11} ppp

Fast ramping rate - 24T/s

High repetition frequency - 3-5Hz

High current superconducting linac -1emA U^{35+}

Fourth generation high current ion source – 1.7 emA U^{35+}

Major Challenges

World's most intense pulsed heavy-ion beams

Institute	Machine	Planned	Achieved	Ion
BNL	AGS Booster		5×10^{9}	Au^{32+}
CERN	LEIR		9×10^{8}	Pb^{54+}
JINR	NICA Booster	4×10^{9}	/	Au^{32+}
GSI	SIS18	1.0×10^{11}	$\sim 4\times10^{10}$	U^{28+}
FAIR	SIS100	4.0×10^{11}	/	U^{28+}
IMP	**HIAF-BRing**	**$>1.0\times10^{11}$**	**/**	**U^{35+}**
IMP	**HIAF-SRing**	**$>5.0\times10^{15}$**	**/**	**U^{92+}**
IMP	**HIRFL-CSR**	**1.0×10^{9}**	**1.0×10^{8}**	**U^{74+}**

Challenge-1:
Beam dynamics

leads to

- **Nonlinear effects**
- **Space charge effects**
- **Collective effects**
- **Dynamic vacuum**

limits

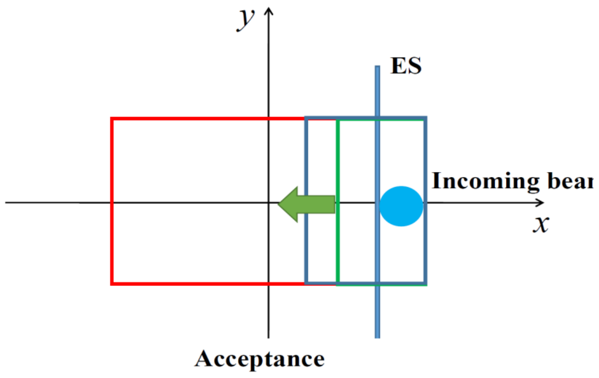
Challenge-2
Technology aspect

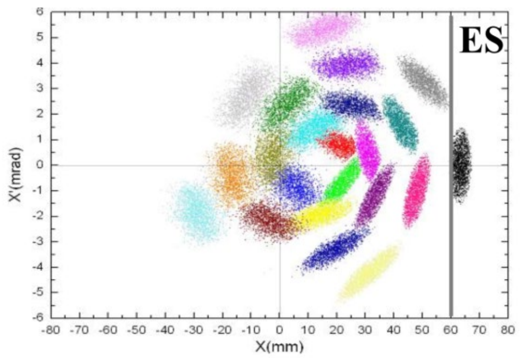
- **Beam production**
- **Low energy manipulation**
- **Fast ramping acceleration**

Beam intensity
Beam quality

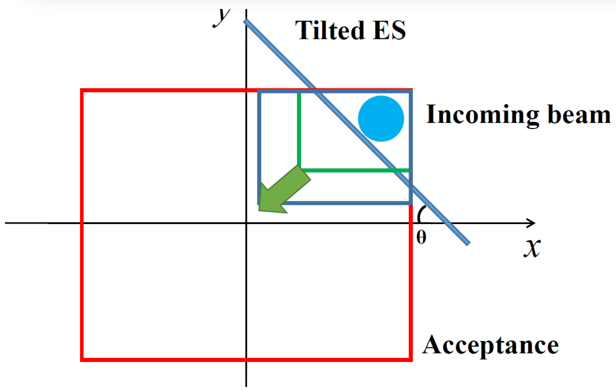
Beam dynamics and challenges

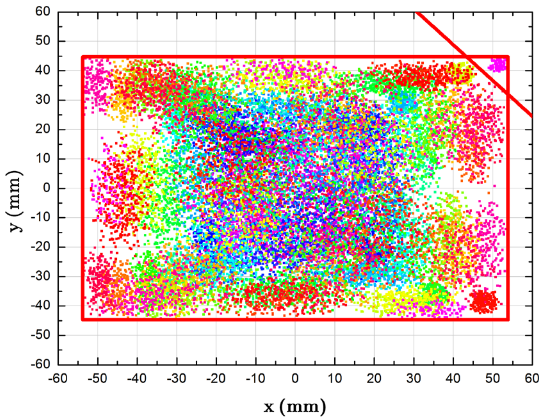
□ Novel dual planes painting injection





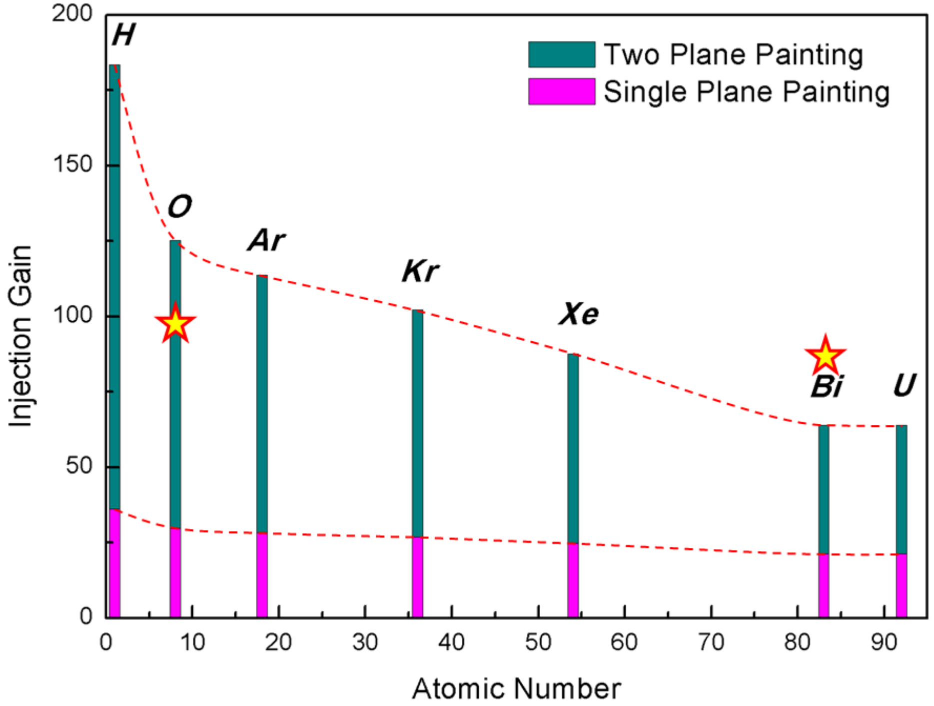
Conventional multi-turn injection





Dual planes painting injection

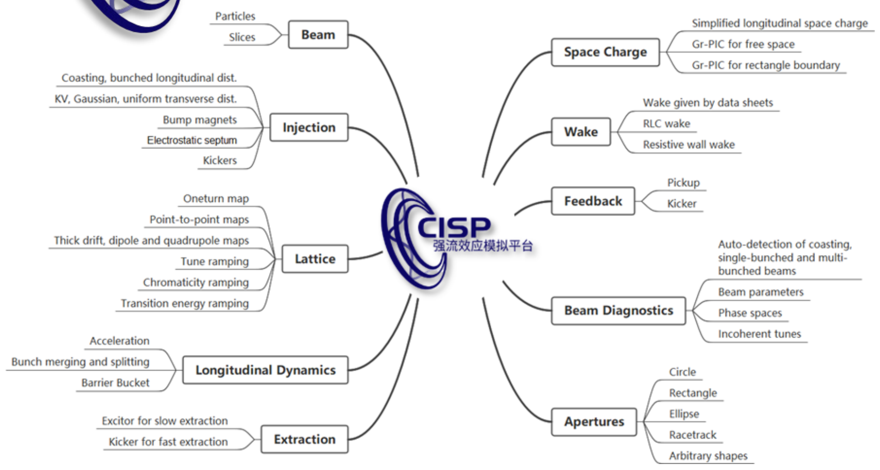
Both the horizontal and vertical painting simultaneous using the tilted E-Septum

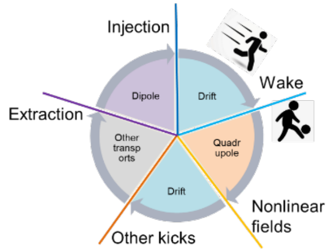


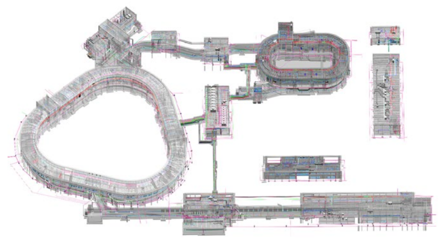
2.0×10^{11} with two planes painting, **nearly 10 times over the conventional multi-turn injection**

Beam dynamics and challenges

CISP (Simulation Platform for Collective Instabilities) and its GPU version are developed to simulate high intensity effects and their coupling effects

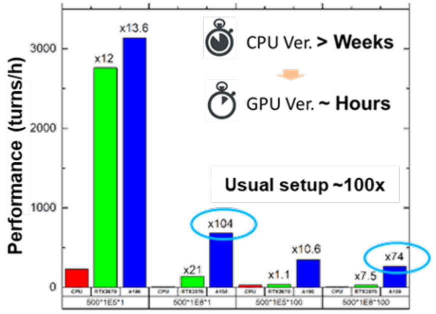


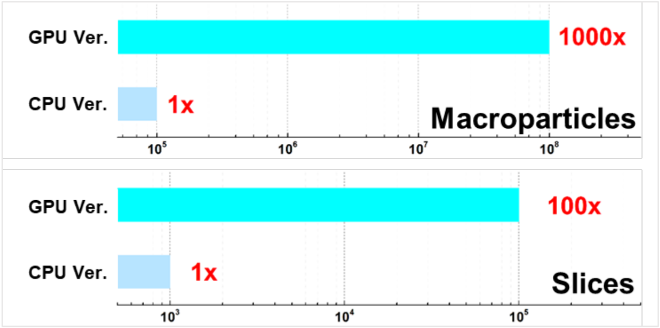


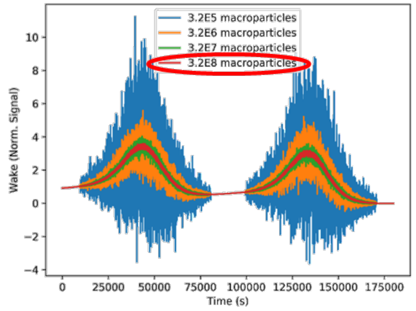


- To perform **1:1 end-to-end** multi-dynamics coupling simulations
- **All effects** are included in a single simulation to get closer to the actual accelerators

CISP-GPU: accelerated parallel computing of all beam dynamics.





