Status & challenges of HIAF project

He Zhao

On behalf of the HIAF project group

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

Outline

1. General information of the HIAF
2. High intensity beam dynamics studies
3. Key technical challenges and R&D
4. Experimental terminals
5. Conclusion

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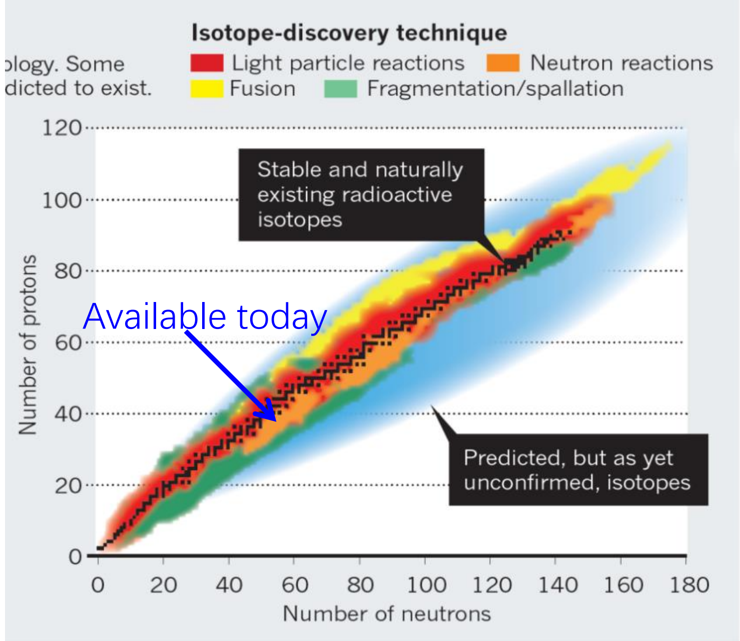
High-Intensity Heavy Ion Accelerator Facility-HIAF

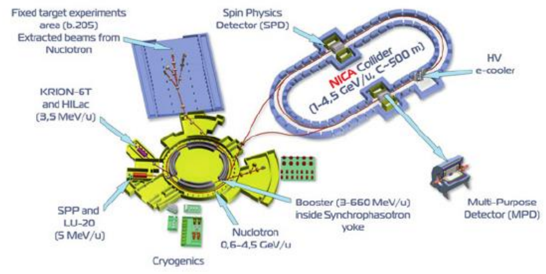
Next-generation high intensity facilities are required for advances in nuclear physics and related research fields:



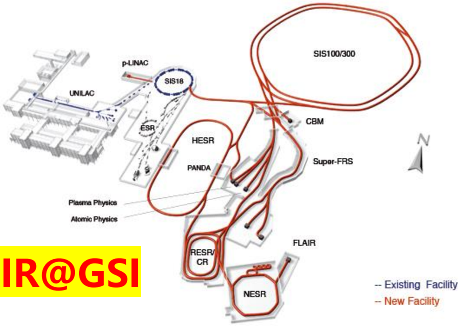
Fascinating and crucial questions

- To explore the limit of nuclear existence
- To study exotic nuclear structure
- Understand the origin of the elements

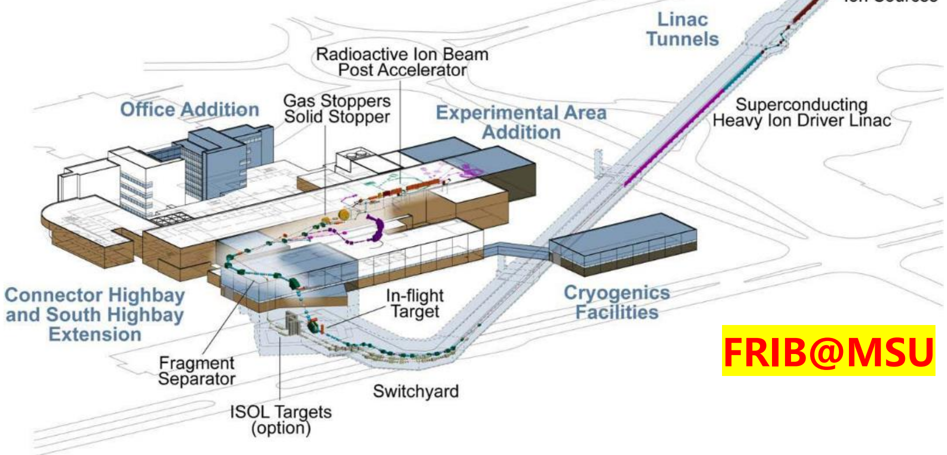
- To study the properties of High-Energy-Density Matter



NICA@JINR



FAIR@GSI



FRIB@MSU

Next-generation facilities are being constructed

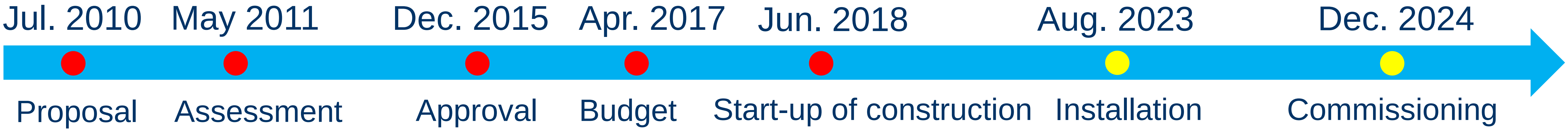
- FAIR at GSI in Darmstadt, Germany
- FRIB at MSU in the U.S.
- NICA at JINR, Dubna, Russia
- HIAF at IMP, China

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



Jul. 2010	May 2011	Dec. 2015	Apr. 2017	Jun. 2018	Aug. 2023	Dec. 2024
Proposal	Assessment	Approval	Budget	Start-up of construction	Installation	Commissioning

Project Manager:

Guo-Qing Xiao

Deputy Manager:

Hong-Wei Zhao, Jia-Wen Xia, Xiao-Hong Zhou

Chief Engineer:

Jian-Cheng Yang

Deputy Chief Engineer:

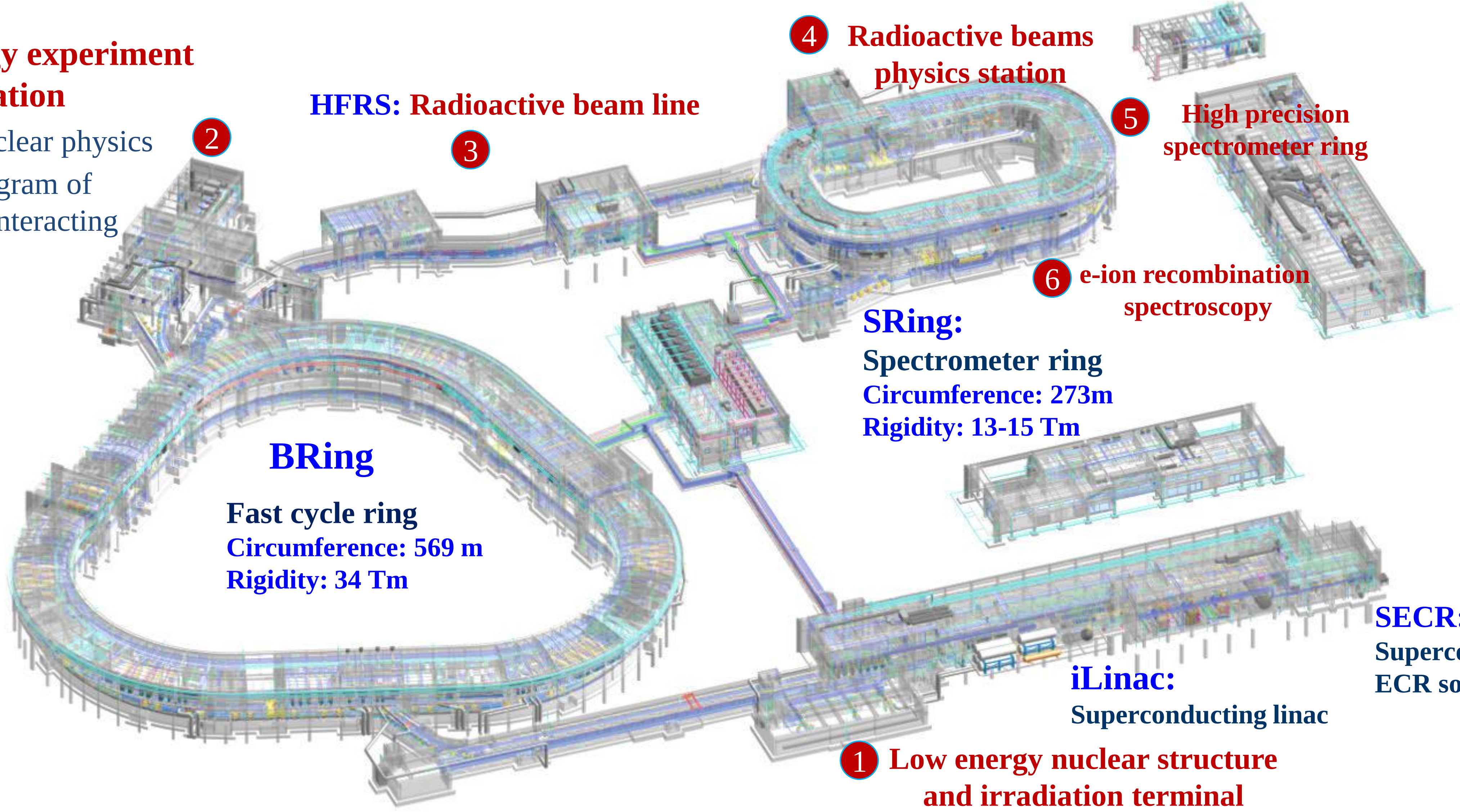
Liang-Ting Sun, Li-Jun Mao

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

Accelerator components and experiment terminals



High energy experiment station

- Hyper nuclear physics
- Phase diagram of strongly interacting matter

② **HFRS: Radioactive beam line**

③

④ **Radioactive beams physics station**

⑤ **High precision spectrometer ring**

⑥ **e-ion recombination spectroscopy**

SRing:
Spectrometer ring
Circumference: 273m
Rigidity: 13-15 Tm

BRing

Fast cycle ring
Circumference: 569 m
Rigidity: 34 Tm

SECR:
Superconducting ECR source

iLinac:
Superconducting linac

① **Low energy nuclear structure and irradiation terminal**

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)**

High-Intensity Heavy Ion Accelerator Facility-HIAF

- **HIAF main parameters**

More typical beams

BRing

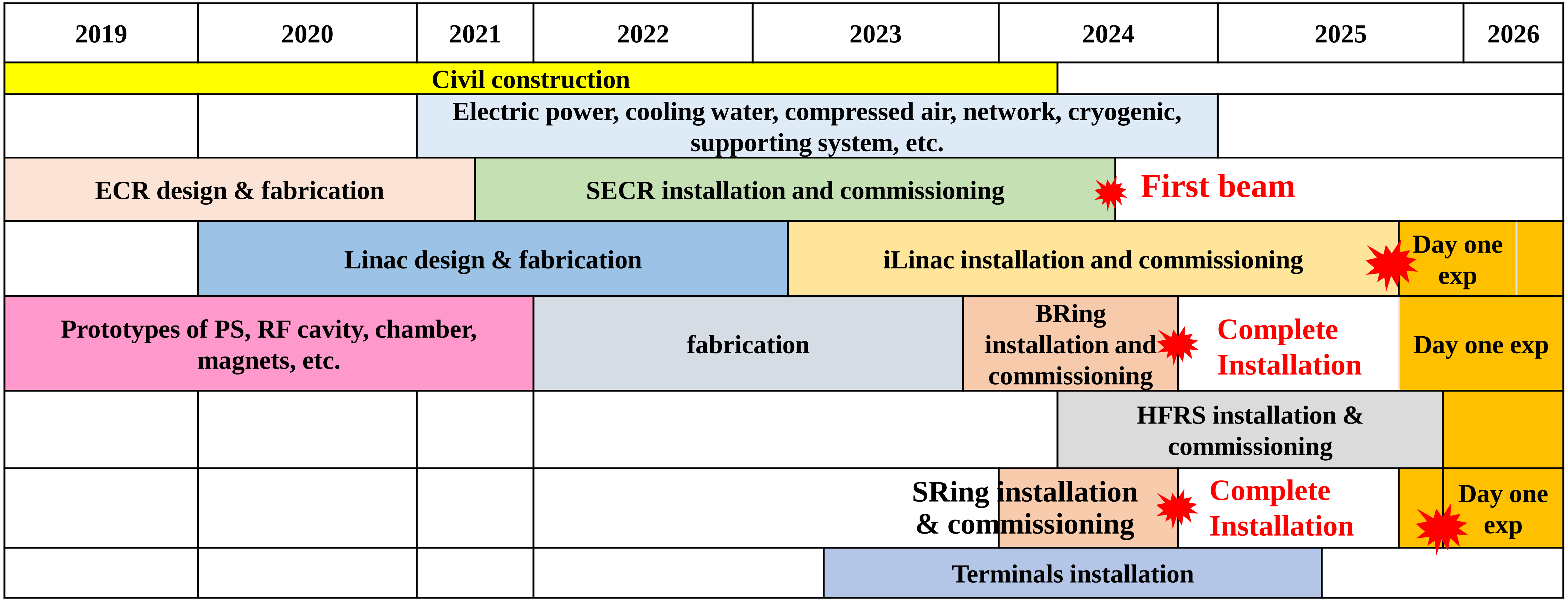
Rigidity	34Tm，fr=3Hz	
Ion	Intensity (ppp)	Energy (GeV/u)
$^{238}U^{35+}$	2.0×10^{11}	0.84
$^{238}U^{76+}$	5.0×10^{10}	2.5
$^{129}Xe^{27+}$	3.6×10^{11}	1.4
$^{78}Kr^{19+}$	5.0×10^{11}	1.7
$^{40}Ar^{12+}$	7.0×10^{11}	2.3
$^{18}O^{6+}$	8.0×10^{11}	2.6
p	5.0×10^{13}	9.3

