中国科学院近代物理研究所
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HIAF overview: Current status and future perspectives

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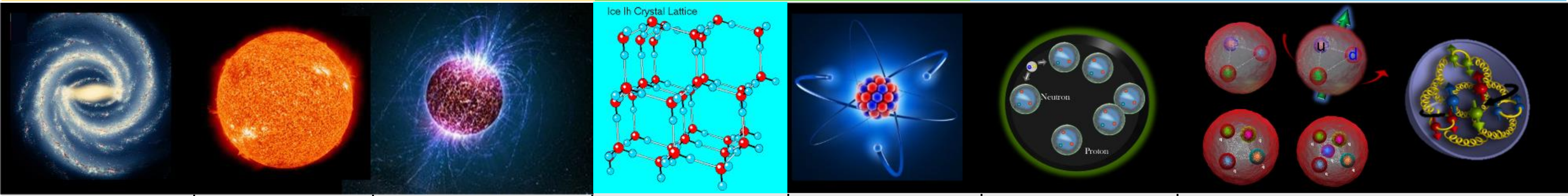
◻ Introduction

Particle accelerators are devices that speed up the particles that make up all matter in the universe and collide them together or into a target. This allows scientists to study those particles and the forces that shape them.

——DOE explains

Gravitational force			Electromagnetic force		Strong force		



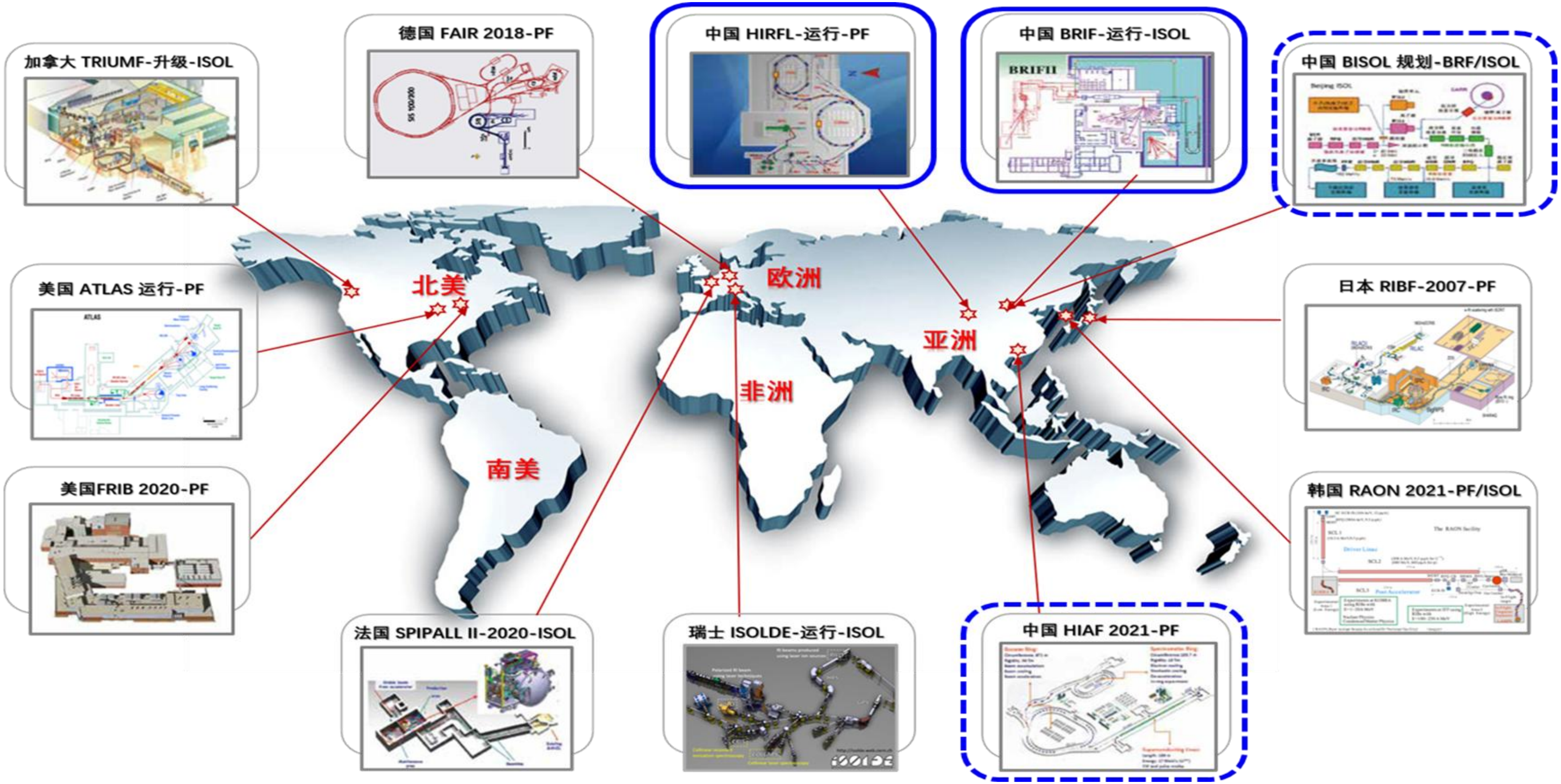
Galaxy $\sim 10^{21}$m	Solar $\sim 10^{9}$m	Neutron star $\sim 10^{4}$m	Crystal $\sim 10^{-8}$m	Atom 10^{-10}m	Atomic nucleus 10^{-15} - ^{14} m	nucleon（10^{-15}m）	
						Quark	Gluon