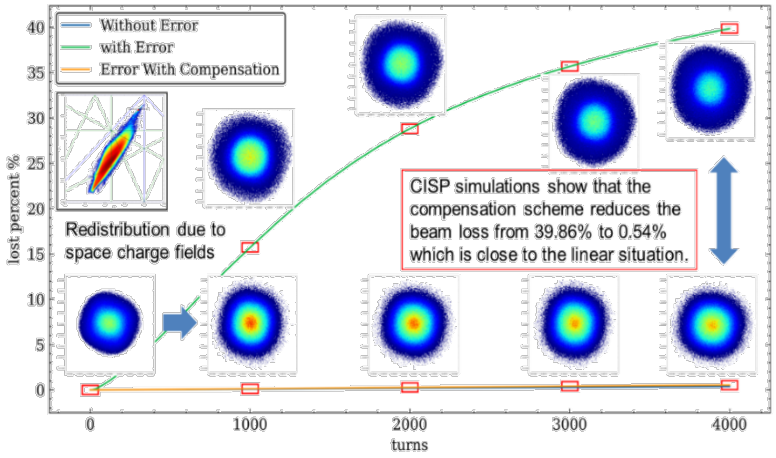


Higher performance → Much higher accuracy

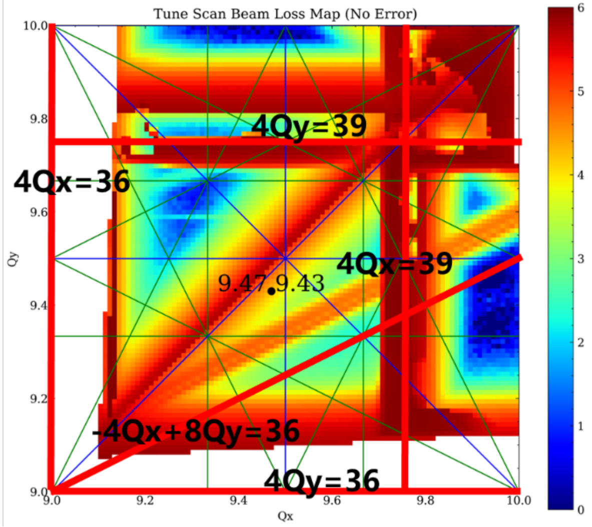
- **~10^8 macroparticles and 10^5 beam slices**
- **Study the interaction between ultra-short wakes and ultra-long bunches, also many other multi-dynamics coupling effects**

High intensity beam dynamics investigation

◻ Nonlinear effect and space charge

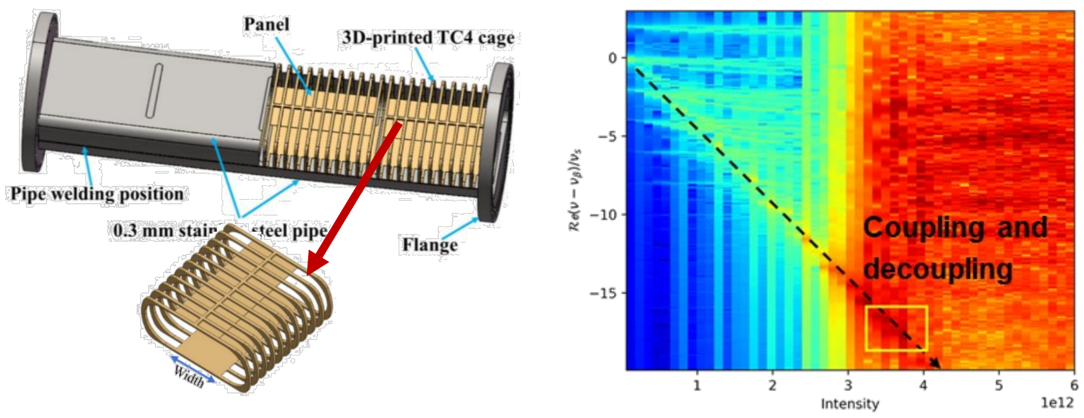


Resonances driven by high order field errors with space charge were corrected to reduce the beam loss



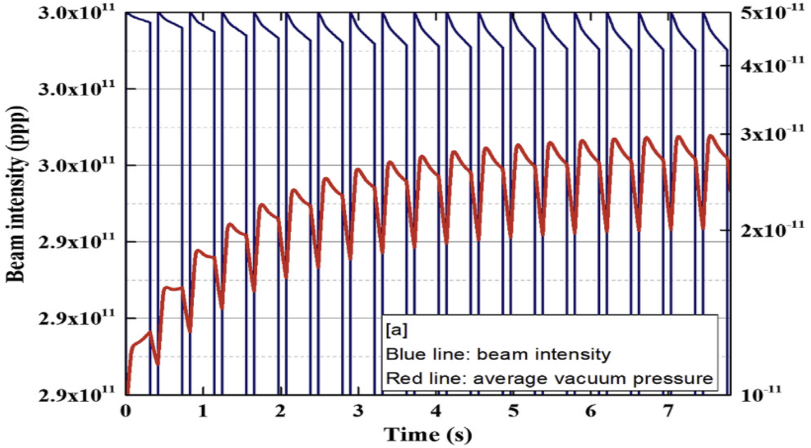
Work point was optimized to avoid the beam loss of structural resonances

◻ Collective instability



Transverse mode coupling of Titanium alloy cage supported vacuum chamber were investigated and compensated

◻ Dynamic vacuum effect

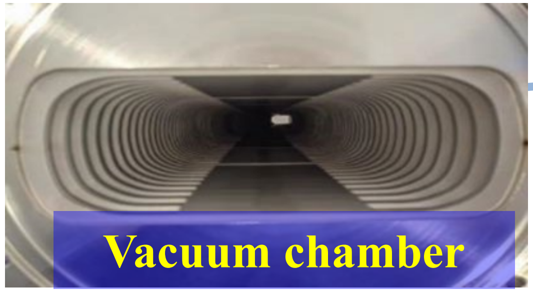


Beam intensity is 3E11 ppp at the equilibrium state the drop of vacuum pressure is acceptable

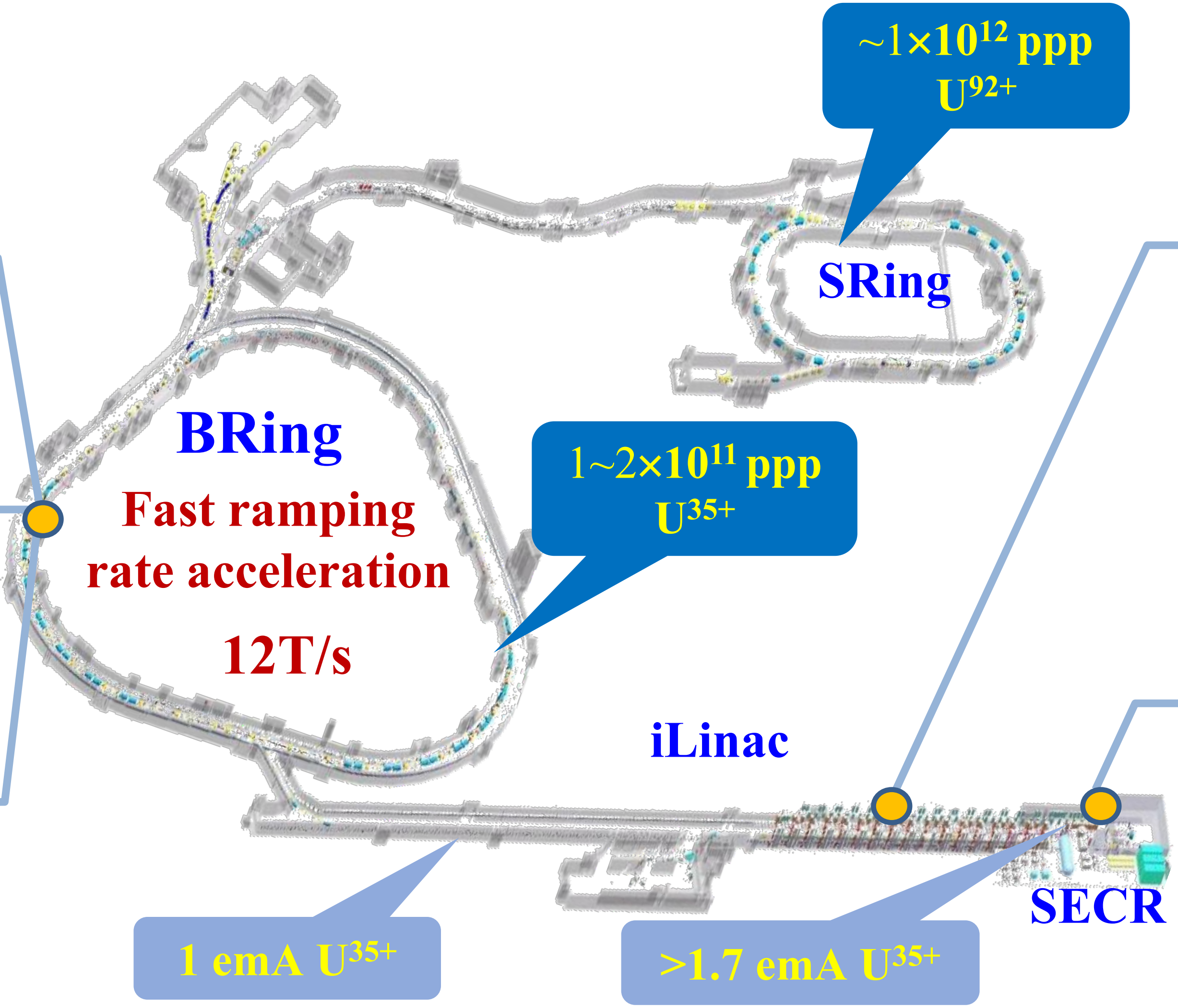
Key technologies and challenges

38kA/s, 3Hz

70kV, 35 kV/m



0.3 mm, <7×10-12 mbar

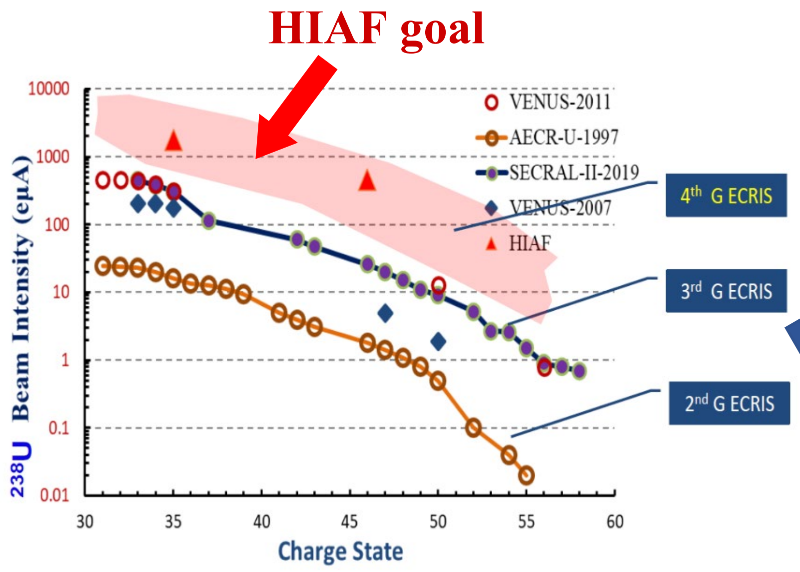


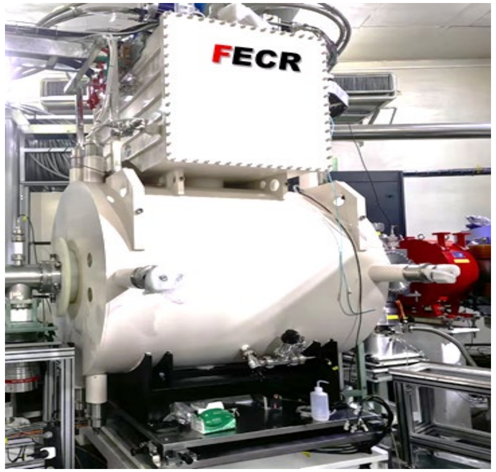
mA level heavy ion beam

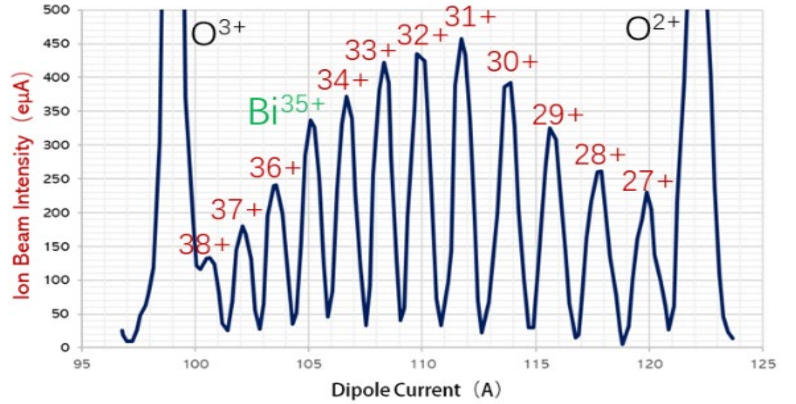
Fourth generation superconducting ECR source