SRing

Rigidity	15 Tm	
Ion	Intensity (ppp)	Energy (GeV/u)
$^{238}U^{92+}$	$(1-5)\times10^{11}$	1.1
$^{129}Xe^{54+}$	$3.6\times5\times10^{11}$	1.2
$^{78}Kr^{36+}$	$5.0\times5\times10^{11}$	1.3
$^{40}Ar^{18+}$	$7.0\times5\times10^{11}$	1.3
$^{18}O^{8+}$	$8.0\times5\times10^{11}$	1.3
p	$2.0\times5\times10^{13}$	3.5

High-Intensity Heavy Ion Accelerator Facility-HIAF

HIAF construction time schedule

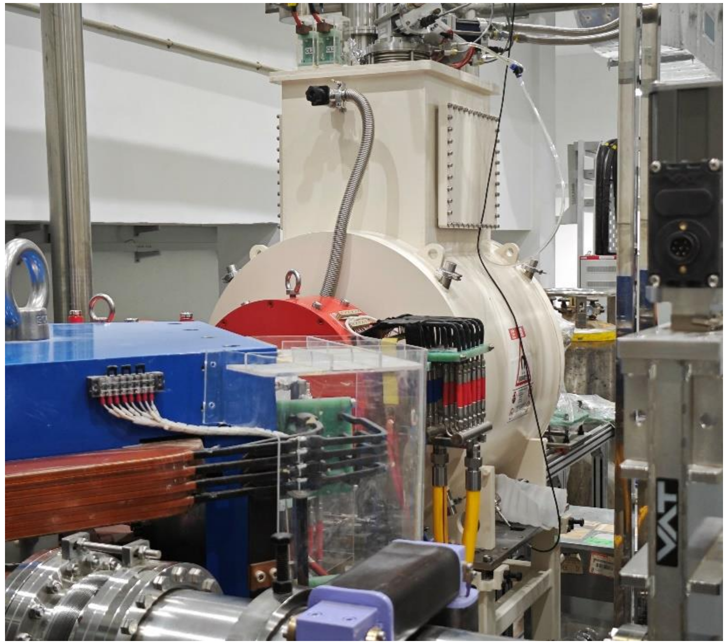


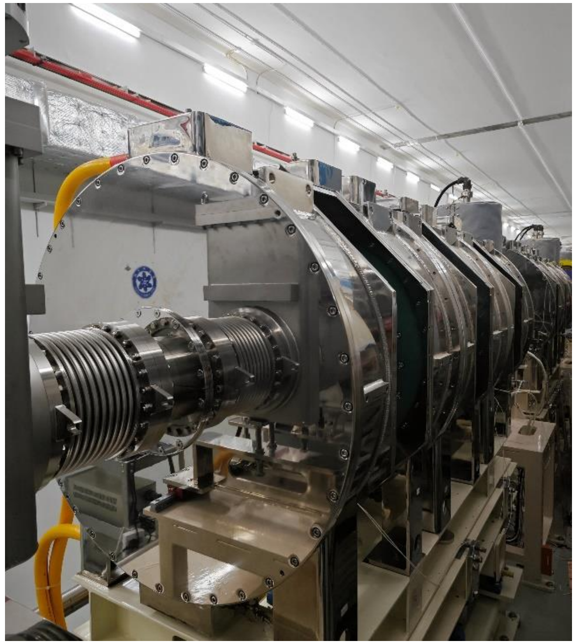
2019	2020	2021	2022	2023	2024	2025	2026
Civil construction							
		Electric power, cooling water, compressed air, network, cryogenic, supporting system, etc.					
ECR design & fabrication		SECR installation and commissioning			First beam		
	Linac design & fabrication			iLinac installation and commissioning		Day one exp	
Prototypes of PS, RF cavity, chamber, magnets, etc.			fabrication	BRing installation and commissioning	Complete Installation	Day one exp	
					HFRS installation & commissioning		
				SRing installation & commissioning	Complete Installation	Day one exp	
				Terminals installation			

- ➢ 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-**I**ntensity Heavy Ion **A**ccelerator **F**acility-**HIAF**

High-Intensity Heavy Ion Accelerator Facility-HIAF





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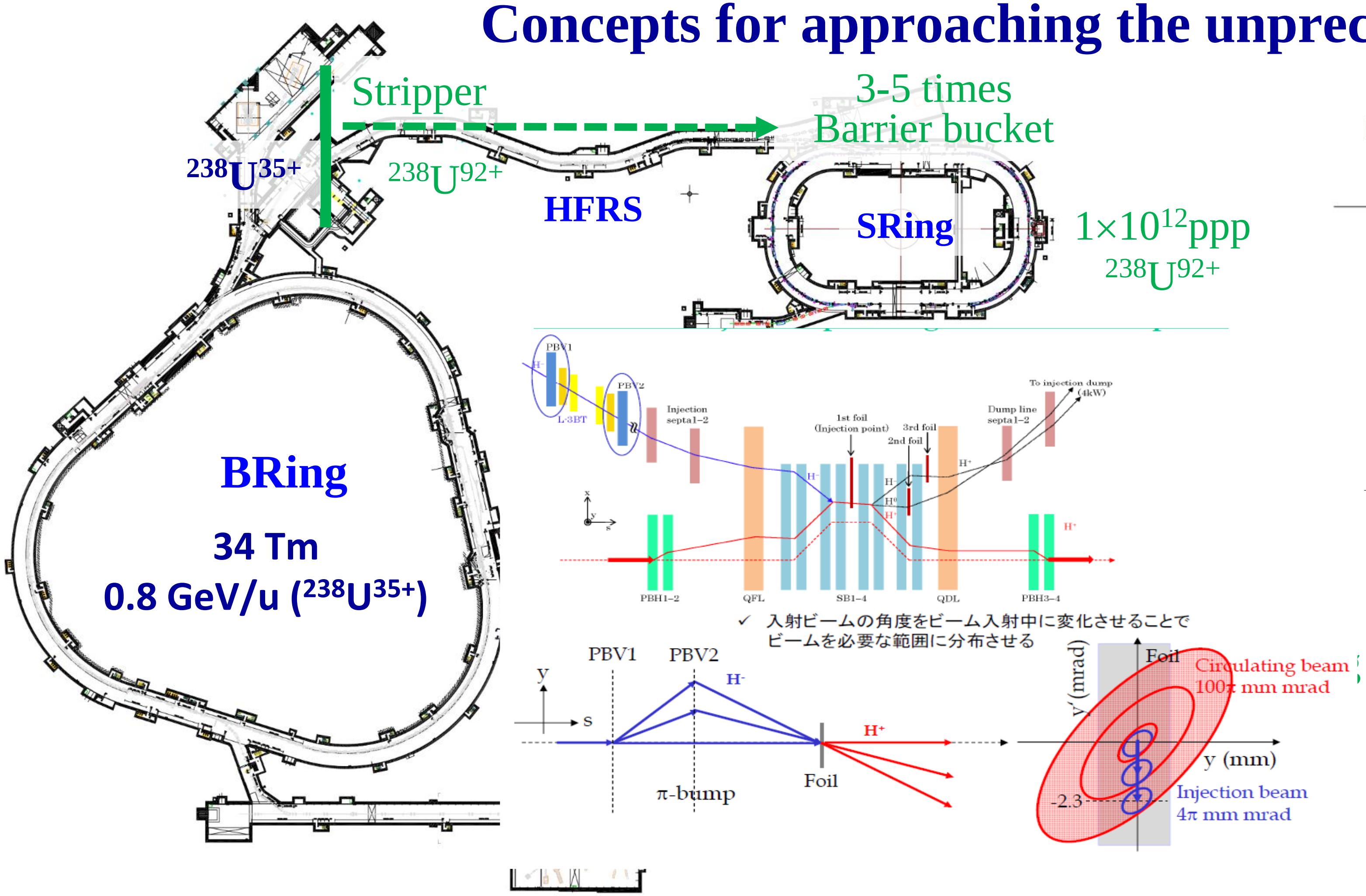
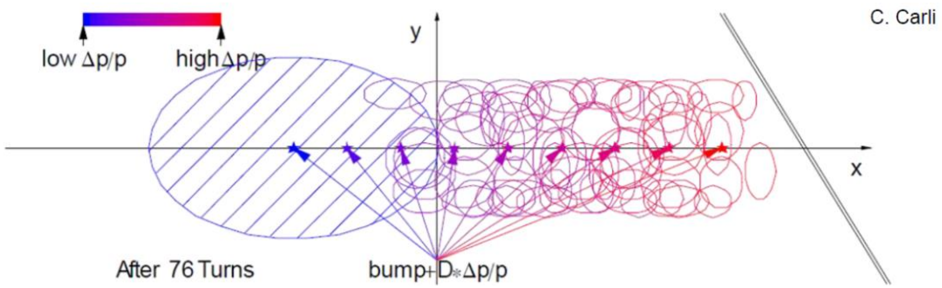
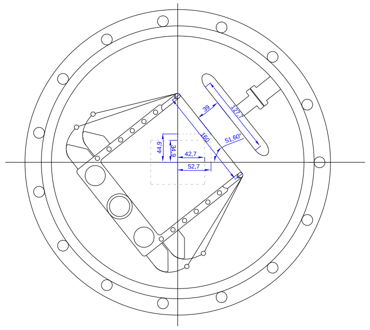
High intensity beam dynamics studies

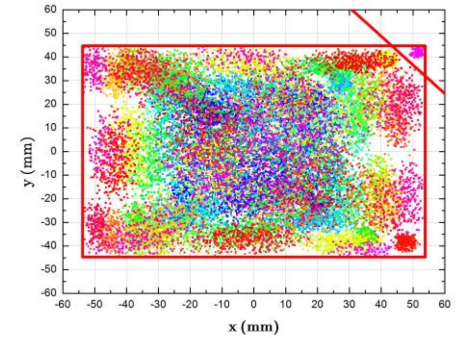
Concepts for approaching the unprecedented heavy ion intensity



✓ 入射ビームの角度をビーム入射中に変化させることで
ビームを必要な範囲に分布させる







Ions	Plane	Injection Turns	Single injection
$^{238}\mathrm{U}^{35+}$	H	33	3.3×10^{10}
	V	16	1.6×10^{10}
	H+V	**150**	$\mathbf{2.0\times10^{11}}$

High current superconducting linac

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

45 GHz superconducting ECR

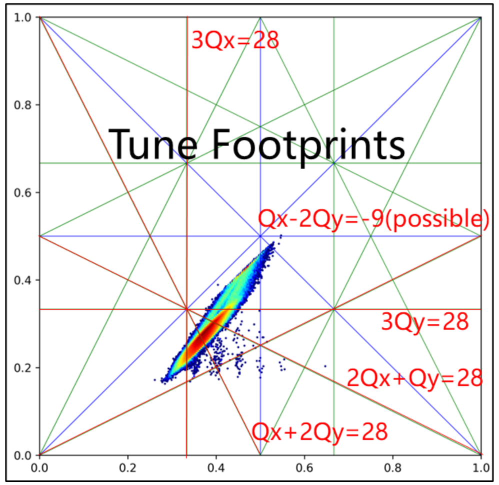
- Pulsed 50 pμA U^{35+}, U^{4x+}
- CW 20 pμA U^{35+}
- 14 KeV/u