High intensity HI beams	RIBs ~1.5-2 GeV/u	Relative. HI beams ~100 GeV/u

← **High Intensity**   **High Energy** →

☐ Introduction

More than **30 facilities** are in operation in the world, with the energy range from **MeV/u to TeV/u**



Introduction

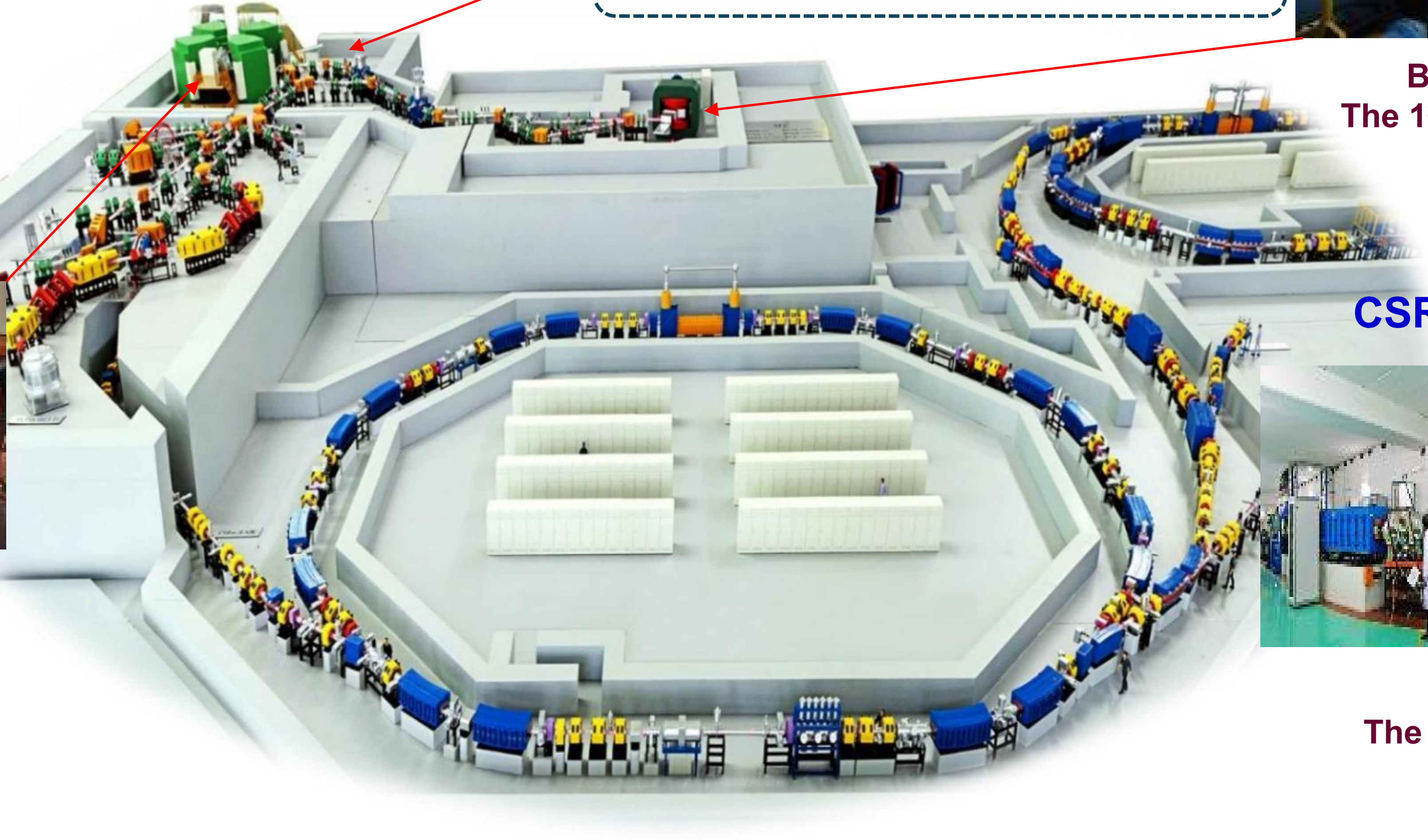
HIRFL: an accelerator complex combined with Linac, cyclotrons and synchrotrons