HCI production

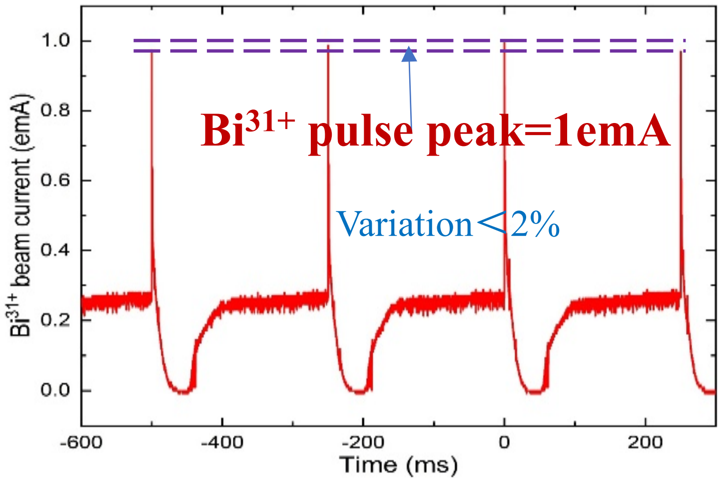
Advanced 3rd & 4th generation ECRIS (First Nb_3Sn ECRIS)







Bi^{35+}: beam current is about 350 eμA , the new record of Bi ion.



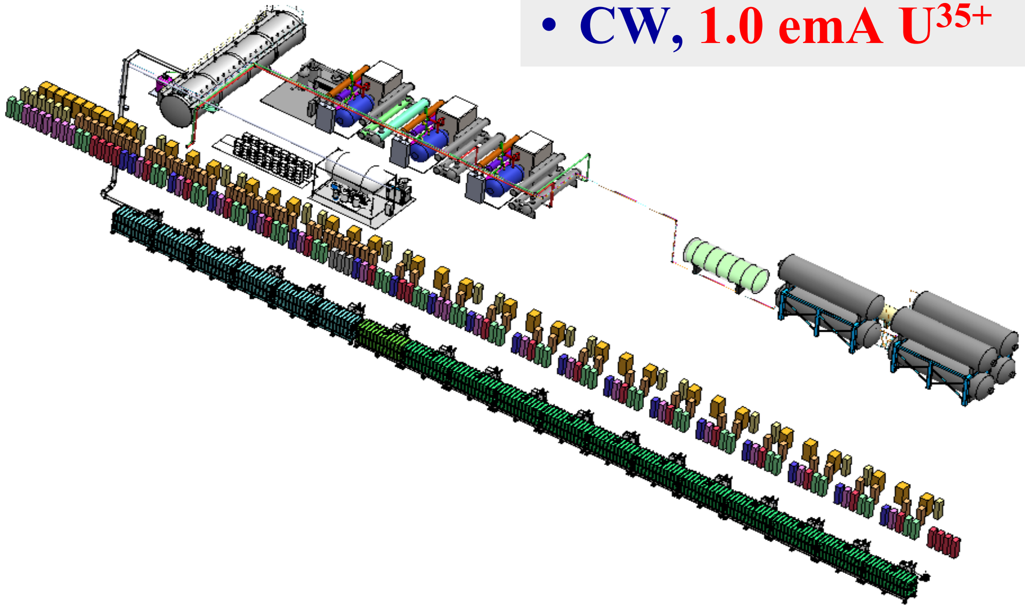
- **Innovative afterglow operation**

Features:

- **45/28 GHz Operation**
- **High Power quasi-optical microwave injection**
- **Micro-channel plasma chamber**

SRF Linac injector

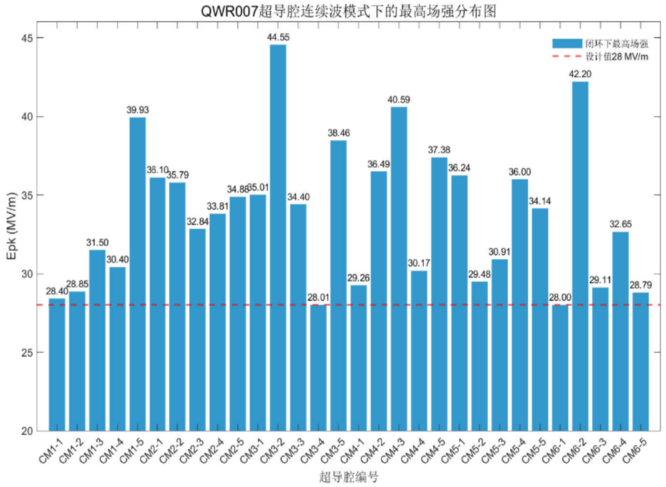
- **Pulsed, 1.7 emA U^{35+}**
- **CW, 1.0 emA U^{35+}**



0.8 MeV/u CW RFQ

QWR 007

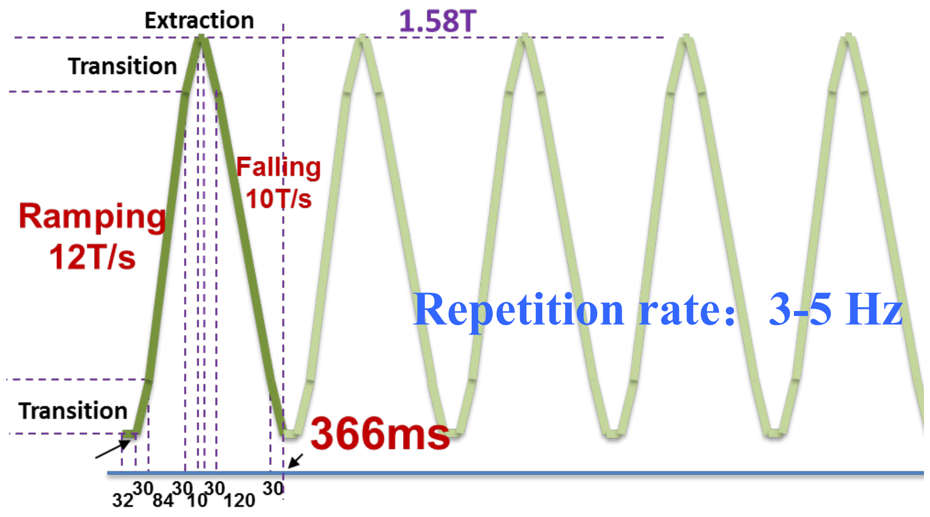
HWR 015



Average E_{pk} = 33.8 MV/m； 20.7% > designed

Fast ramping rate synchrotron

Why? Space charge and Dynamic vacuum dominated beam loss



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

12T/s: The highest ramping rate for heavy ion synchrotron

A major breakthrough via developing innovative technologies

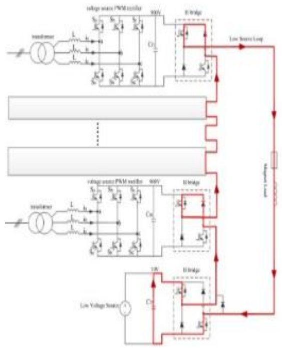
Full energy storage power supply

Magnetic alloy core loaded RF system

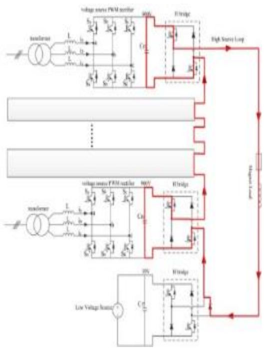
Thin wall UHV vacuum chamber

Fast ramping rate full energy storage PS

Innovative topology:



Energy from capacitor tank to magnet load

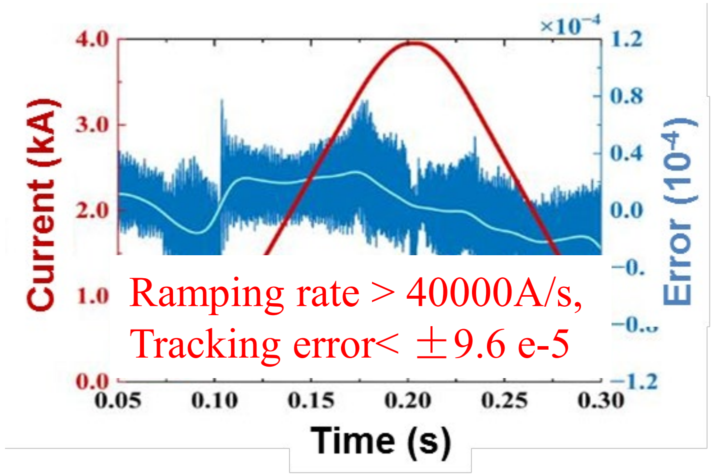


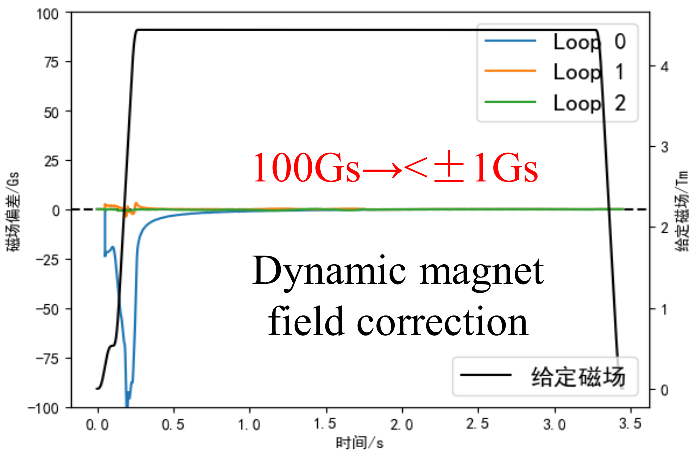
Energy from magnet load to capacitor tank

(variable forward excitation, full energy storage, PWM rectification technology)

A power supply system including 350 power converters has been developed

Achieved leading level performance, and power consumption reduces to 10% of traditional

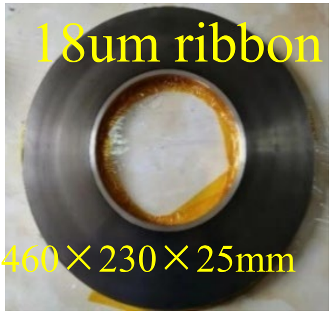




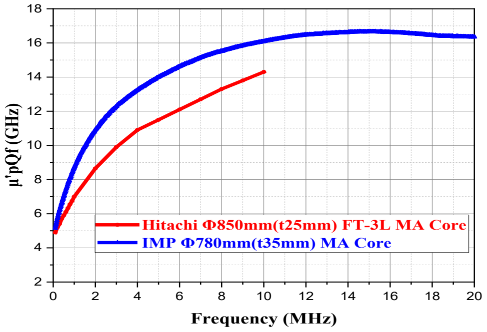
Power requirement (MVA)	Conventional	Energy storage
Bendng magnet	180	15
Quadruple magnet	50	6
Total of BRing	250	41
Total of HIAF	297	88