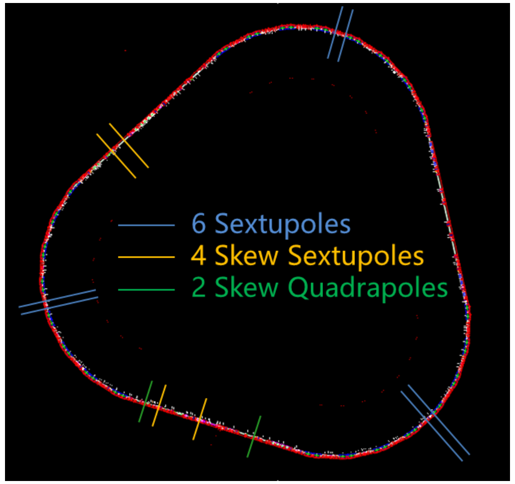
2.0×10^{11} with two planes painting, **nearly 10 times over the conventional single-plane injection.**

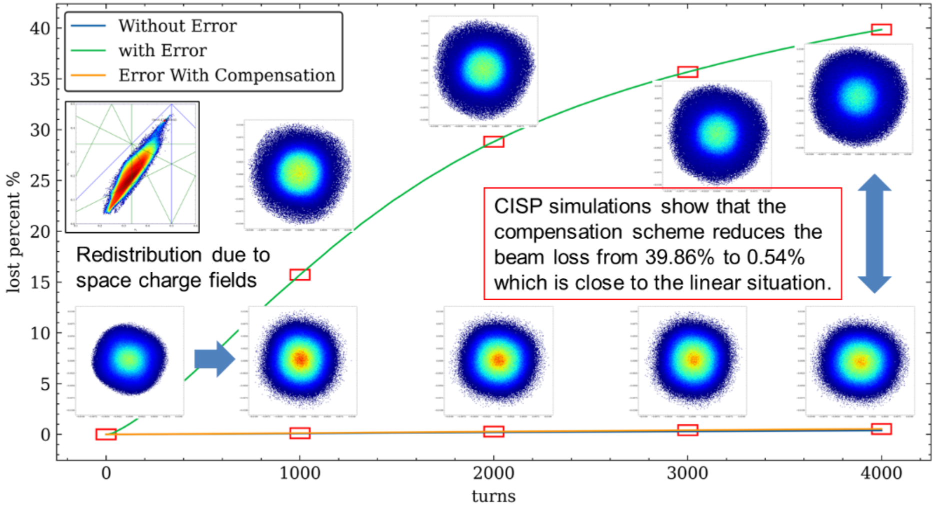
Nonlinearity and Space Charge

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**



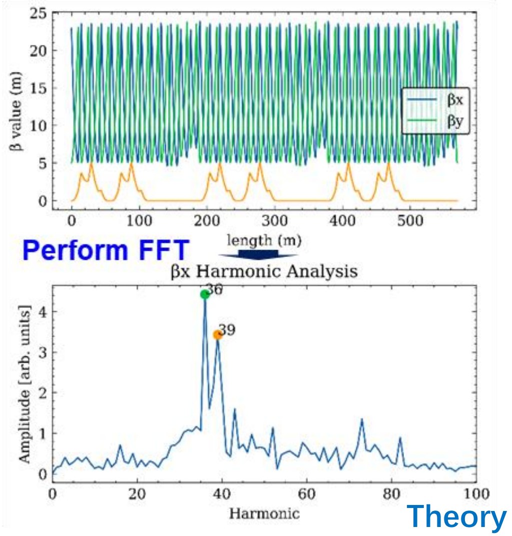


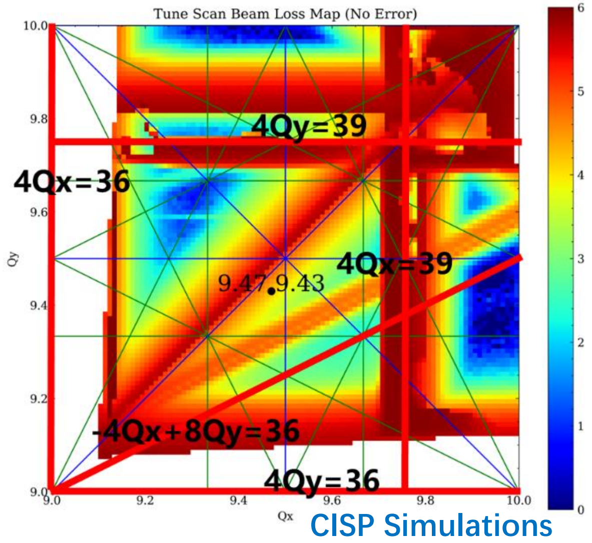


Redistribution due to space charge fields

CISP simulations show that the compensation scheme reduces the beam loss from 39.86% to 0.54% which is close to the linear situation.

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

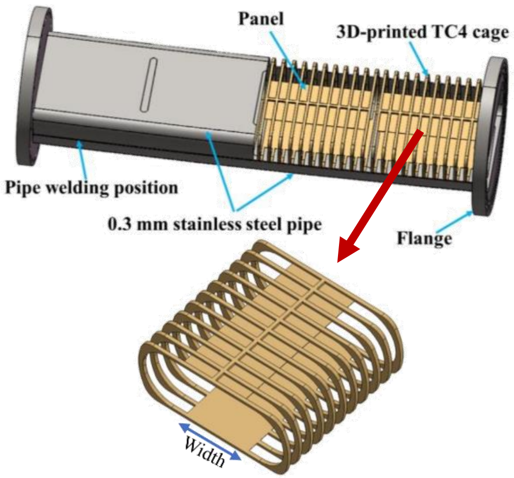


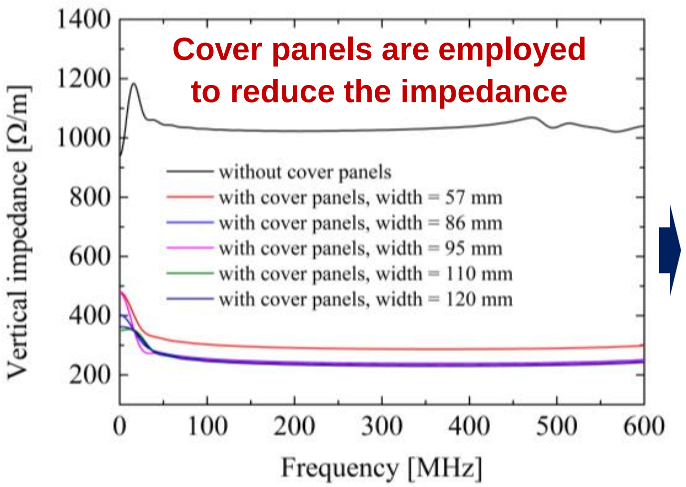


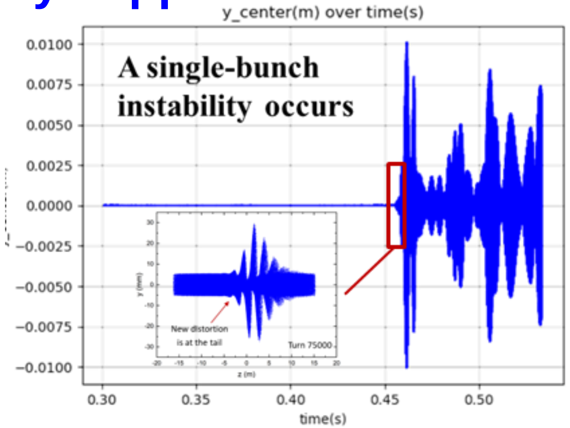
- **Structural resonances mQ_x+nQ_y = 36 or 39** could be driven by space charge fields in the HIAF given by the theory, which is completely verified by the CISP-GPU simulations.
- Work point **stay away from the red area;** correction scheme **is under investigation**

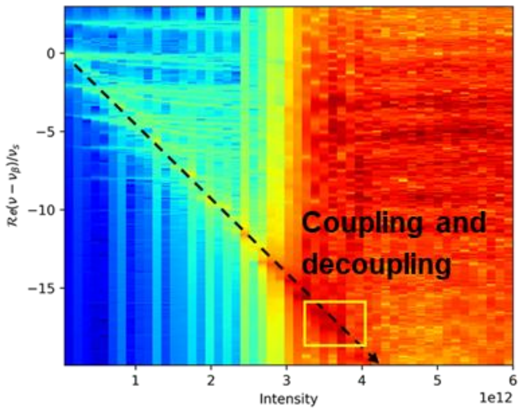
Collective Instabilities

- 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**




Cover panels are employed to reduce the impedance

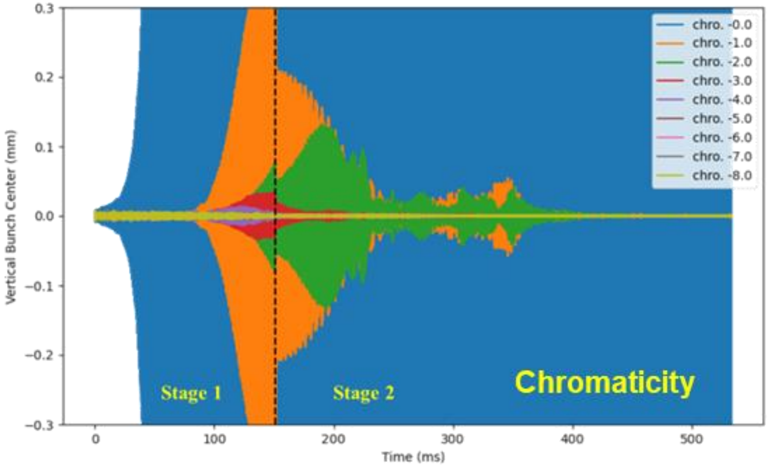

A single-bunch instability occurs

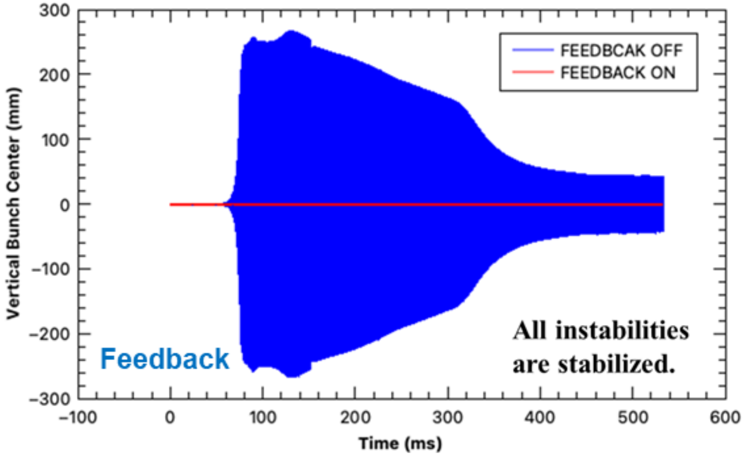

Coupling and decoupling

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


Chromaticity


Feedback

All instabilities are stabilized.

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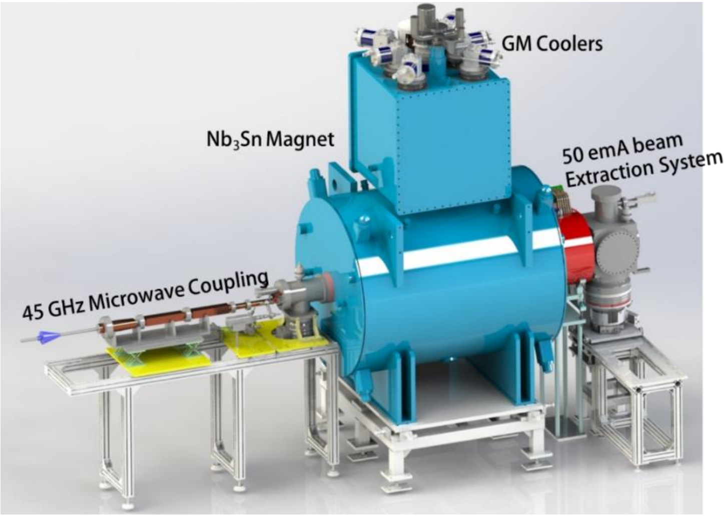
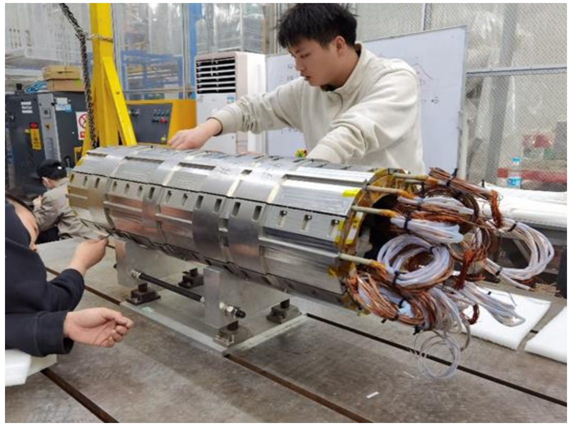
45 GHz superconducting ECR ion source