SSC-Linac：1.4MeV/u

Built in 2019
a new injector for SSC

SFC：~10MeV/u

Built in 1962
The 1st five year plan



SSC：~100MeV/u

Built in 1988
The 7th five year plan

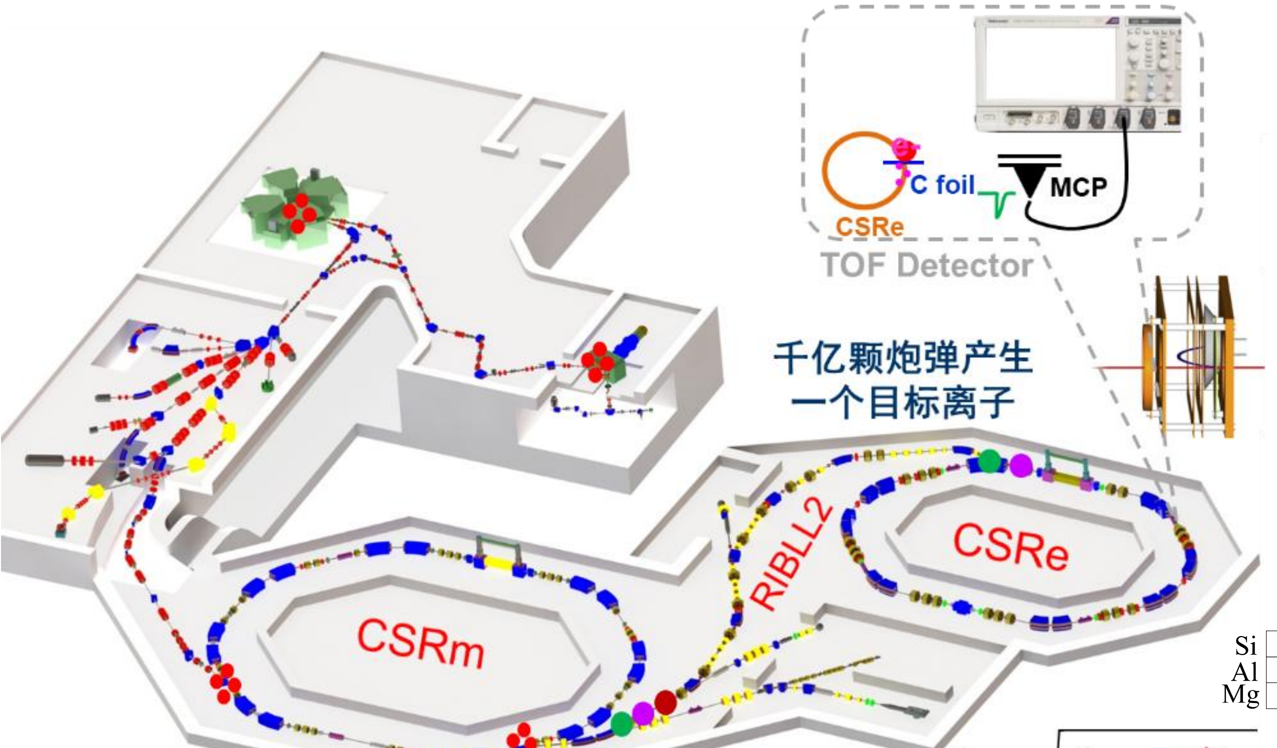
CSR:~1000MeV/u

Built in 2007
The 9th five year plan

Introduction

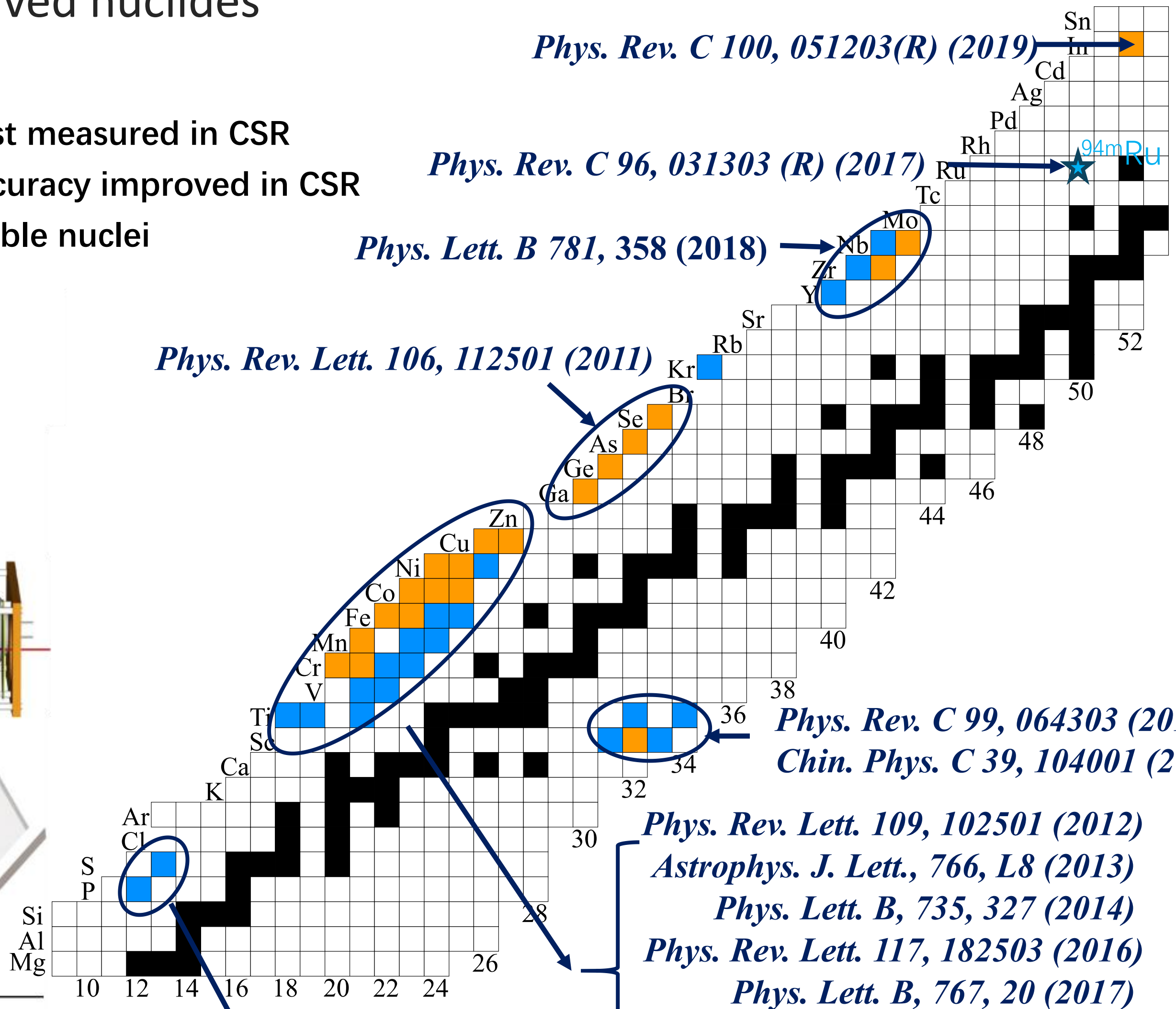
Precise mass measurement spectrometry of short-lived nuclides

Principle of IMS
Isochronous Mass Spectrometry



$$T = \frac{L}{v} = L\sqrt{(\frac{1}{c})^2+(\frac{m/q}{B\rho})^2}$$

- First measured in CSR
- Accuracy improved in CSR
- Stable nuclei



Phys. Rev. C 100, 051203(R) (2019)