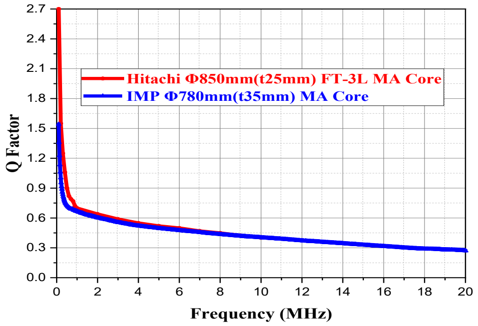
Magnetic alloy core loaded RF

Breakthrough in MA Loaded Cavity



Over ten years exploration





The best level of public reporting at the moment

MA loaded RF system in the tunnel

Facilities	Voltage (kV)	Length (m)	Gradient(kV/m)
JPARC-RCS	41	1.78	23
JPARC-MR	46.7	1.78	26.2
SIS18	50	2	25
HIAF-BRing	70	2	35

Total RF voltage: 350kV

Thin-walled vacuum chamber

Thin wall chambers: Keep eddy currents at a tolerable level

Vacuum system for HIMAC

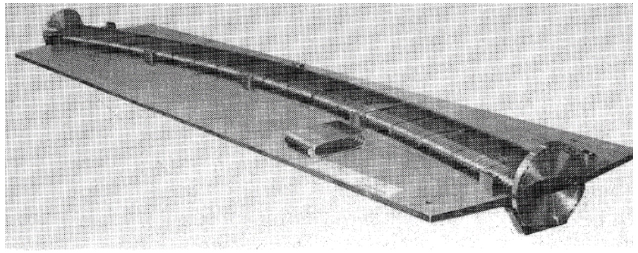
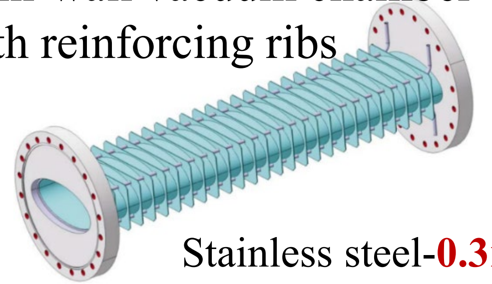


Figure 1a. One section of vacuum chamber set on a steel plate with the same curvature as the bending magnet.

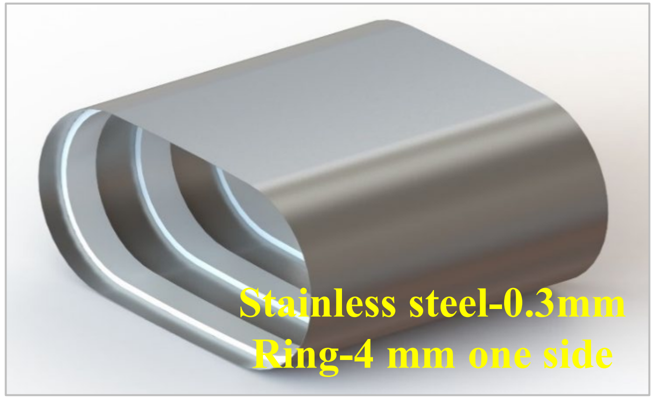
Solution from GSI

Thin-wall vacuum chamber with reinforcing ribs

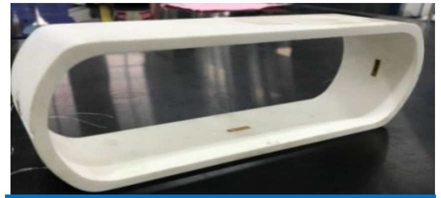


Stainless steel-**0.3mm**
Rib-15mm,one side

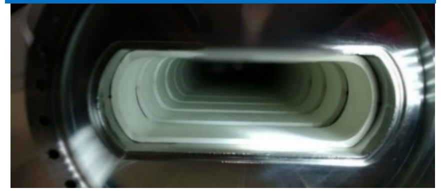
Novel scheme of IMP

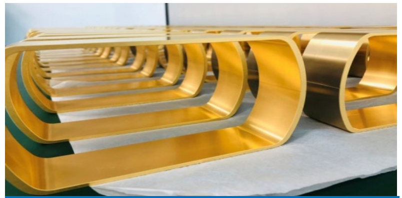


Thin-wall chamber supported by ceramic rings

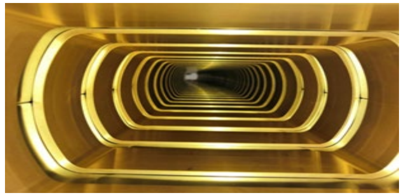


Cerium-stabilized Zirconia ceramics

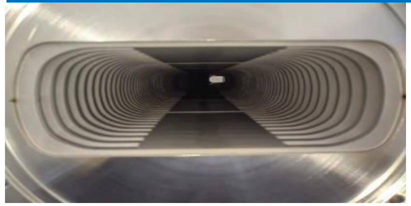




Ceramic rings with golden coating



3D-printed titanium alloy-CT4 cage

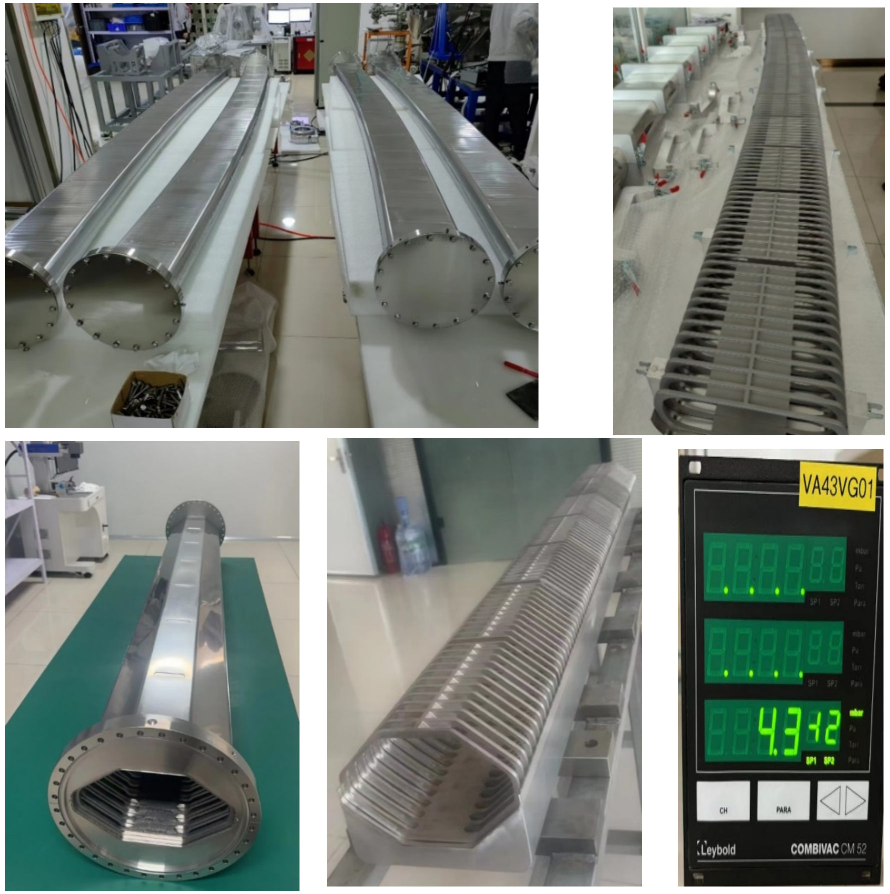


Advantages

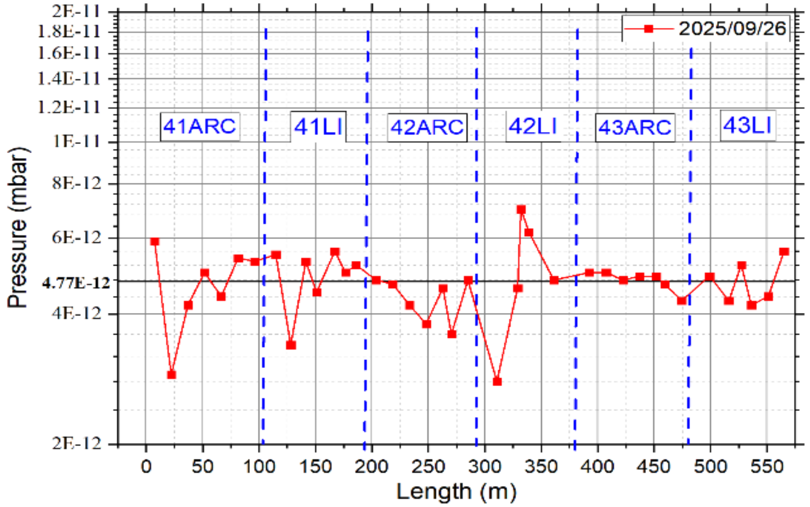
	Outgassing rate mbar·l/s·cm²	Yield strength MPa
Titanium alloy	**1.12×10^{-13}**	**910-960**
Zirconia ceramic	2.1×10^{-13}	380
stainless steel	5×10^{-13}	202

Thin-walled vacuum chamber

The world's largest extreme high vacuum (EHV) system for accelerator

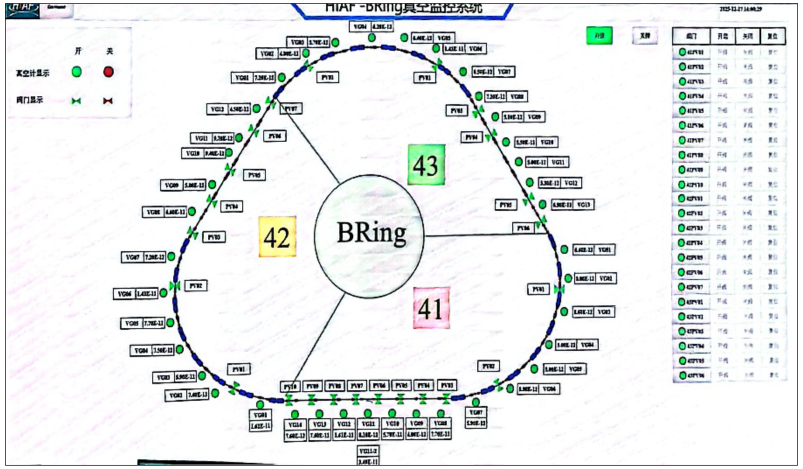


48 sets of bending and over 80 sets of quadrupole magnet chambers



Static average vacuum

4.7×10^{-12} mbar



Vacuum of high intensity Bi commissioning

1×10^{-11} ~ 5×10^{-12} mbar

Achieving the highest static vacuum level internationally

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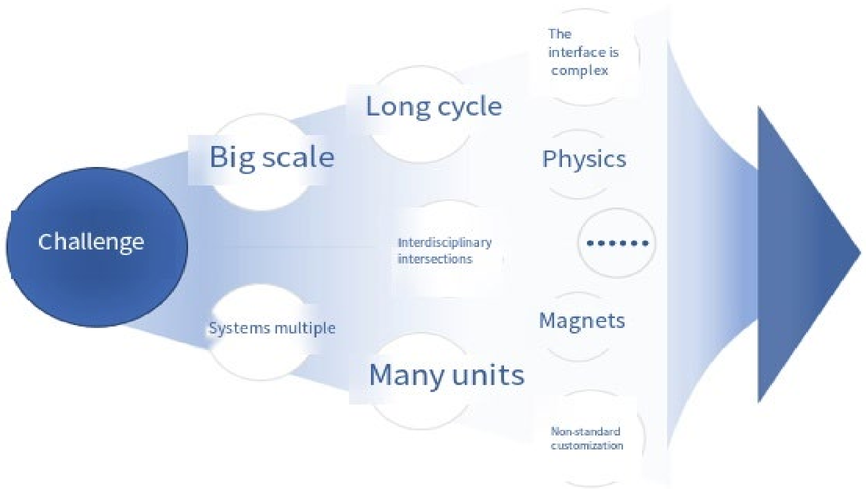
Project Construction