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

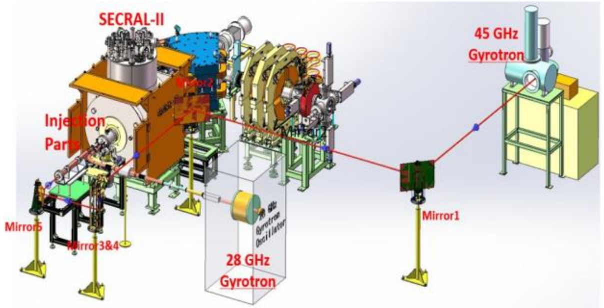


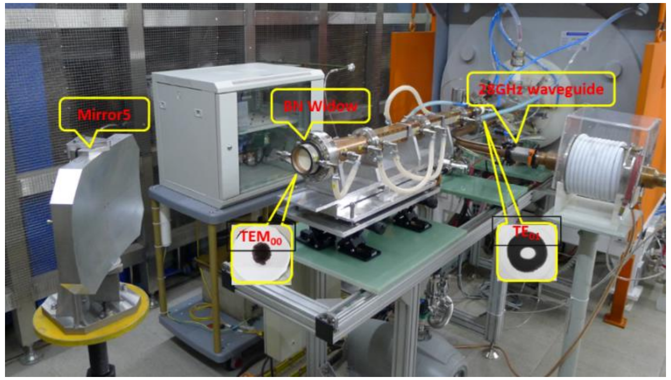
Coils integration

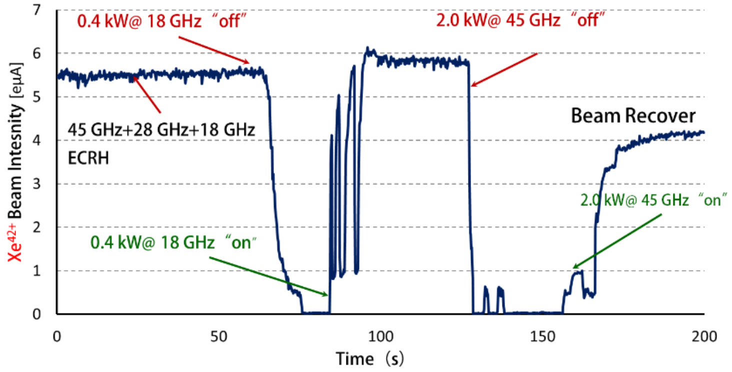
Full-sized cold mass

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

- 45 GHz microwave coupling



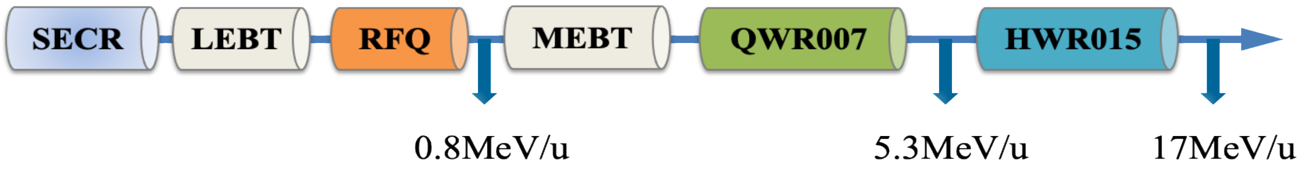




45GHz/20kW microware transmission system based on the quasi-optical design, ECR plasma with 45GHz microwave has been tested with exiting SECRAL2 ion source. The first beam at 45 GHz is expected in 2024

High current superconducting ion linac - iLinac

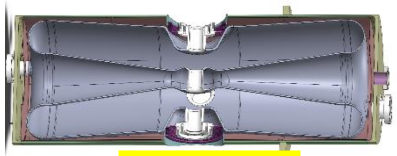
➢ iLinac



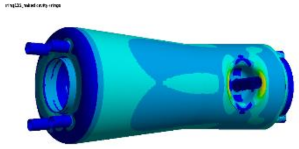
- **Pulsed, 28 pμA U^{35+}**
- **CW, 15 pμA U^{35+}**

To BRing or Terminal 1

RFQ

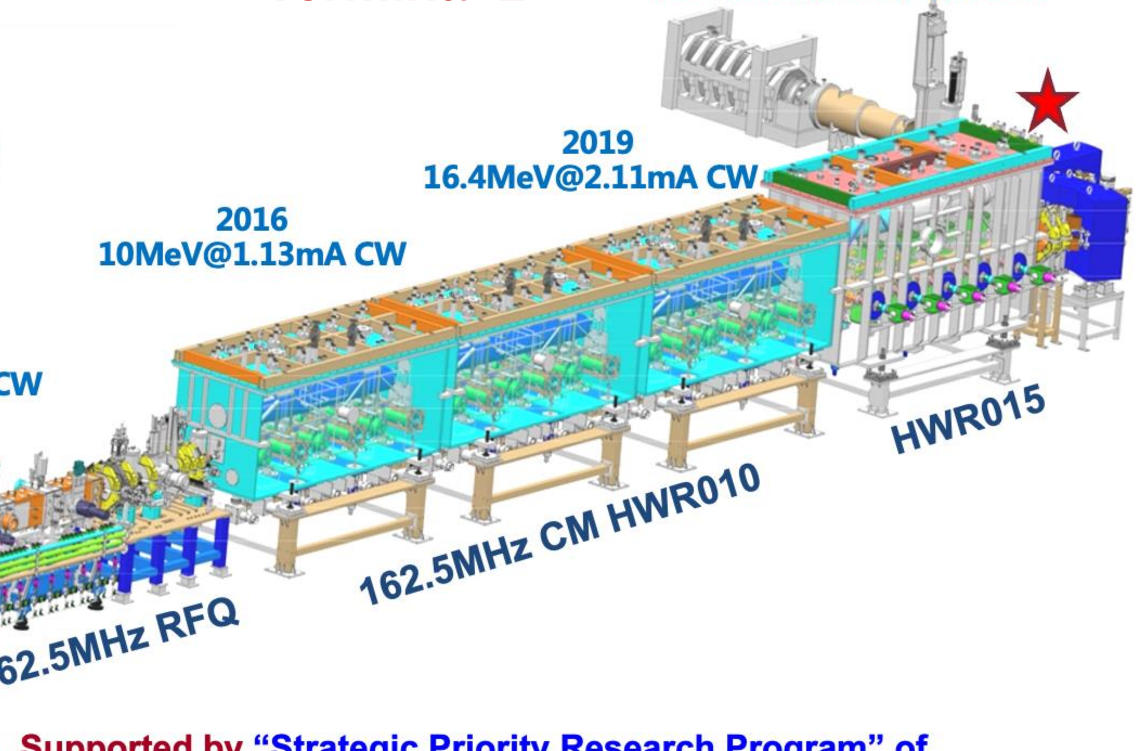


QWR 007



HWR 015

- 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

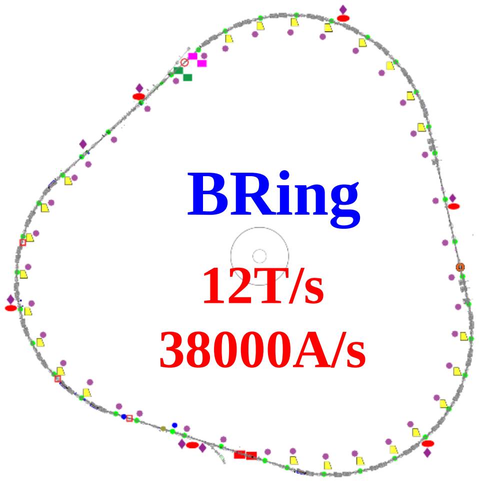
solid state amplifiers

Fast cycle booster synchrotron BRing

- **Fast ramping rate mode**

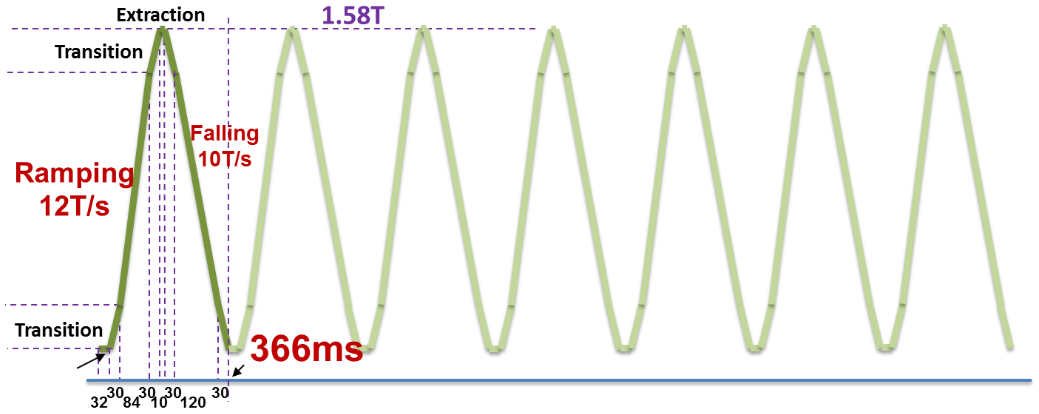
Why?

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


BRing

12T/s

38000A/s



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

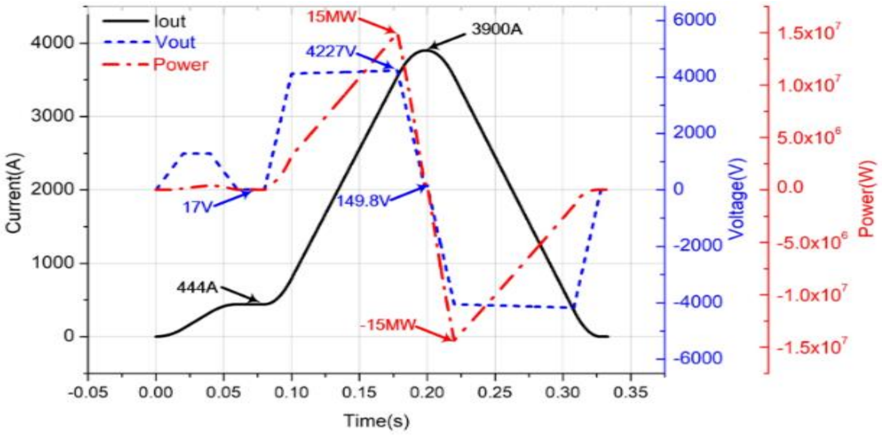
3. Ceramic-lined thin wall vacuum chamber

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

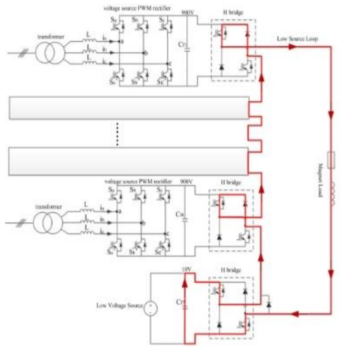


Parameters of BRing bending magnet power supply

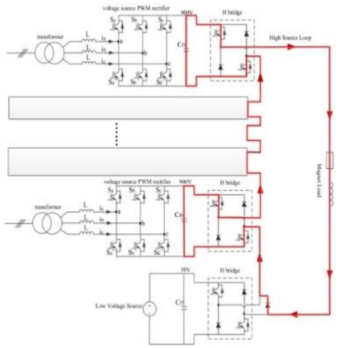
Challenges:

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

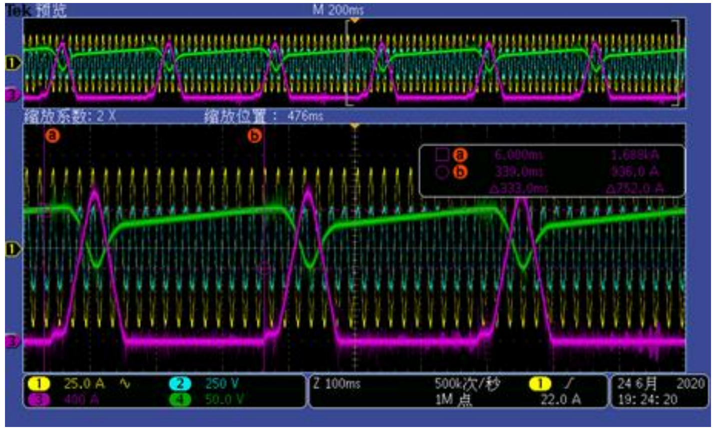
Circuit diagram of bending magnet power supply

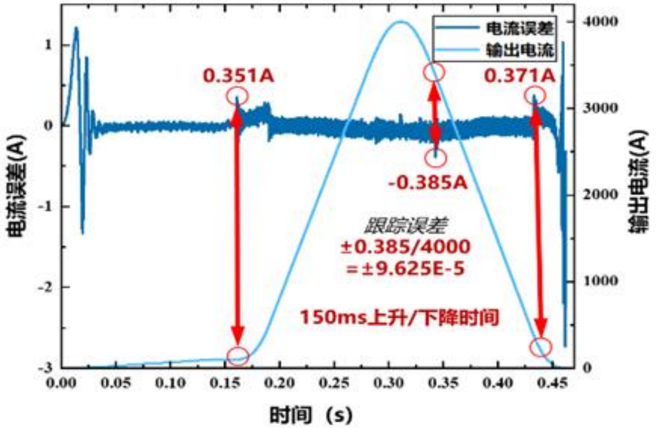
- Energy capacitor will be used to store energy during the falling, and provide the energy for next fast ramping

- The energy can be controlled by PWM rectification technology, only active power will be taken from the grid!