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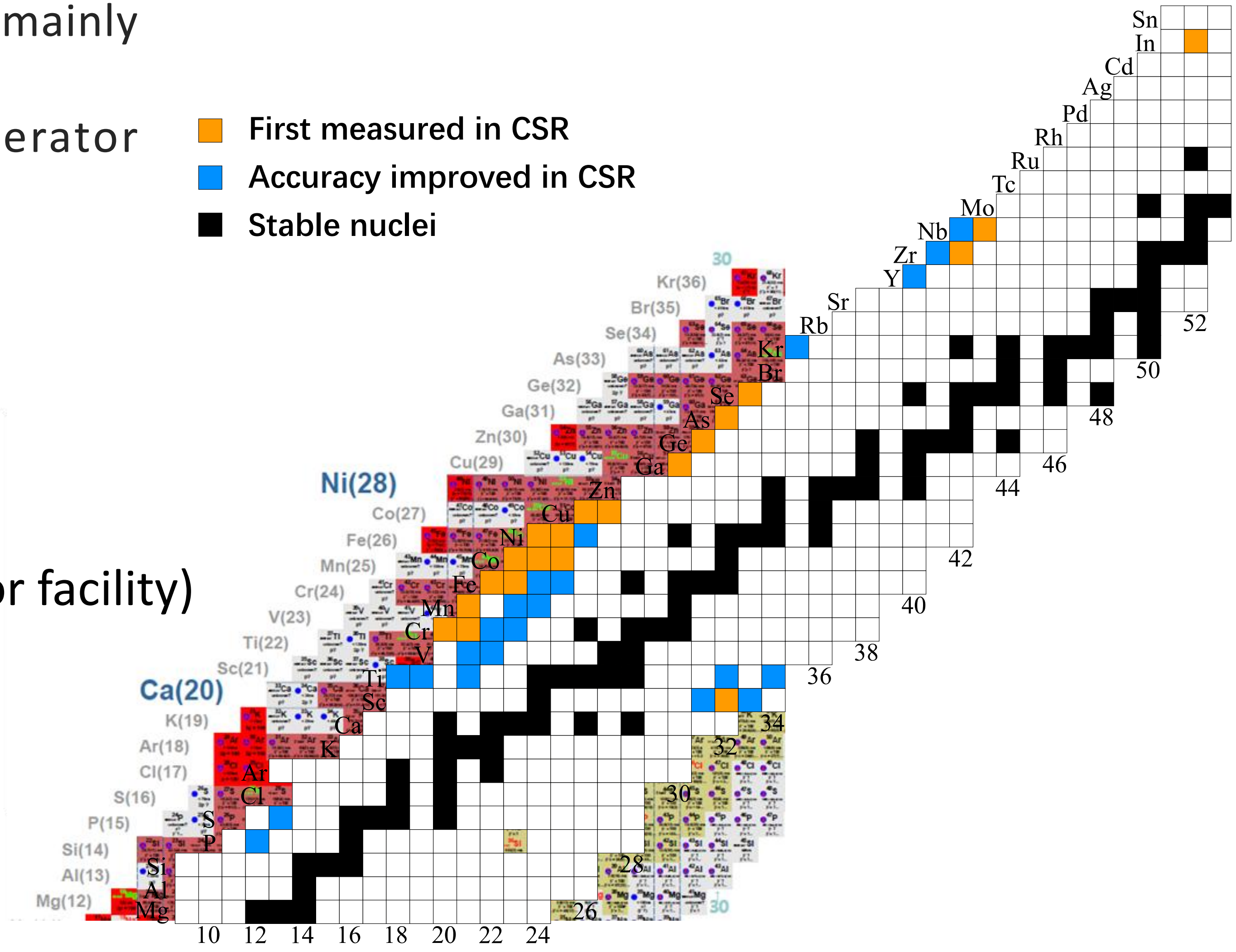
Phys. Rev. C 98, 014319 (2018)
Phys. Rev. C, 102, 054311 (2020)

Phys. Rev. C 98, 014315 (2018)

◻ Introduction

- Too many isotopes can not be produced, mainly because of **very small** cross-section
- A **high intensity** heavy ion beam accelerator facility is needed



HIAF (High Intensity heavy-ion Accelerator facility)