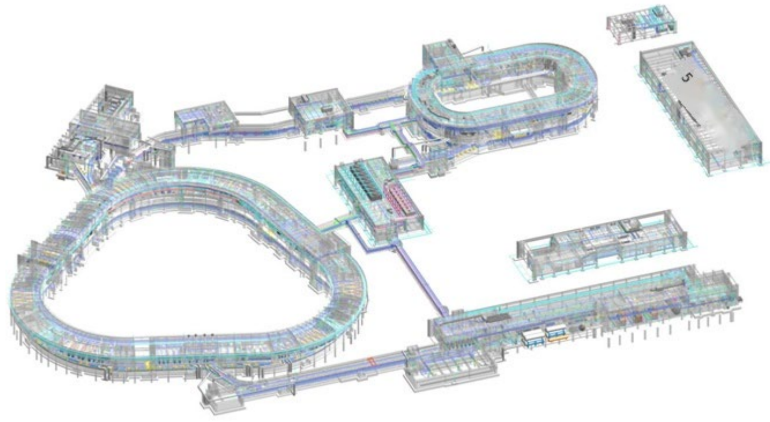
Digital Twins for high-quality and efficient construction of large scale scientific project



Digital twin driving construction

Create new models for engineering construction

Achieve a End-to-End Digital closed loop

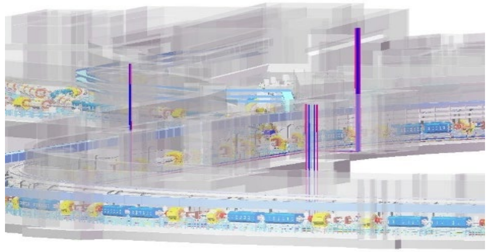


High intensity Heavy ion accelerator -HIAF

Digital Twin collaborative platform

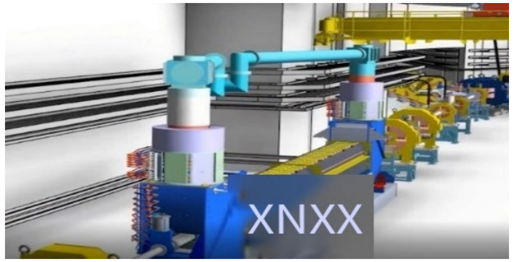
Design

The standardized design of non-standard equipment is rapidly iterated



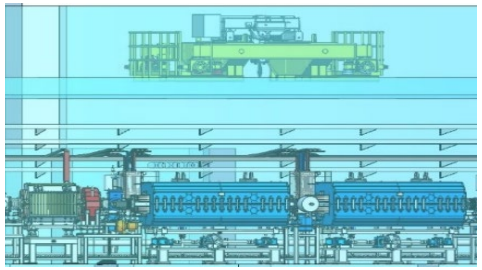
Manufacture

Digital-driven modular prefabrication boosts efficiency



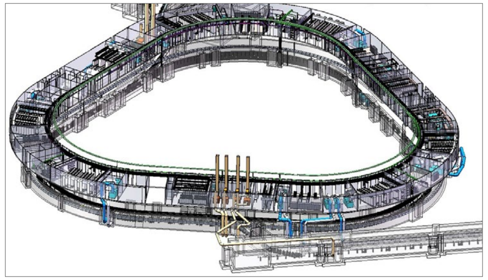
Installation

Three-dimensional virtual visualization of assembly optimization processes



Management

Full-chain data sharing for dynamic decision-making



Project Construction

Civil construction

Occupies **80 acres**, total construction area **58,000 m^2**,

BRing building

SRing building

Cryo center

Testing&Assembly hall

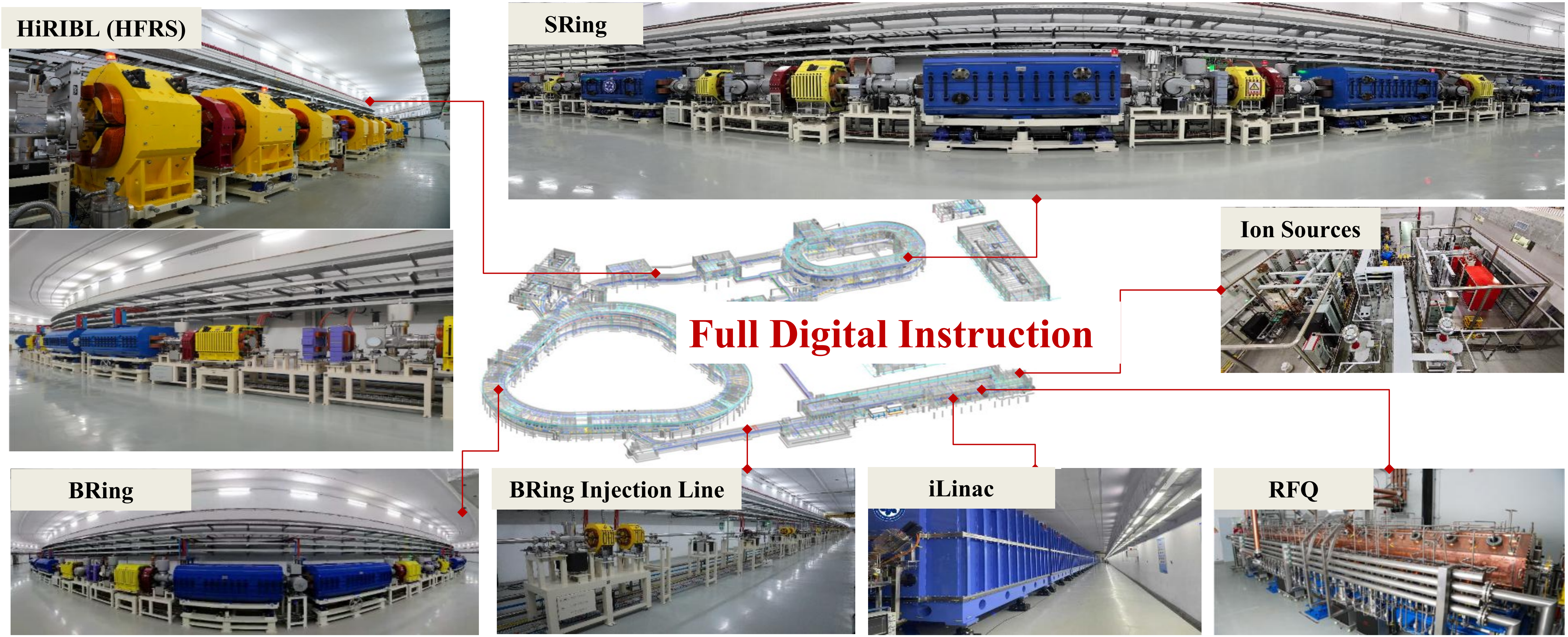
Linac building

Central control building

10 above-ground building and a 2-kilometer-long underground tunnel at a depth of 13 meters

Project Construction

Tunnel installation was completed in 8 months



The period for a 2-kilometer beam line has been shortened from 2-3 years to 8 months

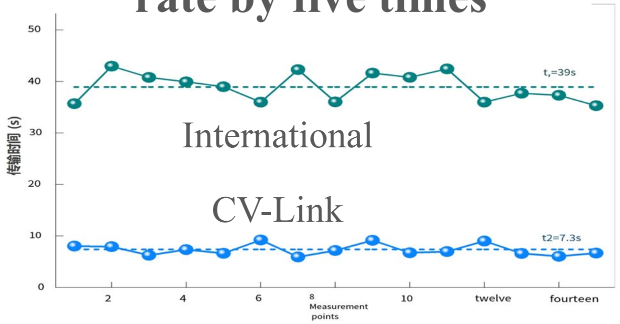
Beam Commissioning

AI-driven beam control software platform

A new full-stack intelligent software system for communication, control, storage, and analysis

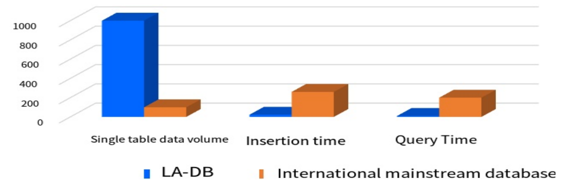
Internationally pioneering high-speed communication protocol CV-Link

Increase the transmission rate by five times



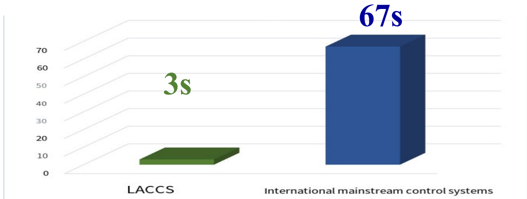
Innovative big data access and analytics LA-DB

Big data access speed is 10 times faster



High reliability distributed intelligent control system LACCS

Dynamic control performance is enhanced by 20 times



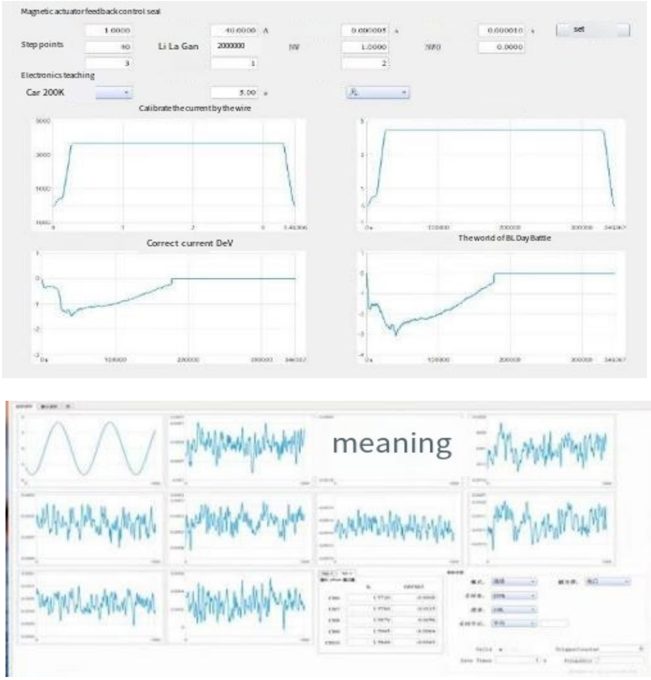
The entire chain guarantees the security of data for the accelerator's large scientific facility and core research experiments, with high performance

Beam Commissioning

HIAF implementation: integration and joint commissioning of 141 beam dynamics, 3,559 large-scale devices, and 230,000 control variables