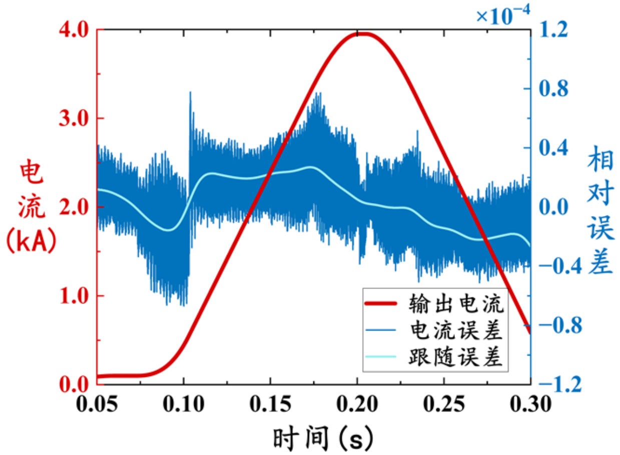
Key technical challenges and R&D

- ➢ **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**



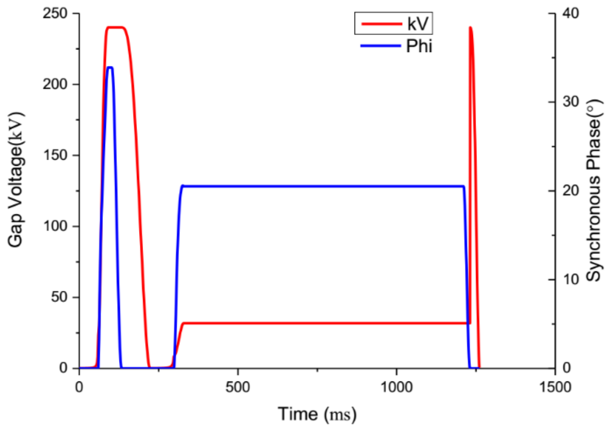
Power requirement (MVA)	Conventional	Energy storage
BRing bendng magnet	180	15
BRing quadruple magnet	50	6
Total of BRing	250	41
Total of HIAF	297	88

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

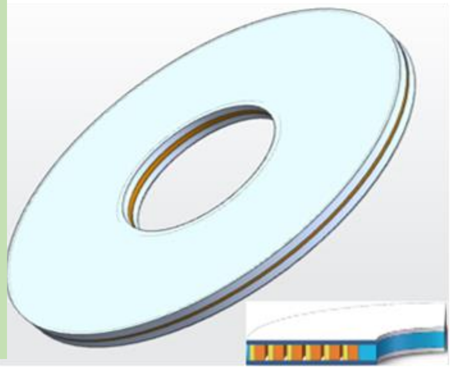
Large size oil cooled MA core

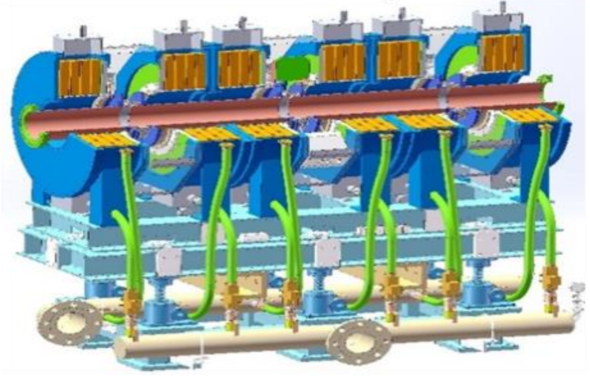
High gradient direct cooling MA- loaded cavity

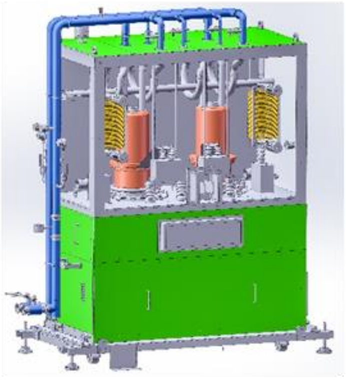
Broadband push-pull tetrode amplifier

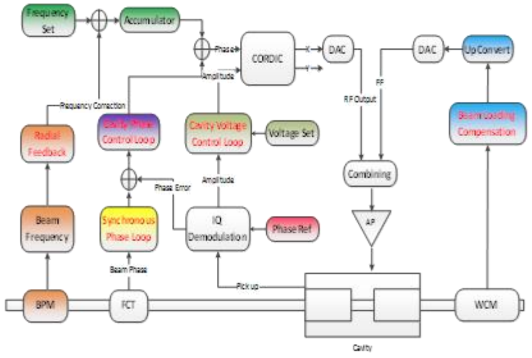
Multi harmonic digital LLRF

MA fabrication:
Q value: (0.65~0.3)@(0.1~20MHz),
μ'_pQ_f :5.3GHz @0.3MHz



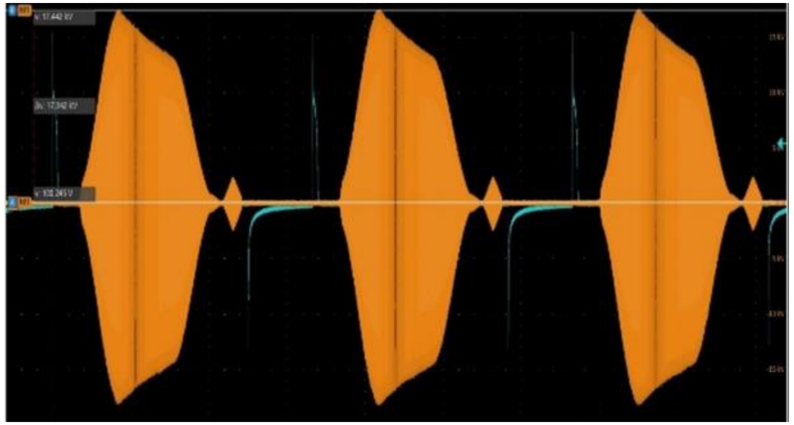




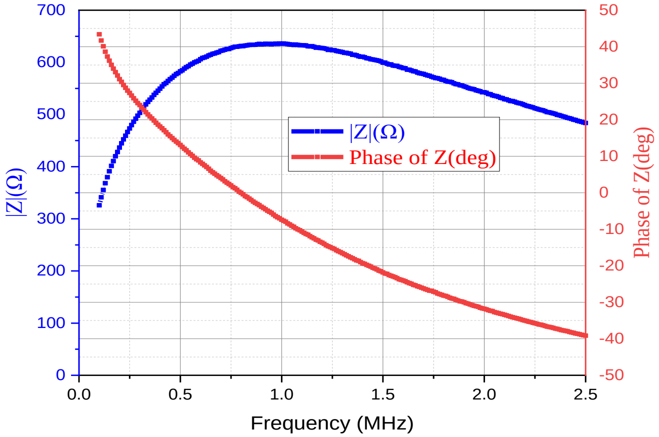


Magnetic alloy core loaded RF system

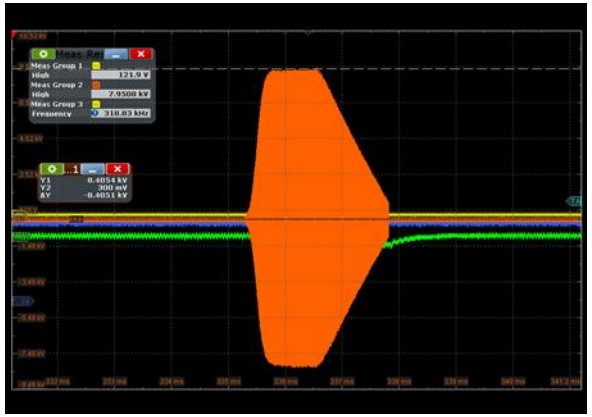
- **MA RF system with oil cooling has been constructed and power test show the good performance**
  - ☐ **The cavity RF voltage can reach 66kV@0.3~2.1MHz, with 3Hz and 70% duty cycle operating mode**



Cavity pick (3Hz operating mode)



Impedance of MA cavity



Meas Group 1
High 121.9 V
Meas Group 2
High 7.9500 kV
Meas Group 3
Frequency 310.83 kHz

Y1 0.4054 kV
Y2 300 mV
ΔY -0.4051 kV

High voltage pulse (50kV/10us)

MA loaded RF system prototype

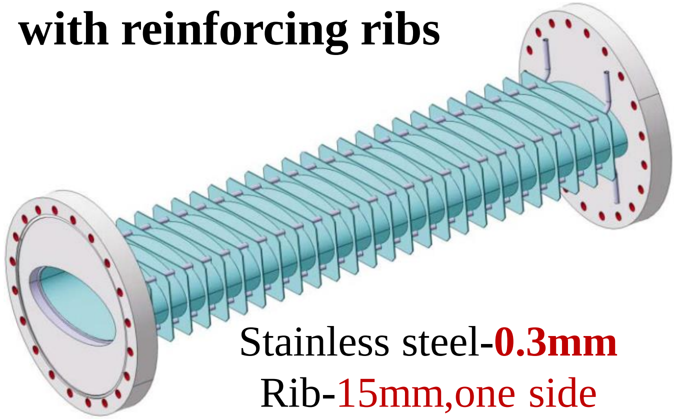
MA loaded cavity

LLRF VPX hardware

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.

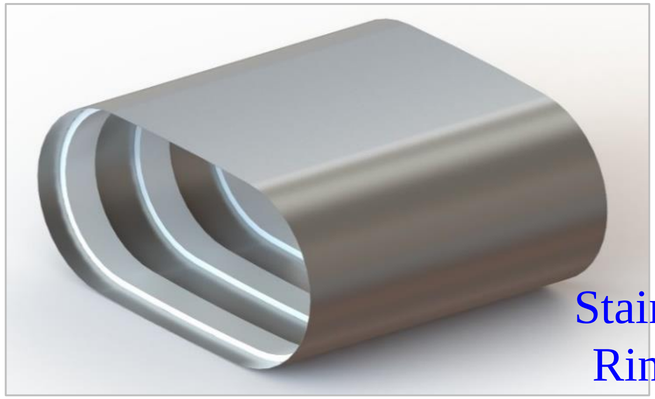
■ Thin-wall vacuum chamber with reinforcing ribs

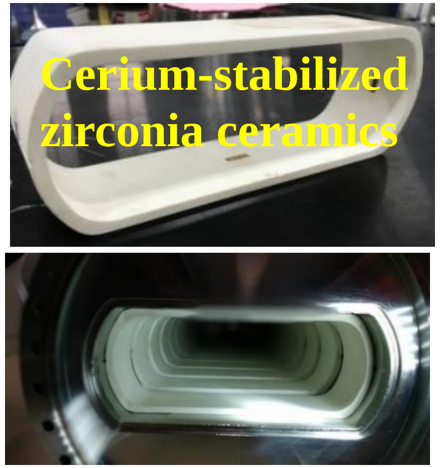

Stainless steel-**0.3mm**
Rib-15mm,one side

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

■ New scheme:

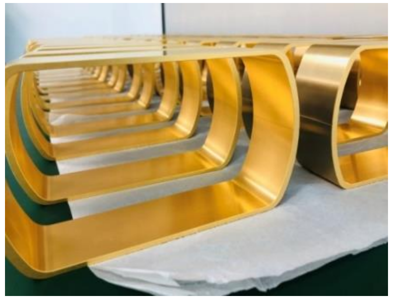
Thin-wall chamber supported by ceramic rings