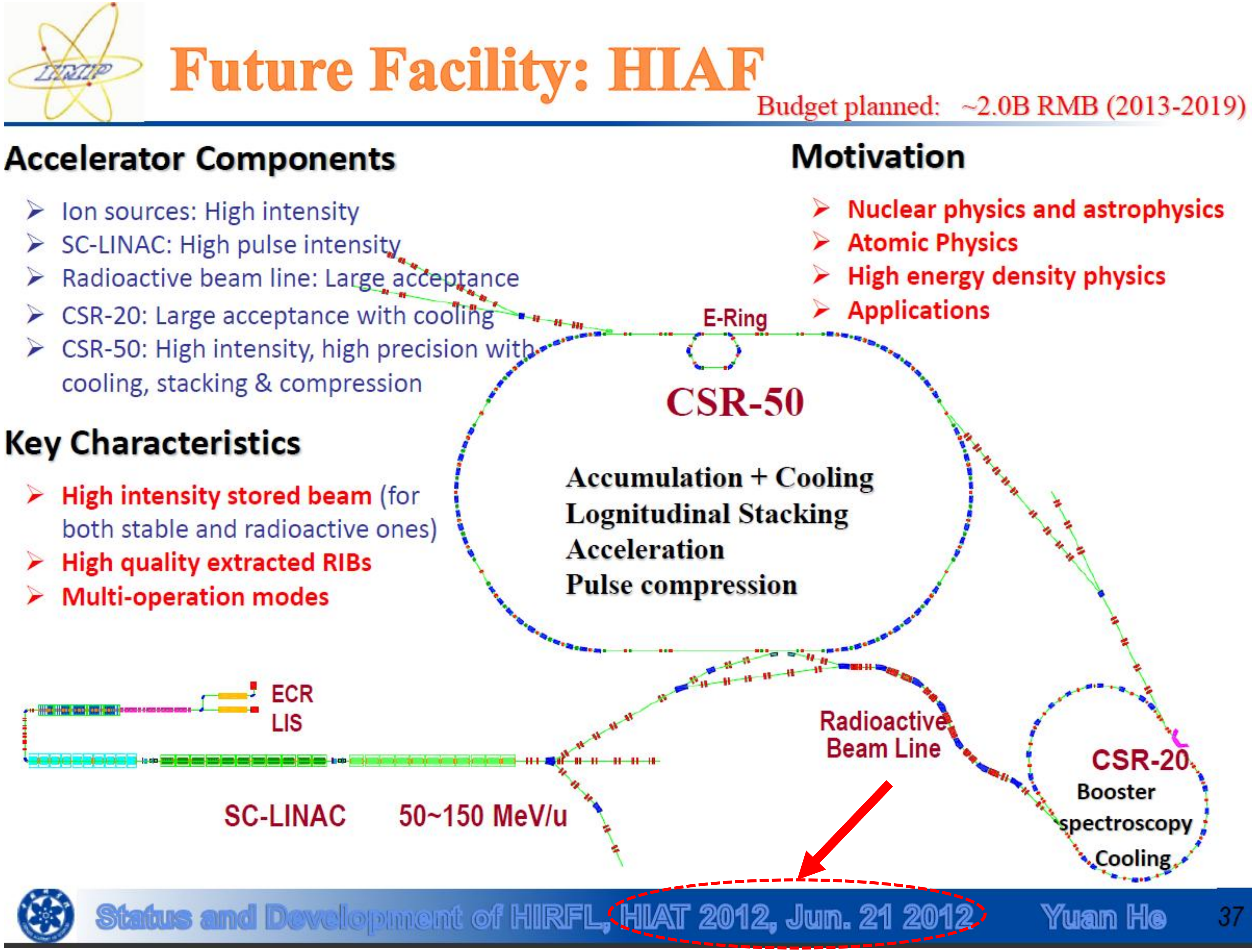
---proposed in 2011

---approved in 2015

---construction from 2018

---beam commissioning in 2025

Introduction



☐ Introduction

Table 1
HIAF main design parameters of typical U^{34+} ion beam. ppp denotes particle per pulse.

Machine	Ion	Energy	Intensity
ECR source	U^{34+}	60 kV/q	0.02 pmA
LIS source	U^{34+}	60 kV/q	0.1 pmA
HISCL	U^{34+}	25 MeV/u	0.015–0.075 pmA
	U^{76+}	40 MeV/u	0.003–0.015 pmA
ABR-45	U^{34+}	1.2 GeV/u	$0.25–1.3 \times 10^{11}$ ppp
	U^{76+}	3.4 GeV/u	$0.5–2.5 \times 10^{10}$ ppp
CSR-45	U^{34+}	1.2 GeV/u	$1.0–5.0 \times 10^{11}$ ppp
	U^{76+}	3.4 GeV/u	$0.2–1.0 \times 10^{11}$ ppp
	U^{92+}	4.4 GeV/u	$0.2–1.0 \times 10^{11}$ ppp
MCR-45-1(2)	U^{34+}	1.2 GeV/u	$1.0–5.0 \times 10^{11}$ ppp
	U^{76+}	3.4 GeV/u	$0.2–1.0 \times 10^{11}$ ppp
	U^{92+}	4.4 GeV/u	$0.2–1.0 \times 10^{11}$ ppp