LACCS
大型加速器集群控制

Full cover of all accelerator nodes

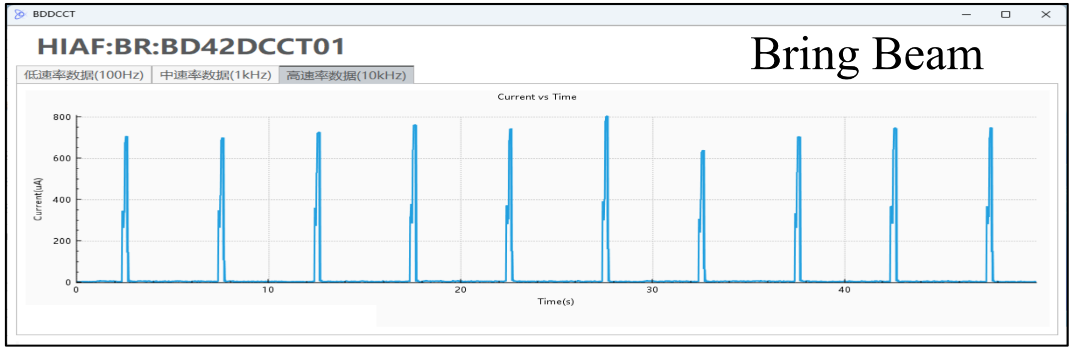


Implantation of beam dynamic operation

Achieve real-time online processing of large data, automatic control, and AI intelligent debugging for large accelerators

Beam Commissioning

The commissioning, including its 2-kilometer-long beamline, was completed in just 16 hours, setting a new speed record for large-scale scientific facilities



Heavy-ion Accelerator Fires Up

Heavy-ion accelerator fires up

An accelerator that will produce the world's most intense pulses of heavy ions generated its first beam on 28 October. When fully operational, China's High Intensity heavy-ion Accelerator Facility (HIAF), nestled among the mountains of southern Guangdong province, will send pulses of exotic, short-lived ions into fixed targets or into a storage ring to support research on the properties of atomic nuclei and how stars forge heavy elements, as well as material sciences and biomedicine. The research center, which joins the ranks of similar facilities worldwide, represents a $420 million investment by the Chinese Academy of Sciences's Institute of Modern Physics. Institute officials say HIAF will be open to foreign researchers. —Dennis Normile

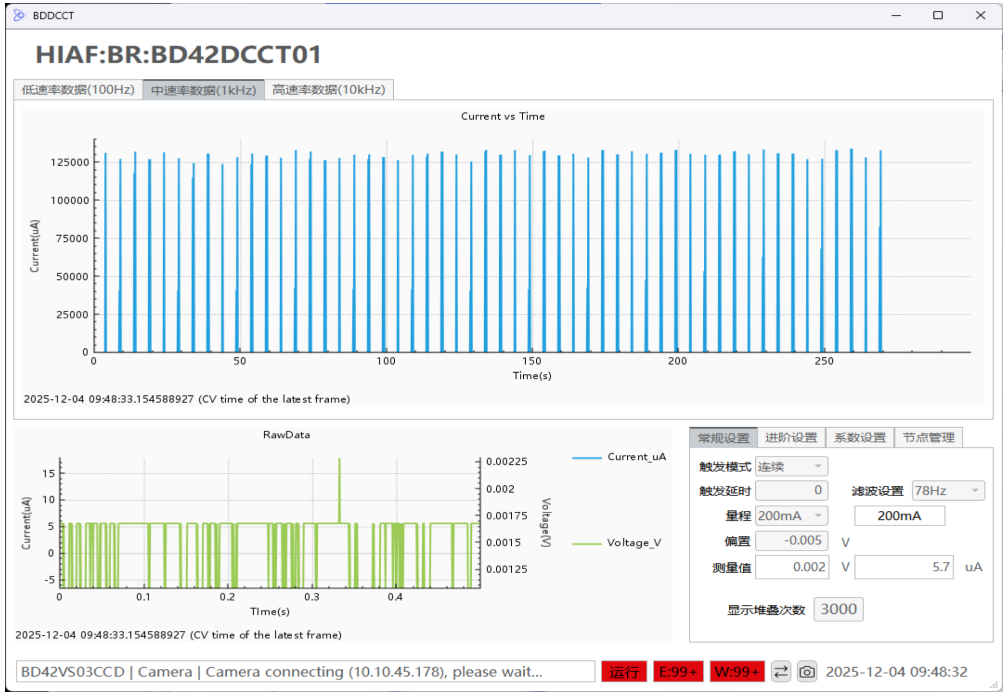
Science, 6 NOVEMBER 2025, P.559

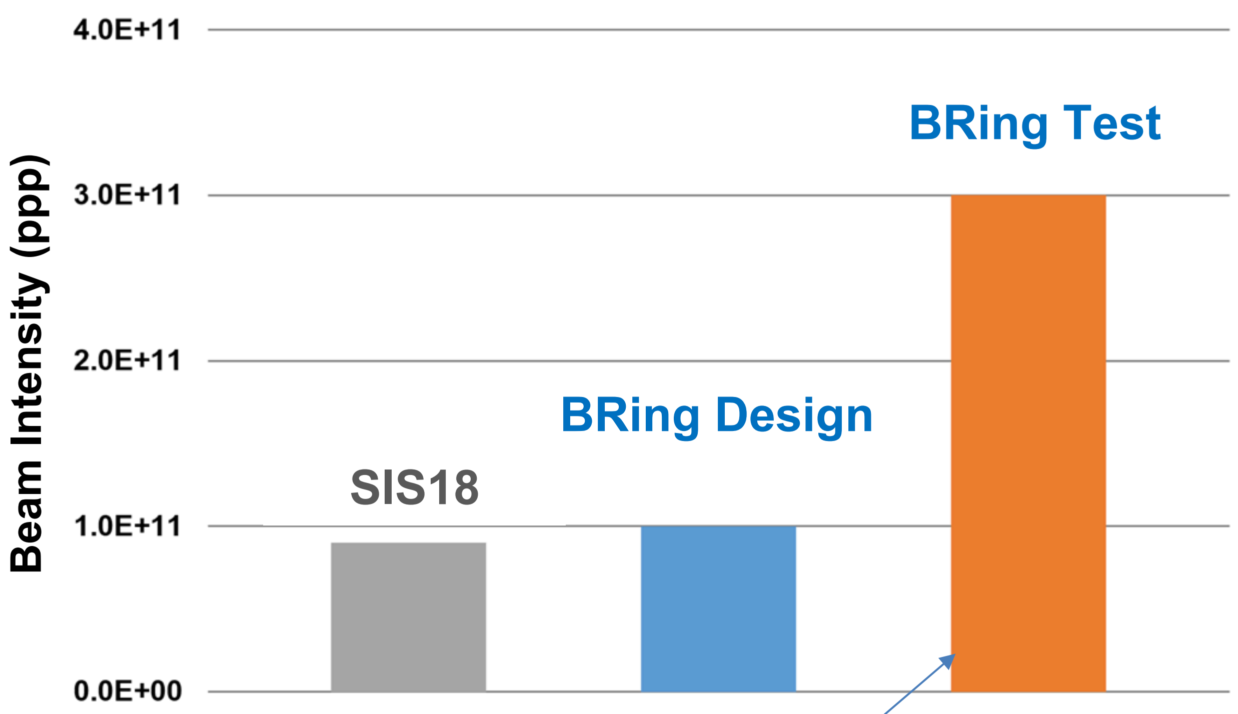
Science **magazine promptly reported the successful commissioning**