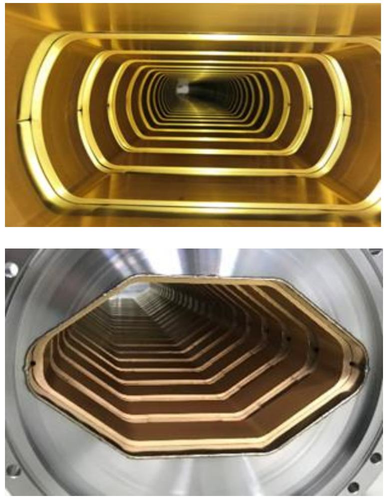

Stainless steel-**0.3mm**
Ring-4 mm,one side


Cerium-stabilized zirconia ceramics

Thickness :5mm

Ceramic ring with golden coating


Thickness :4mm



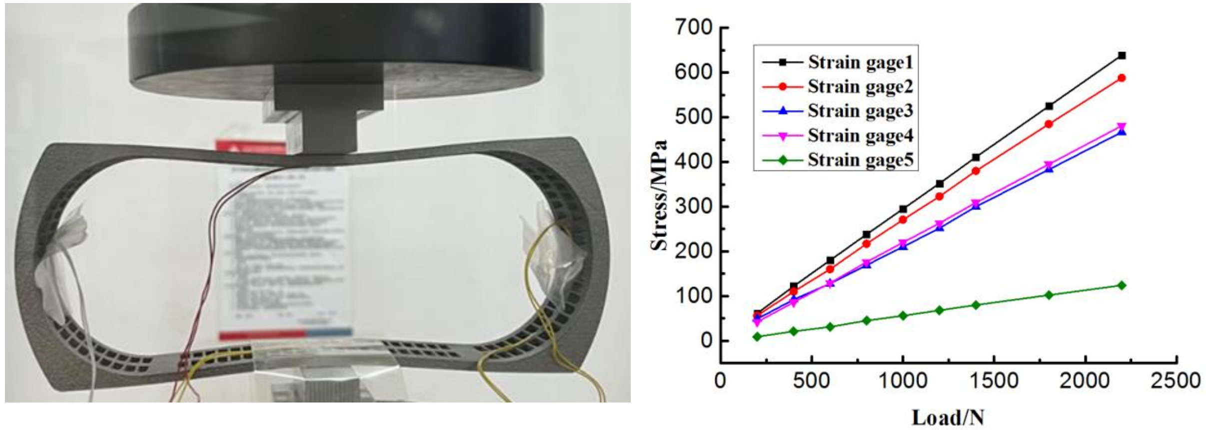
Titanium alloy-CT4 cage


Thickness :4mm

Titanium alloy lined thin-wall vacuum chamber

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

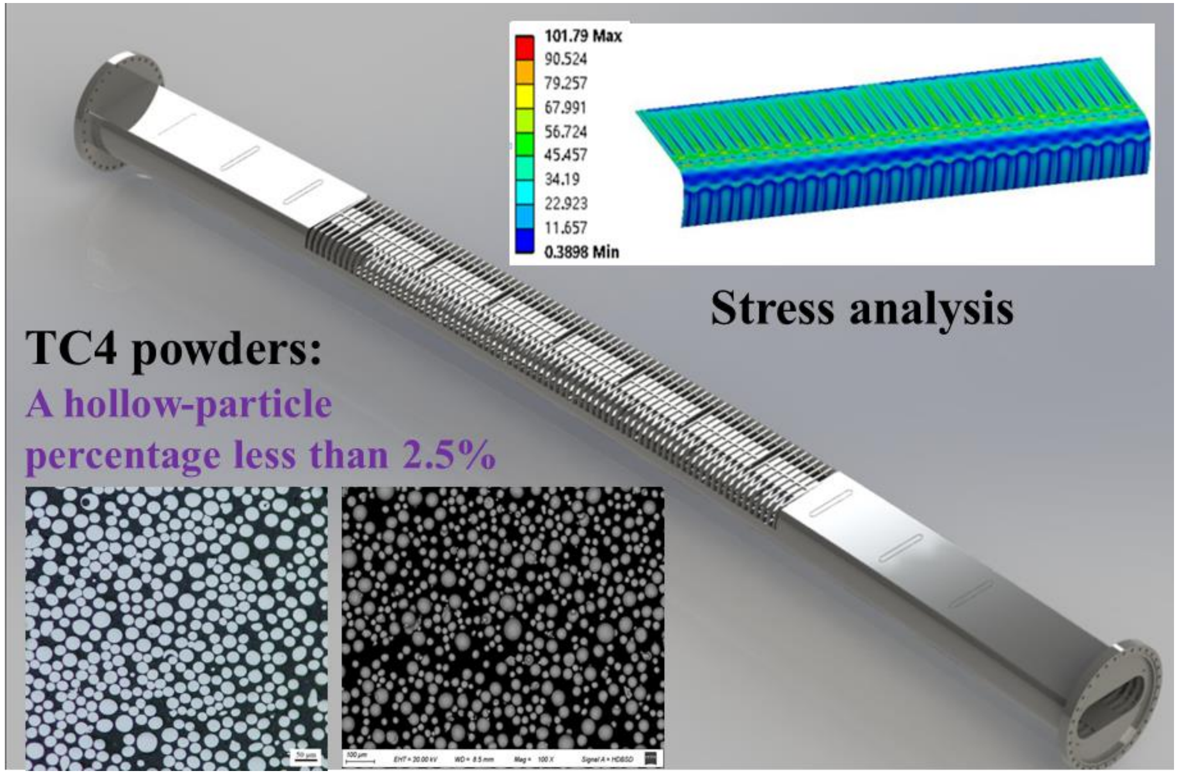
- Occupied a less magnetic gas gap; A higher yield strength with 912 MPa; A lower outgassing rate with 1.12×10^{-13} mbar.l/s.cm^{-2} ; In addition, high reliability, easy to manufacture, and low cost……



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



TC4 powders:
A hollow-particle percentage less than 2.5%

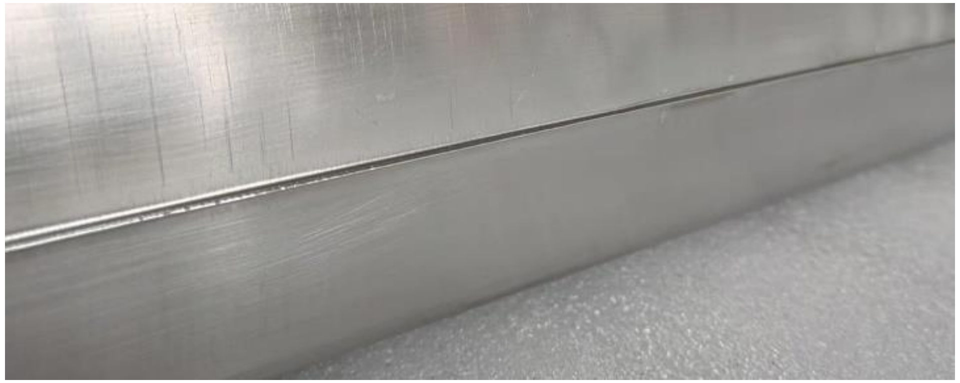
The titanium alloy-lined thin-wall vacuum chamber

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



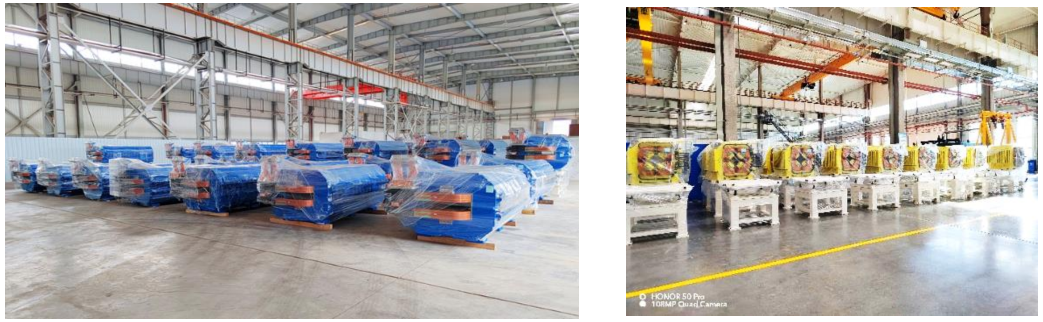
Welding quality

- 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.

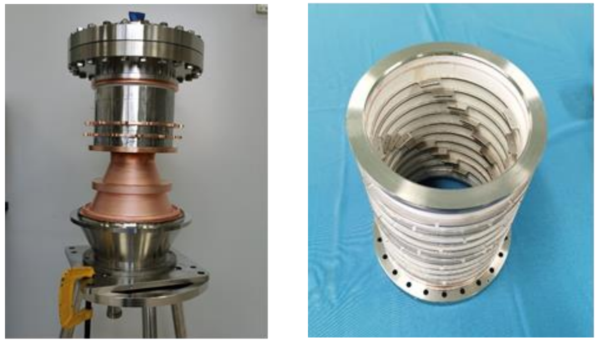
Hardware components

■ Mass production and fabrication


Solenoid of front-end

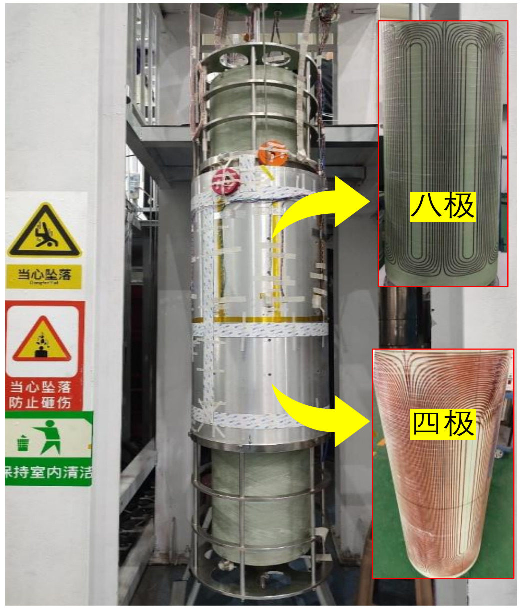

Fast ramping bending and quadrupole magnets of BRing


Superferric bending magnet
with warm iron


Electron cooling device

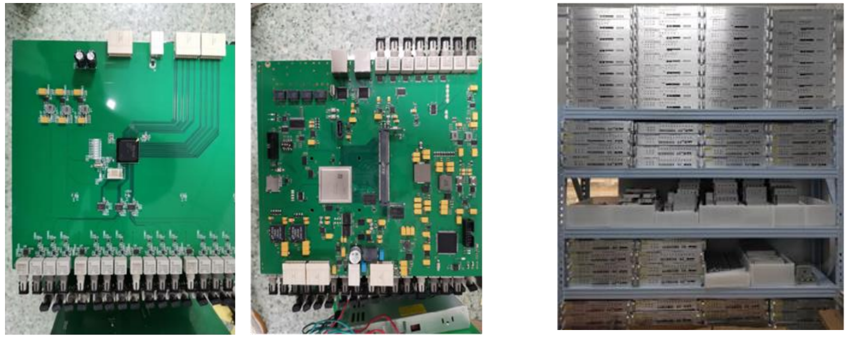

Sextupole magnets


Beam diagnostic devices & instruments



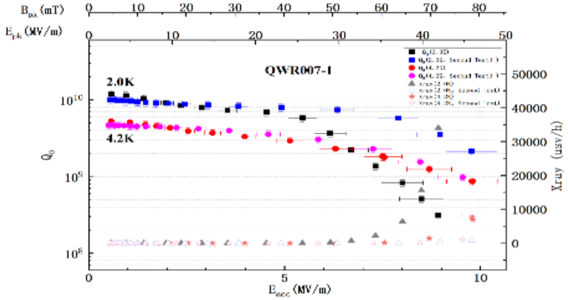
Coil dominated Canted Cosine
Theta multipoles magnets

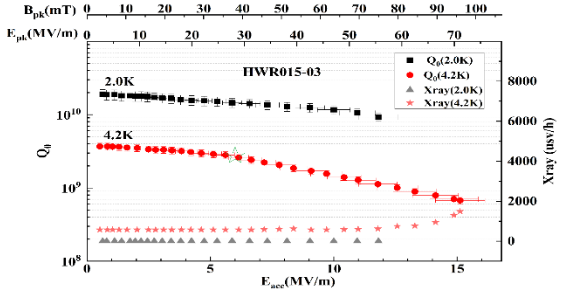

Fast ramping full energy storage power supply


Electronics devices

Hardware components

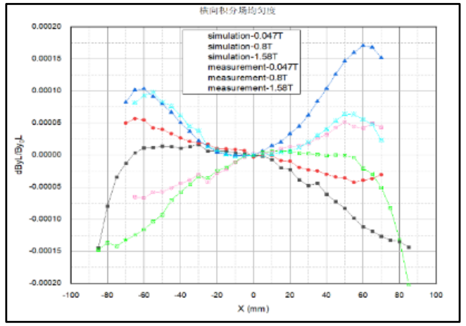
■ Test and measurement of key system and devices