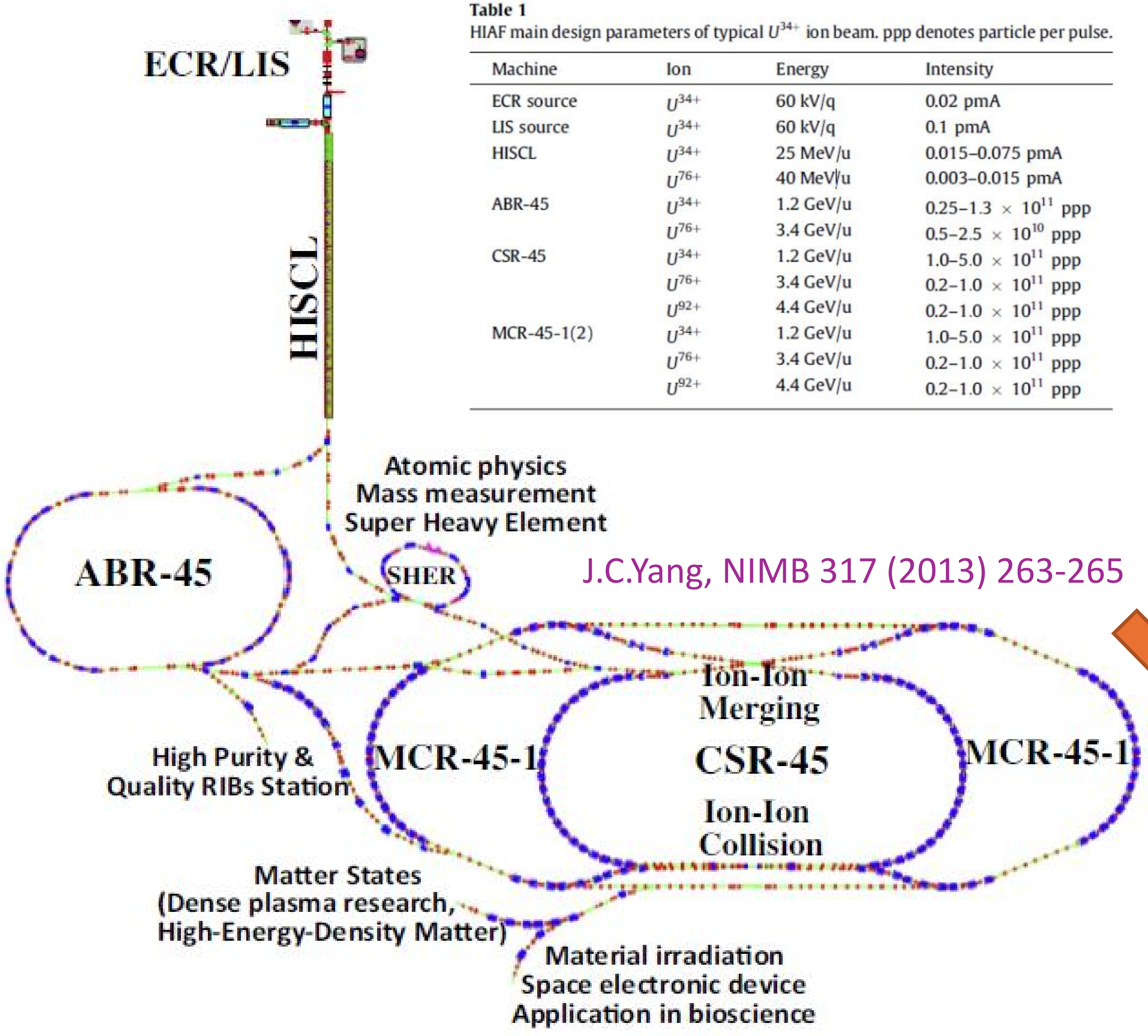
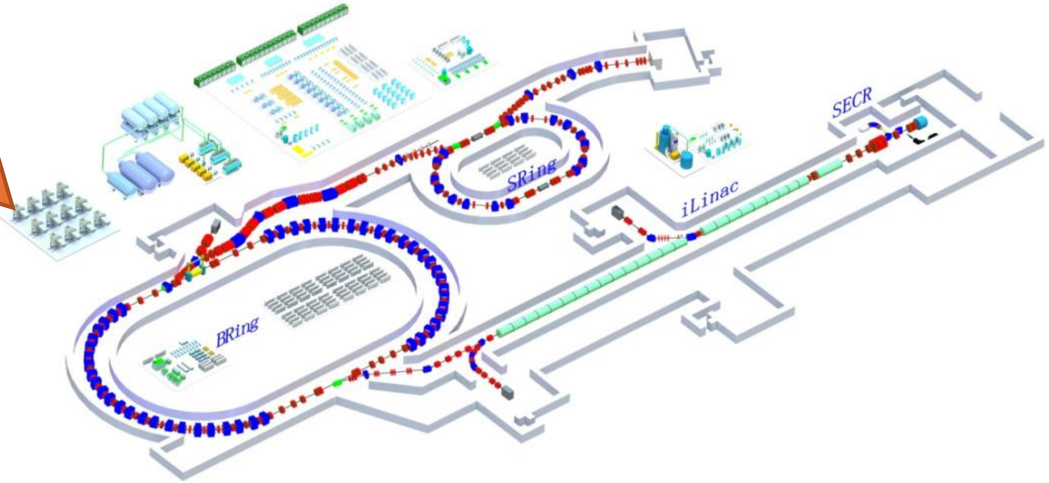


Fig. 1. Layout of the HIAF complex

J.C.Yang, NIMB 317 (2013) 263-265

Later, a very complicated accelerator complex was proposed, to provide beams for **super heavy element**, **high energy density matter**, **ion-ion collision** and so on.