Beam Commissioning

Typical nonmetallic ions ^{18}O

New High Energy ^{18}O Beam Intensity Record



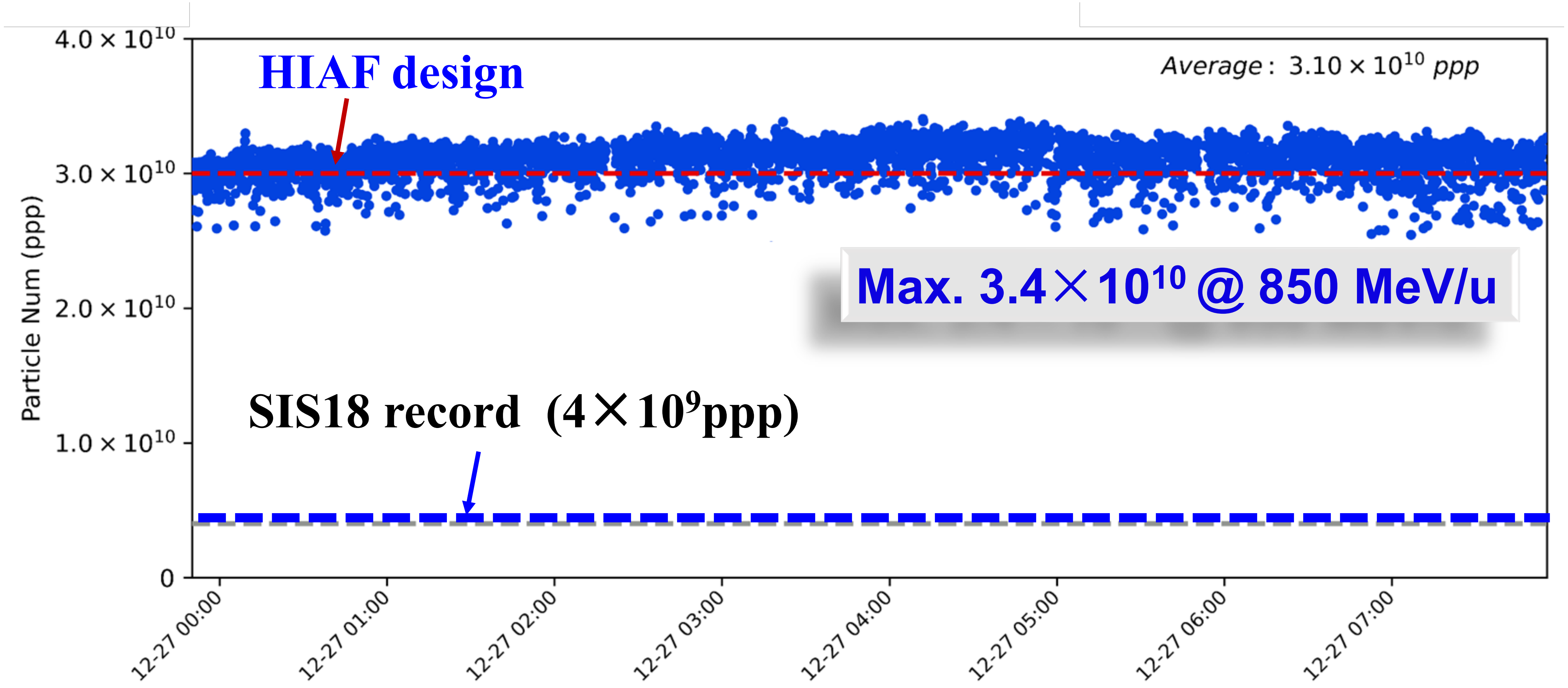


Max. 3.0×10^{11}@2.6 GeV/u

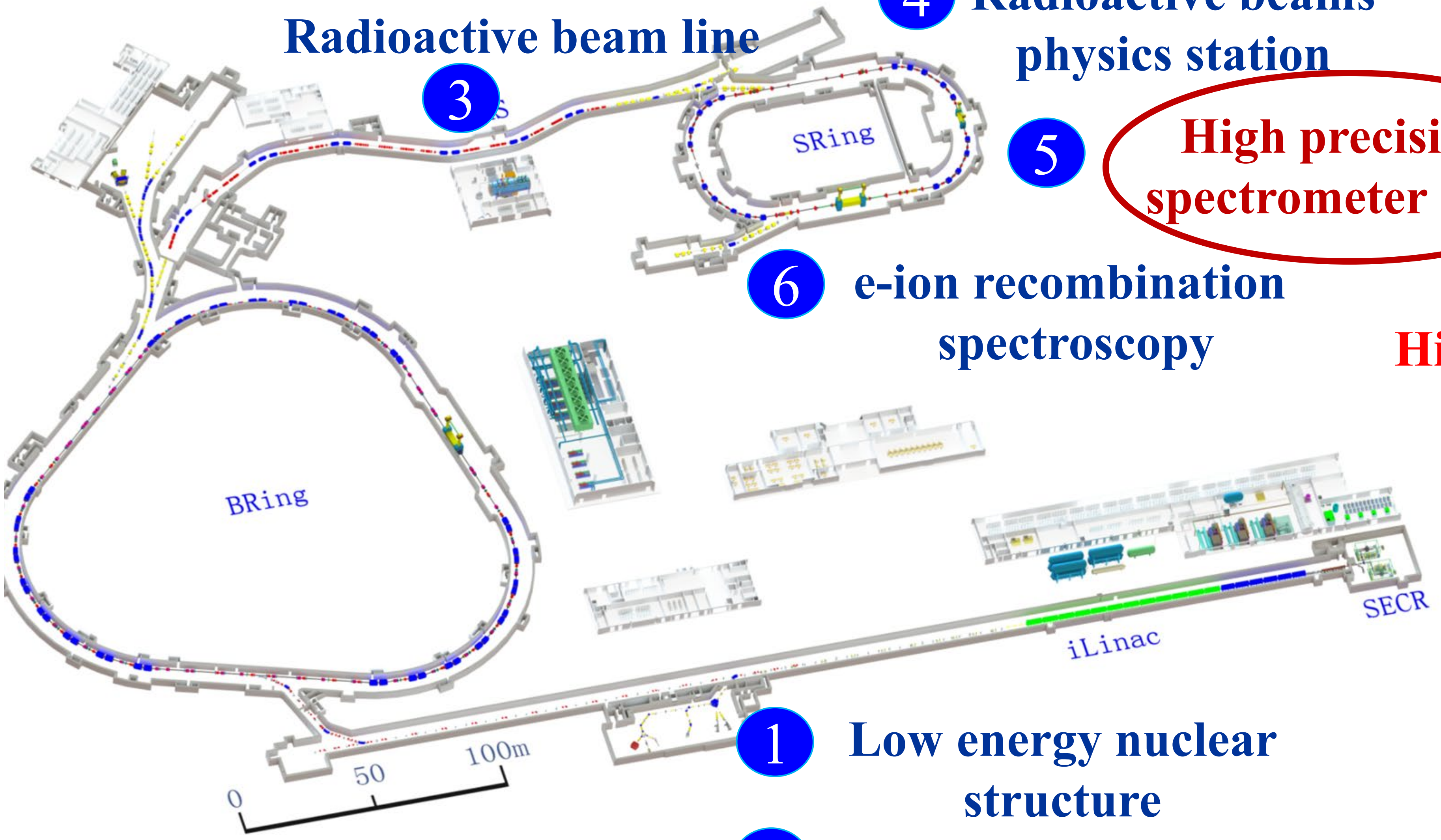
Beam Commissioning

Typical metallic ions ^{209}Bi

New High Energy ^{209}Bi Beam Intensity Record



Pilot experiments



3 Radioactive beam line

4 Radioactive beams physics station

5 High precision spectrometer ring

High precision mass measurement

6 e-ion recombination spectroscopy

1 Low energy nuclear structure

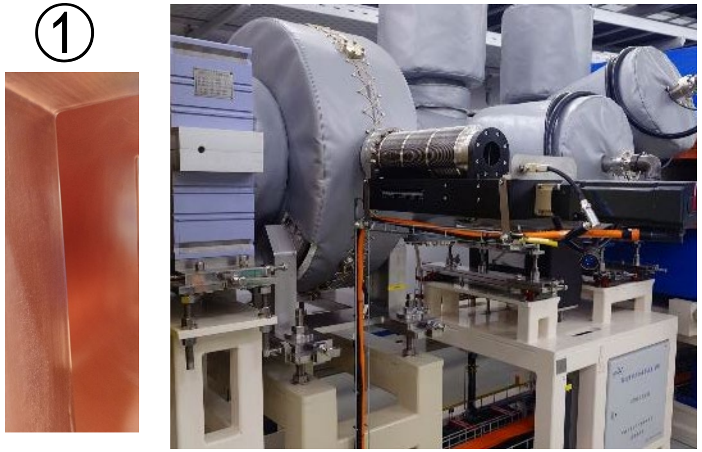
2 Irradiation terminal

High precision mass measurement

Schottky mass spectrometry

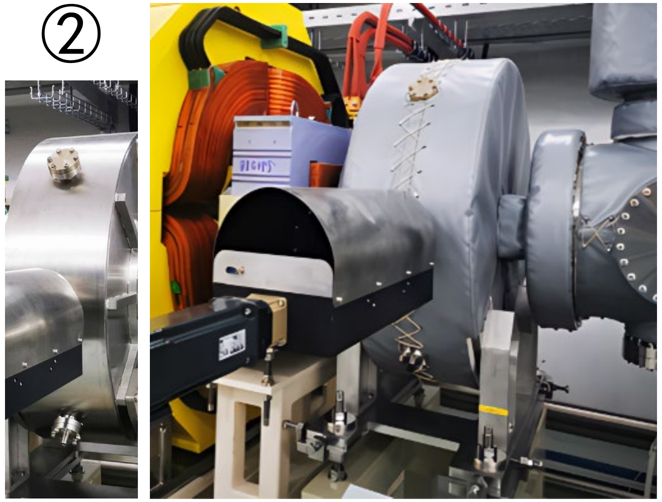
Isochronous mode with TOF

①

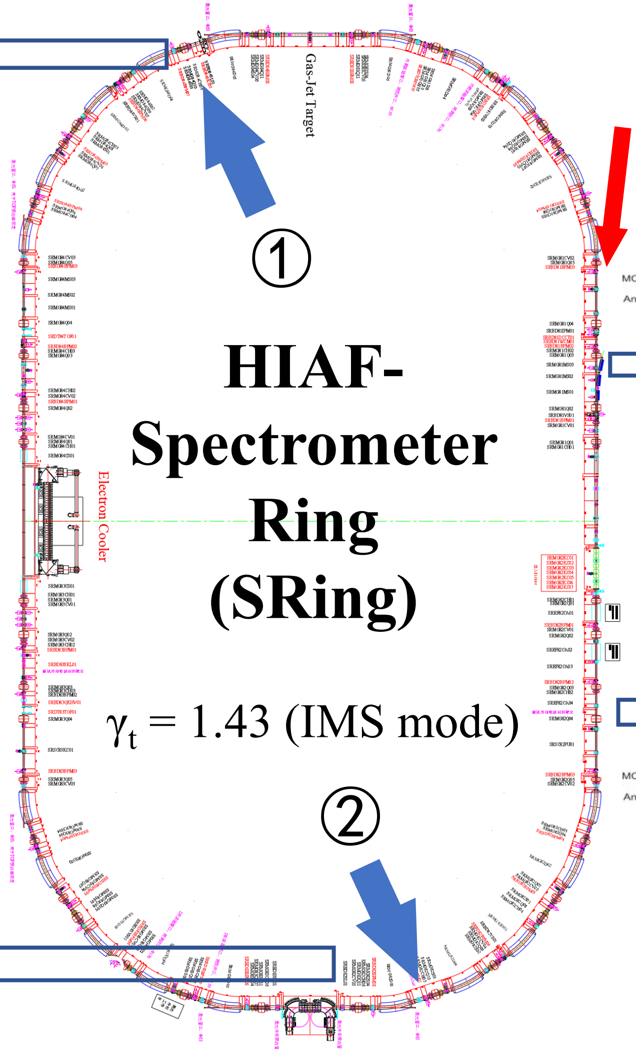


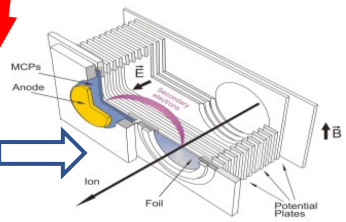
Copper-coated

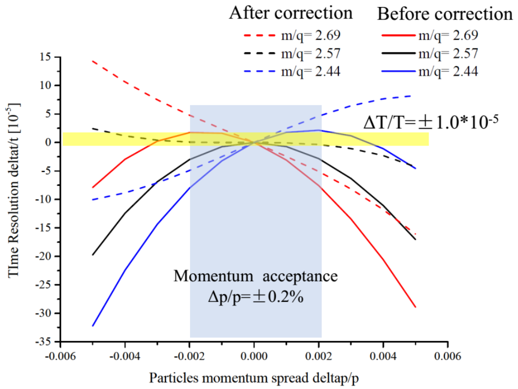
②

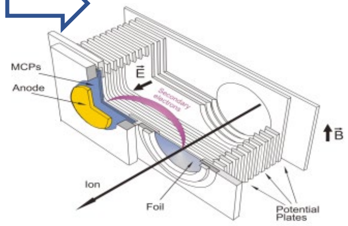


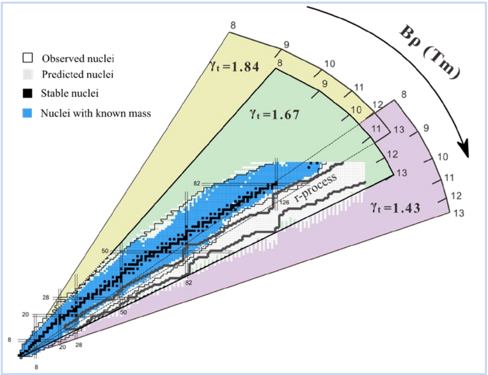
Stainless-steel cavities







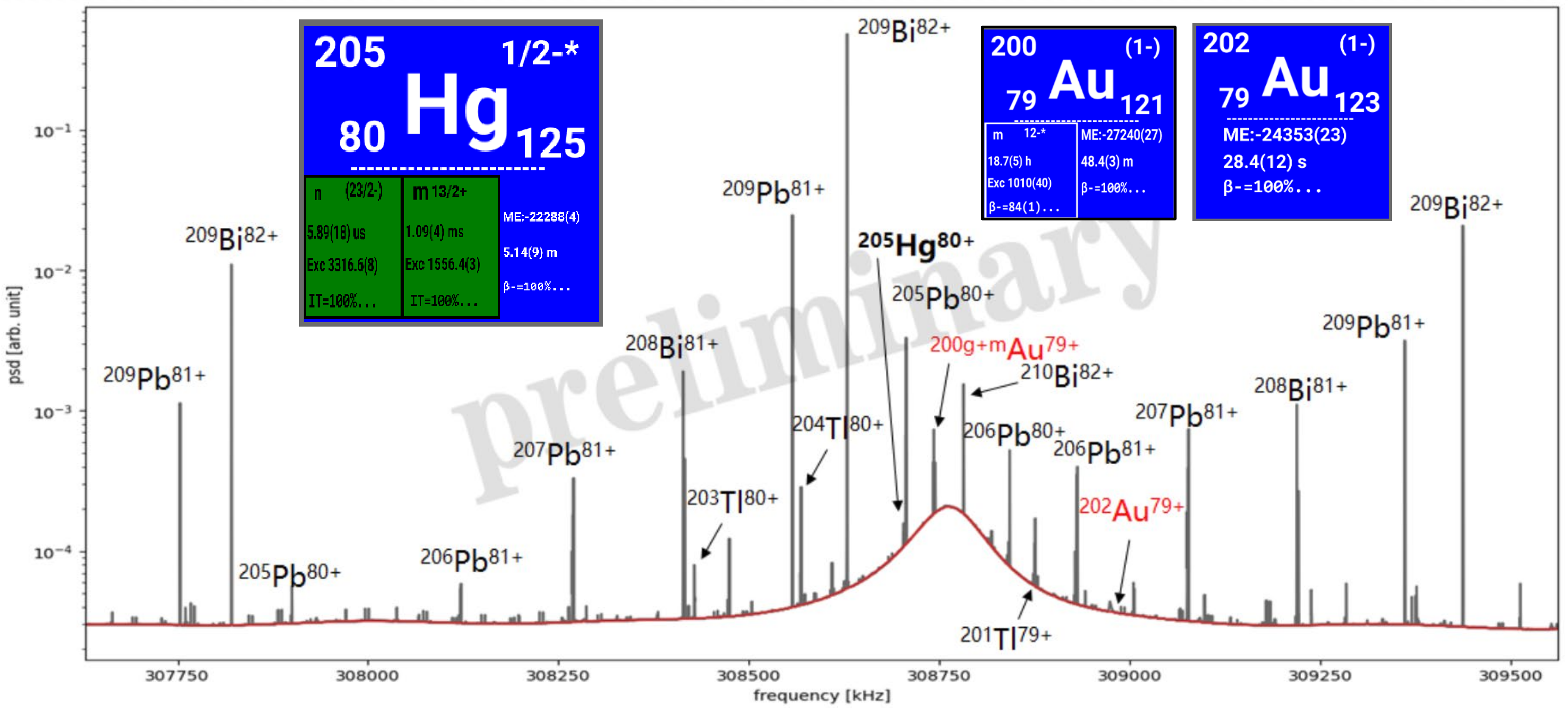




$\Delta M/M \sim 10^{-7}$-10^{-8}

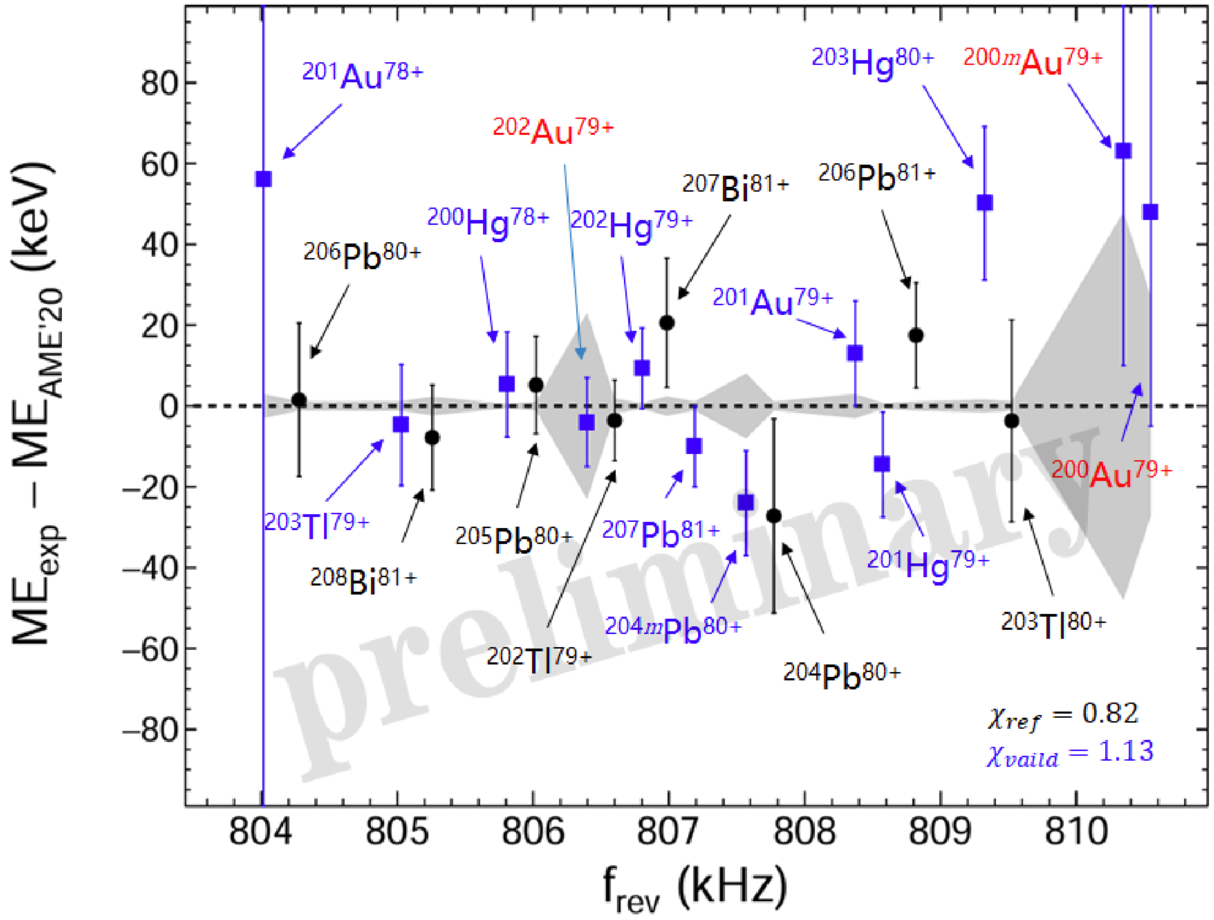
High precision mass measurement

$^{209}Bi^{35+}$ ~546 MeV/u , 1e10 ppp every 3 seconds， 10mm-Graphite target



High precision mass measurement

The highest precision of isochronous mass measurement



$$\frac{\sigma(m)}{m} \sim \frac{11\,keV}{202\,u} \sim 5.8 \times 10^{-8}$$

ME (^{202}Au)exp = -24357 keV ± 11 keV

ME(^{202}Au)AME = -24353 keV ± 23 keV