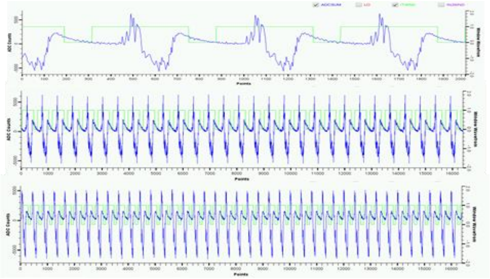


SRF cavity vertical test

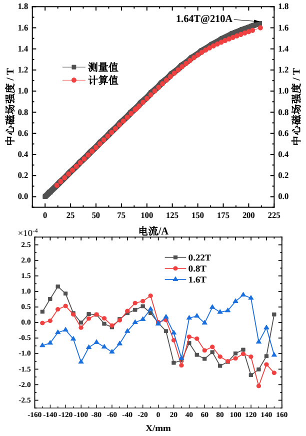
Cryomodule test



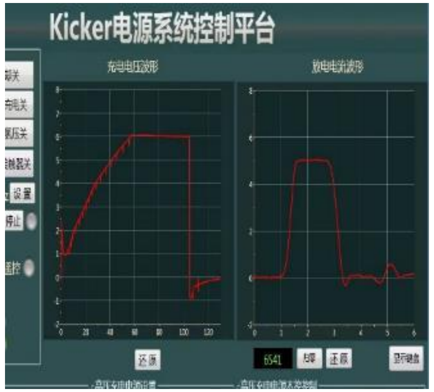
Field measurement of bending magnets



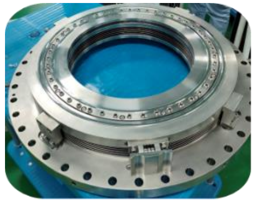
Online beam test of BPM electronics



Test and measurement of superferric magnet



Kicker power supply test with real load



High power primary target test

Outline

1. General information of the HIAF

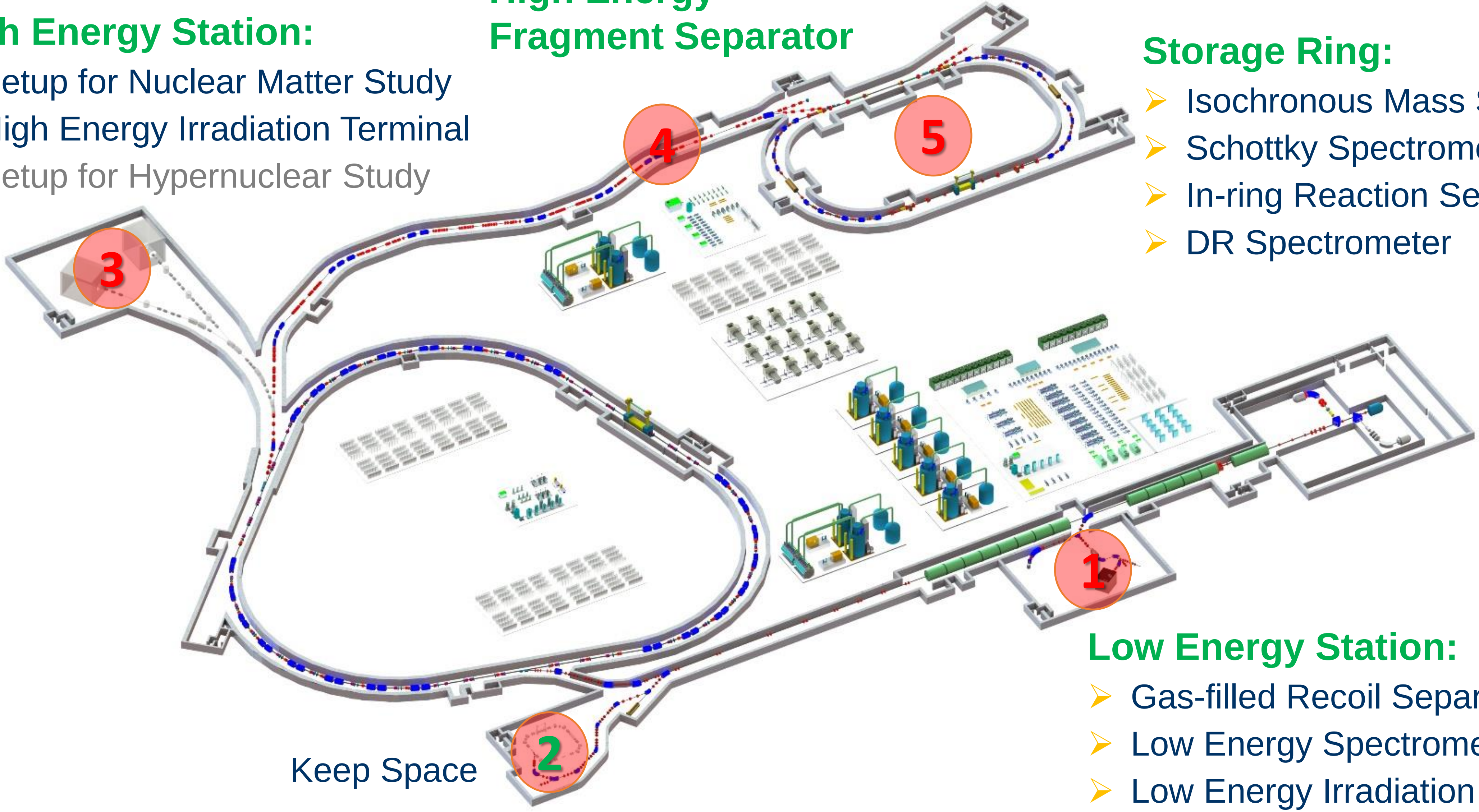
2. High intensity beam dynamics studies

3. Key technical challenges and R&D

4. **Experimental terminals**

5. Conclusion

Experimental Setups



High Energy Station:

- Setup for Nuclear Matter Study
- High Energy Irradiation Terminal
- Setup for Hypernuclear Study

High Energy Fragment Separator

Storage Ring:

- Isochronous Mass Spectrometer
- Schottky Spectrometer
- In-ring Reaction Setup
- DR Spectrometer

Low Energy Station:

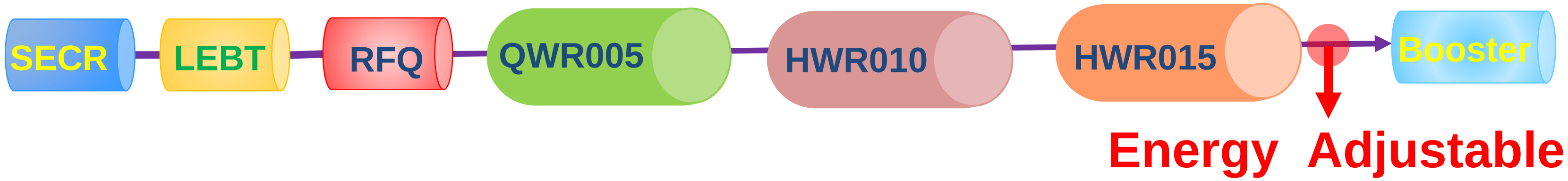
- Gas-filled Recoil Separator
- Low Energy Spectrometer
- Low Energy Irradiation Terminal

Keep Space

Experiments@iLinac

Low Energy Station

Pulse Mode: injector of the Booster; **CW Mode:** deliver intense beams for low-energy experiments



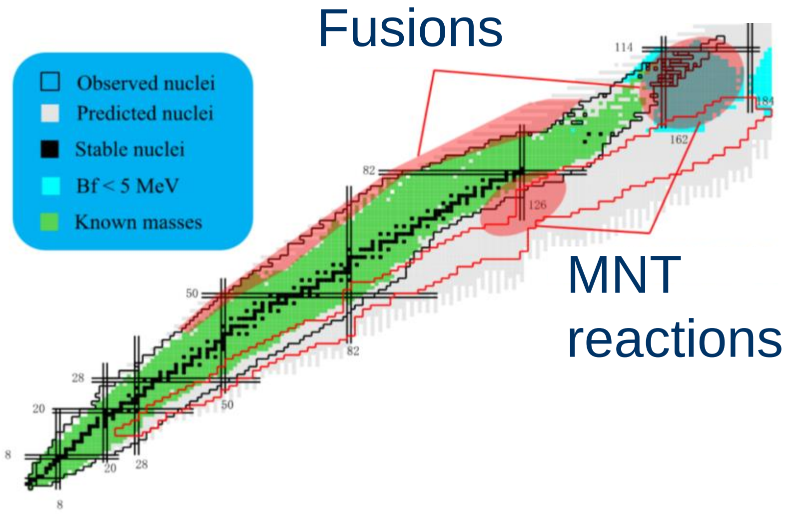
Pulse mode:

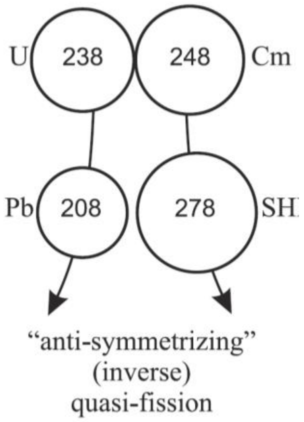
1.0 emA beams with A/Q=2~7

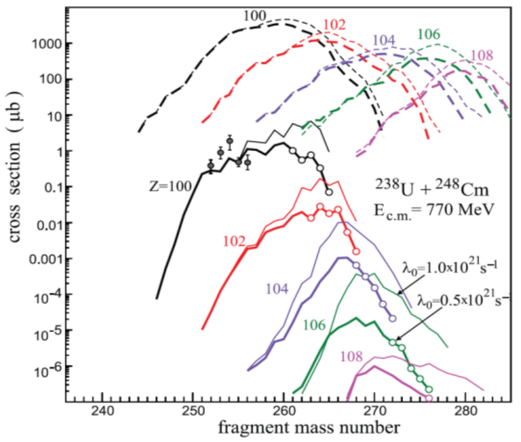
CW mode:

10 pμA beams with A/Q=2~5

Fusion and MNT Reactions







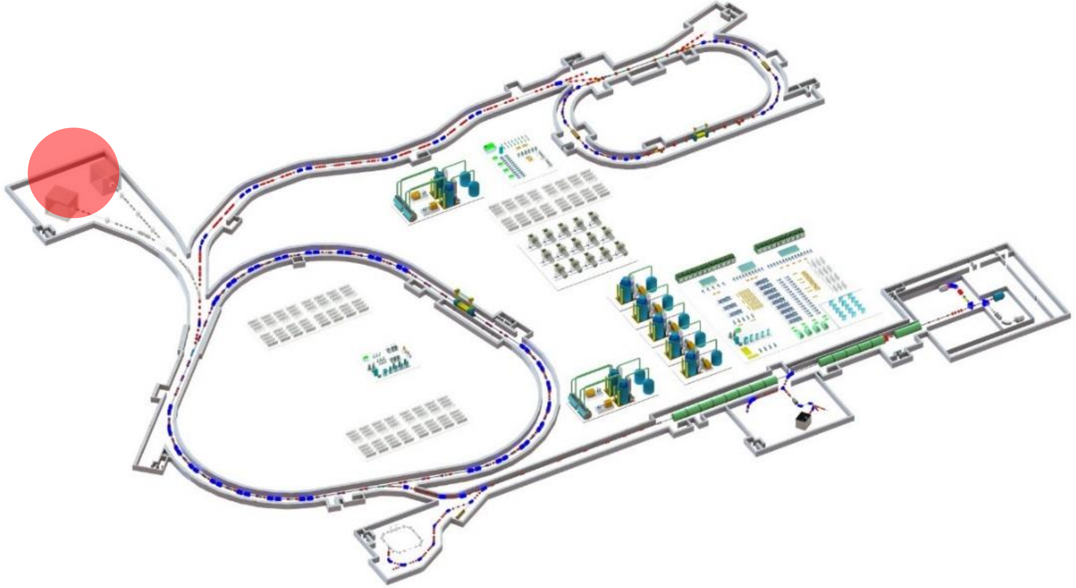
- synthesize new elements and isotopes
- measure nuclear masses and lifetimes
- build the decay schemes
- map out the drip lines
- build a bridge to the island of SHN
- simulate the *rp* and *r* processes
- study the evolution of shell structure

To produce heavy and super-heavy nuclei by fusion reactions and by multi-nucleon transfer reactions

Experiments@BRing

High Energy Station

- Stable beams provided by the Booster
- DC-type extraction from the Booster



Typical beam parameters from the Booster Ring

Ions	Energy(GeV/u)	Intensity (ppp)
p	9.3	2.0×10^{12}
$^{18}O^{6+}$	2.6	6.0×10^{11}
$^{78}Kr^{19+}$	1.7	3.0×10^{11}
$^{209}Bi^{31+}$	0.85	1.2×10^{11}
$^{238}U^{34+}$	0.8	1.0×10^{11}

Slow extraction: ~ 3s beam duration

Not supported by the approved budget

The high-energy stable beams are ideal to produce hypernuclei and nuclear matter

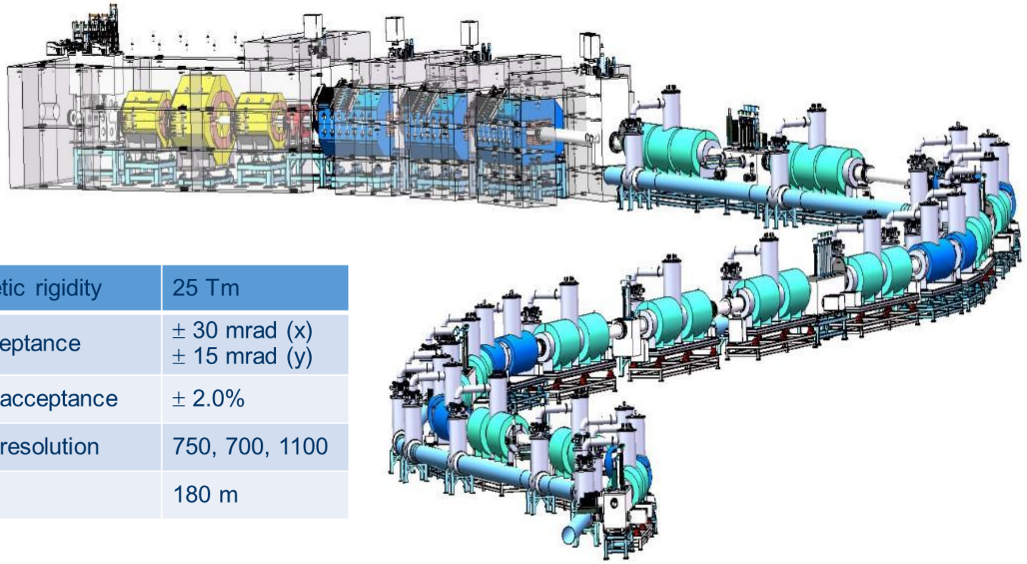
- Properties of nuclear matter: supported already by CAS and NSFC, about 200 Million CNY
- Synthesis of new hypernuclei: seeking for financial support, international collaboration?

Moderate beam intensity and higher energies. A/Z=2 primary beams up to 4.25 GeV/u energy will be available

Experiments@HFRS

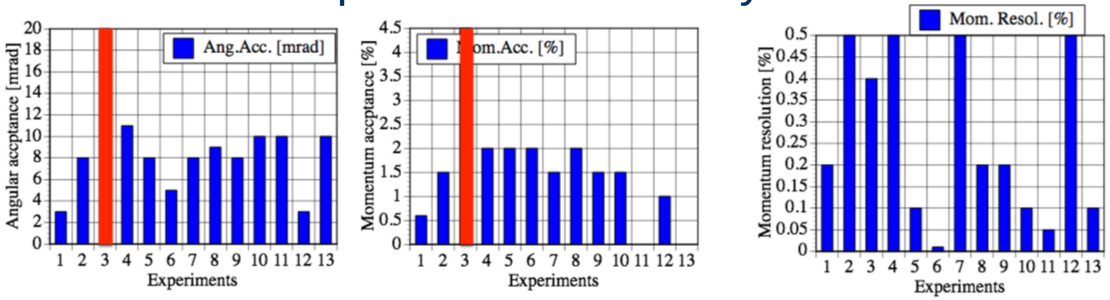
<u>H</u>igh Energy <u>Fr</u>agment <u>S</u>eparator (HFRS)

- ➢ Slowly extracted beams from the Booster
- ➢ Radioactive ion beams produced by HFRS



Max. magnetic rigidity	25 Tm
Angular acceptance	± 30 mrad (x) ± 15 mrad (y)
Momentum acceptance	± 2.0%
Momentum resolution	750, 700, 1100
Total length	180 m

Requirements from Physics



Acceptance, and Momentum Resolution

Physics Cases @HFRS

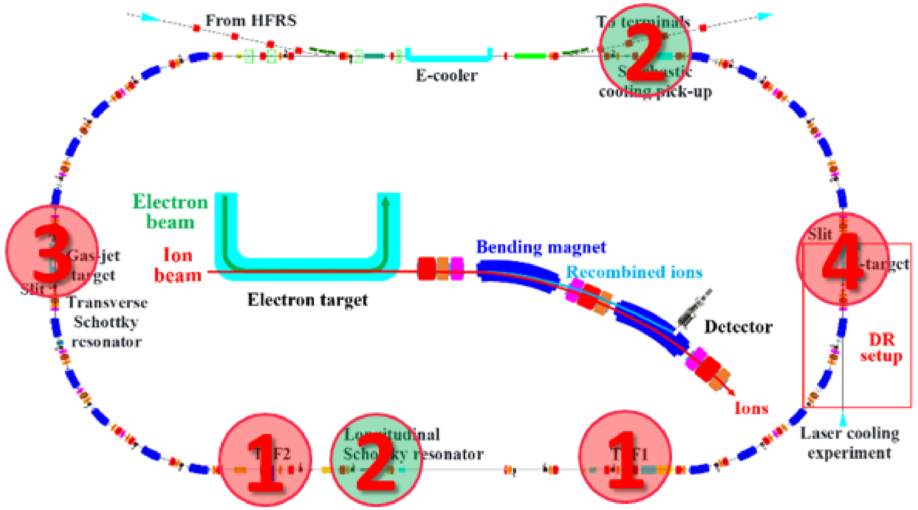
- ✓ New isotopes in the south east of ^{208}Pb (PF of ^{208}Pb and ^{238}U)
- ✓ Neutron dripline up to Ni isotopes (PF of Kr and Xe)
- ✓ New isotopes by ^{238}U fission (In-flight fission of ^{238}U)
- ✓ New isotopes using two step projectile fragmentations
- ✓ Synthesis of neutron rich hypernuclei
- ✓ Study of tensor interactions: a basic change in structure model
- ✓ Particle decay in flight of unbound nuclei
- ✓ Nuclear matter radii (Interaction cross sections)
- ✓ Nuclear proton radii (Charge changing cross sections)
- ✓ Charge exchange reactions and β decay of r-process nuclei
- ✓ Nucleon excitations in nuclei
- ✓ Giant resonance of neutron rich nuclei
- ✓ Elastic scattering and transfer reactions
- ✓ Spectroscopy of meson-nucleus bound system
- ✓ …

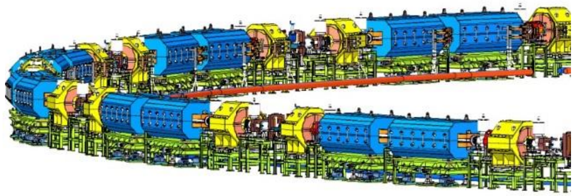
Various experiments can be done at HFRS

Experiments@SRing

Spectrometer Ring: Multi Working Modes of Storage Ring

With fast extracted projectiles from the Booster, HFRS produces, separates and injects the isotopes of interests into the Spectrometer Ring





Experiments:

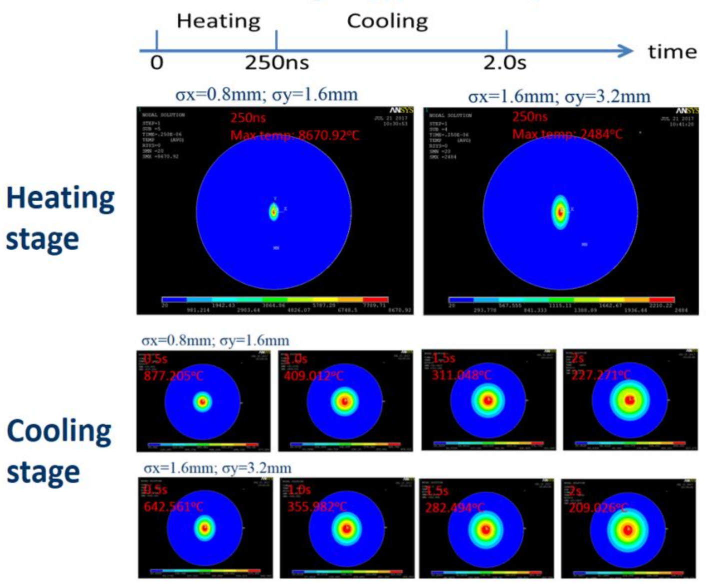
- Isochronous Mass Spectroscopy
- Schottky Spectroscopy
- DR Spectroscopy
- In-ring Nuclear Reactions

Spectrometer Ring:

- Circumference:188.7 m
- Rigidity: 15 Tm
- Electron cooler
- Stochastic cooler

Fast extraction (pulse width 250ns/3s)

^{238}U: 800AMeV@10^{11}ppp, Carbon target



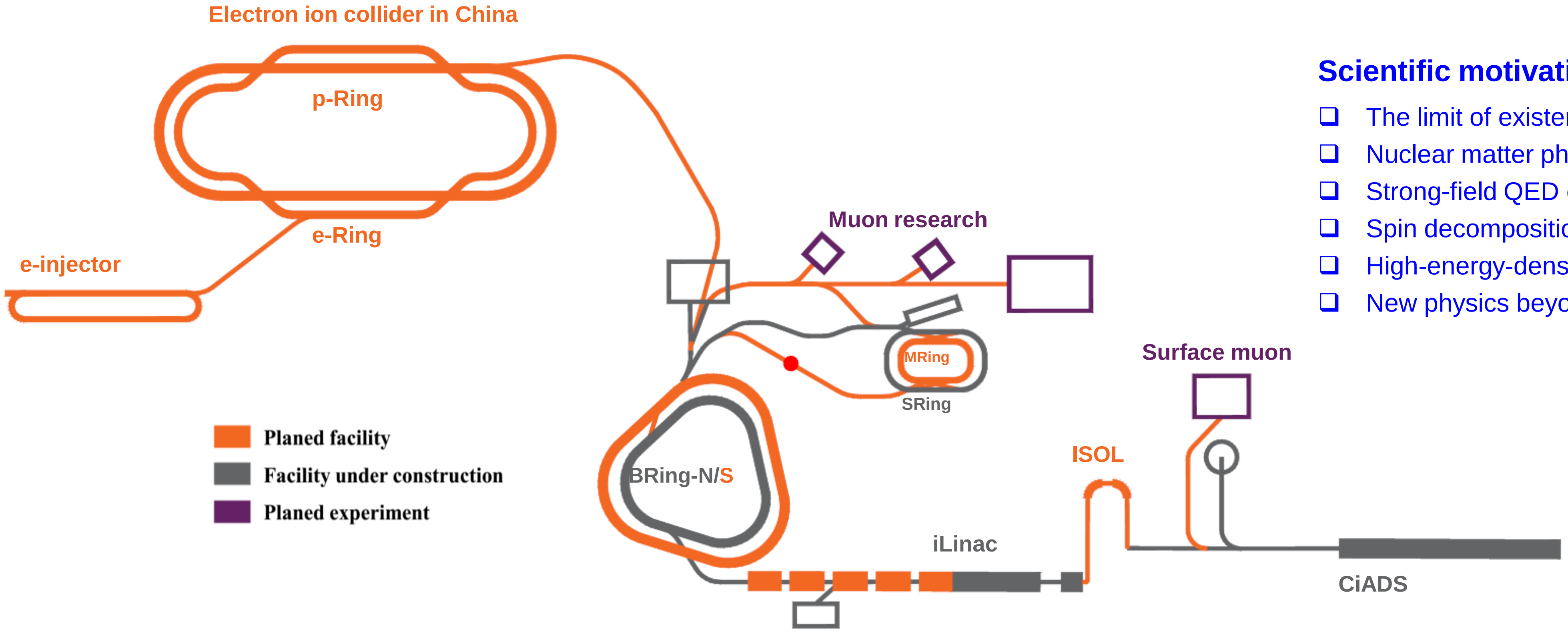
Carbon target sustainable to beam power

Conclusion

- **The HIAF project can provide stable ions up to Uranium, and produce many kind of secondary isotopes**
- **The maximum magnetic rigidity is 34Tm, which corresponds to the energy of Uranium is about 830 MeV/u and proton is 9.3 GeV**
- **High beam intensity and fast ramping (12T/s) is the main feature of the synchrotron**
- **The first beam will be extracted in 2025**
- **HIAF will play a key role for sustainable development of heavy-ion science and technology in China. International collaboration and theories in assistance are very needed!**

Future facility - CNUF

China advanced NUclear physics research Facility - An upgrade of the HIAF and CiADS



Scientific motivation:

- ☐ The limit of existence of nuclides
- ☐ Nuclear matter phase structure
- ☐ Strong-field QED effect
- ☐ Spin decomposition and origin of mass
- ☐ High-energy-density physics
- ☐ New physics beyond SM

EicC

Consists of p-Ring, e-Ring and beam injectors, realizes dual-polarized high intensity electron ion collision, with full energy beam injection and rapid replacement based on e-injector and BRing-S.

HIAF-U

Upgrade HIAF with 200MeV/u iLinac, fast-cycle injector BRing-N, superconducting synchrotron BRing-S and the merging ring MRing, providing high-intensity, high-quality ion beams from proton to uranium.

ISOL

Driven by the high power proton beam from CiADS Linac, producing high intensity neutron-rich nuclides and be post-accelerated by HIAF-U. Also producing high flux surface muon.

Thanks for your attention!