The highest precision

$$\frac{\sigma(m)}{m} \sim \frac{11\,keV}{202\,u} \sim 5.8 \times 10^{-8}$$

A major leap: $\sim 10^{-7}$ → $\sim 10^{-8}$

Summary and perspective

Every challenge is an opportunity to innovate !!!

Production

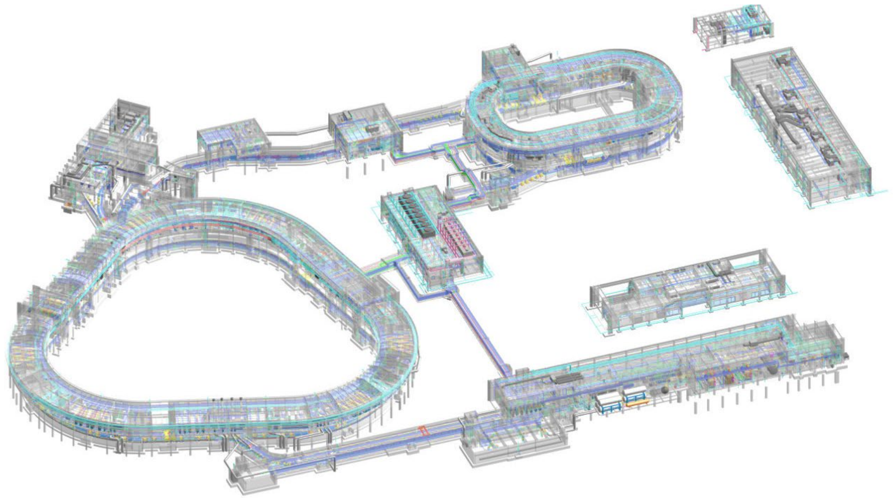
4th generation ECR
SFR Lianc

Accumulation

Dual-plane painting injection

Acceleration

The highest ramping rate 12T/s



Construction

Digital twin drives construction

Commissioning

AI-driven control software platform

High quality and efficiency

World leading level beam intensity

Summary and perspective

New Records Achieved

Tunnel installation – **Fastest completion of tunnel assembly**

Beam commissioning – **Shortest time from first beam to design parameters.**

Beam intensity

Bi (bismuth) ions: 8× increase

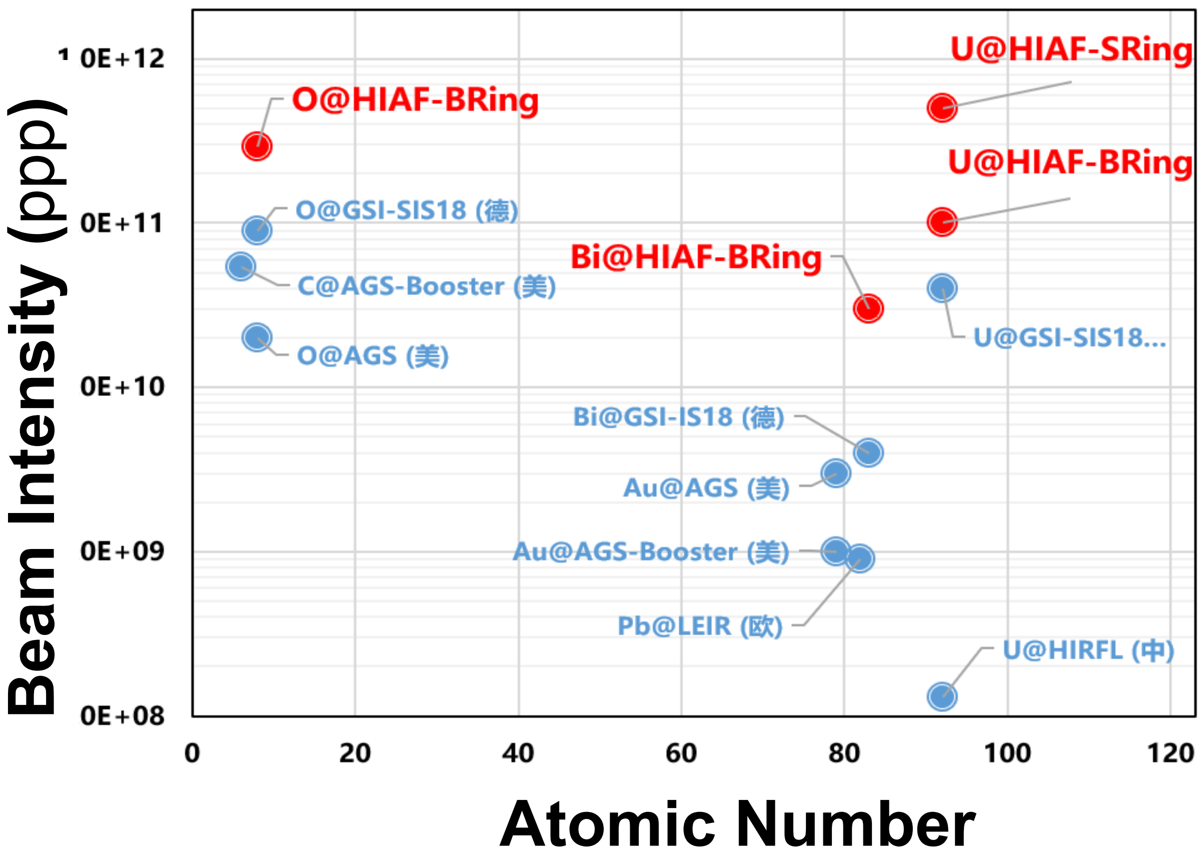
O (oxygen) ions: 3× increase

Mass measurement precision – **Highest precision achieved for short-lived nuclei** (uncertainty reduced to $\delta m/m \sim 10^{-8}$ range)

Summary and perspective

Ongoing efforts are focused on

- Beam dynamics study and machine performance improvement
- New techniques implementation for higher intensity
- Reliable and high efficiency operation for Users



World first class performance for researchers worldwide

We appreciate the strong collaboration and support from the international scientific community during the construction of the HIAF

Thanks for your attention!