Then, due to budget, the conceptual design has reverted back to its initial state, mainly for nuclear physics.



Conceptual design assessment

◻ Introduction

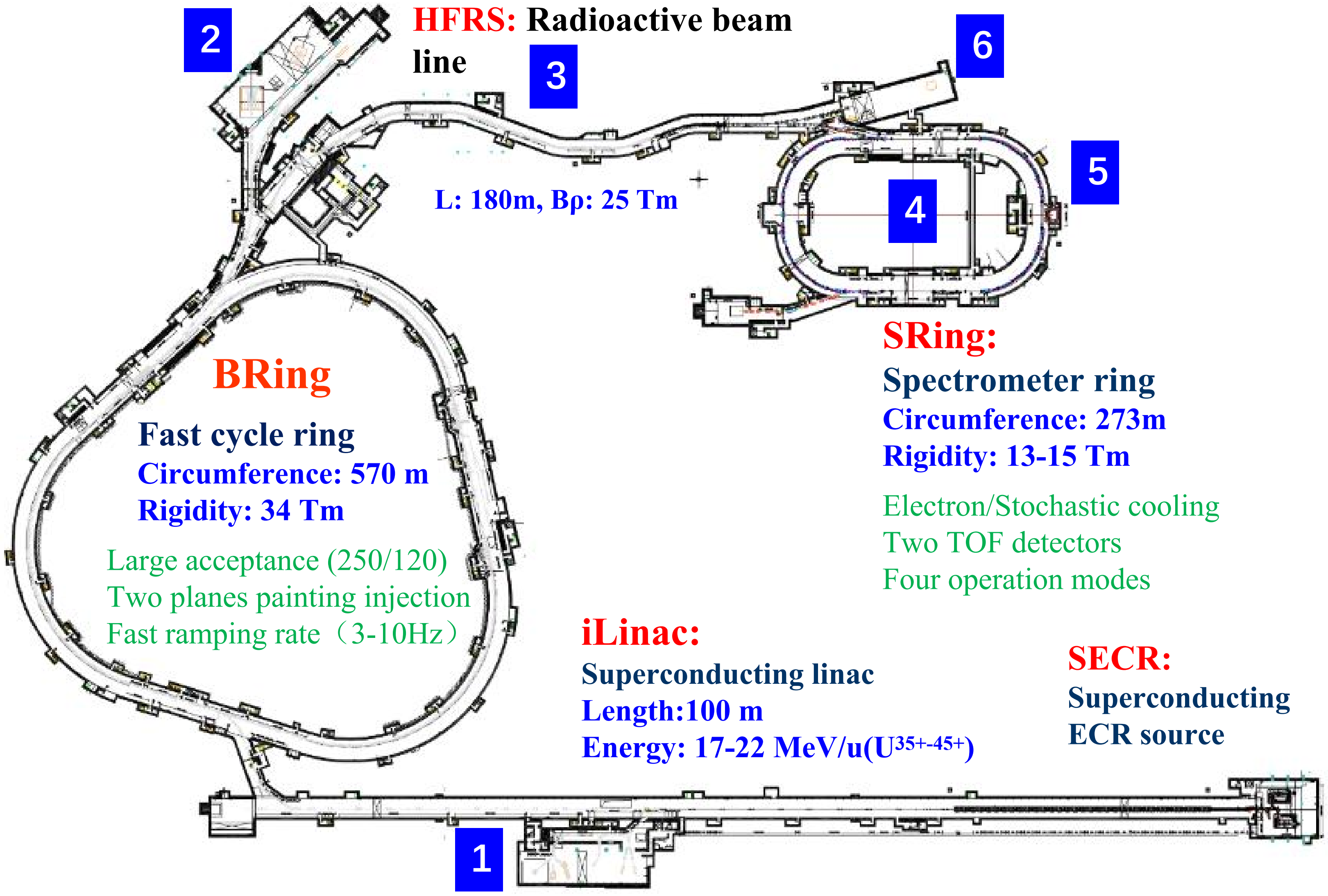
- **HIAF** (**H**igh **I**ntensity heavy-ion **A**ccelerator **F**acility)

  - **Accelerators**

  super conduction ECR ion source
  \+ super conducting CW Linac
  \+ fast ramping synchrotron

  - **Terminals**

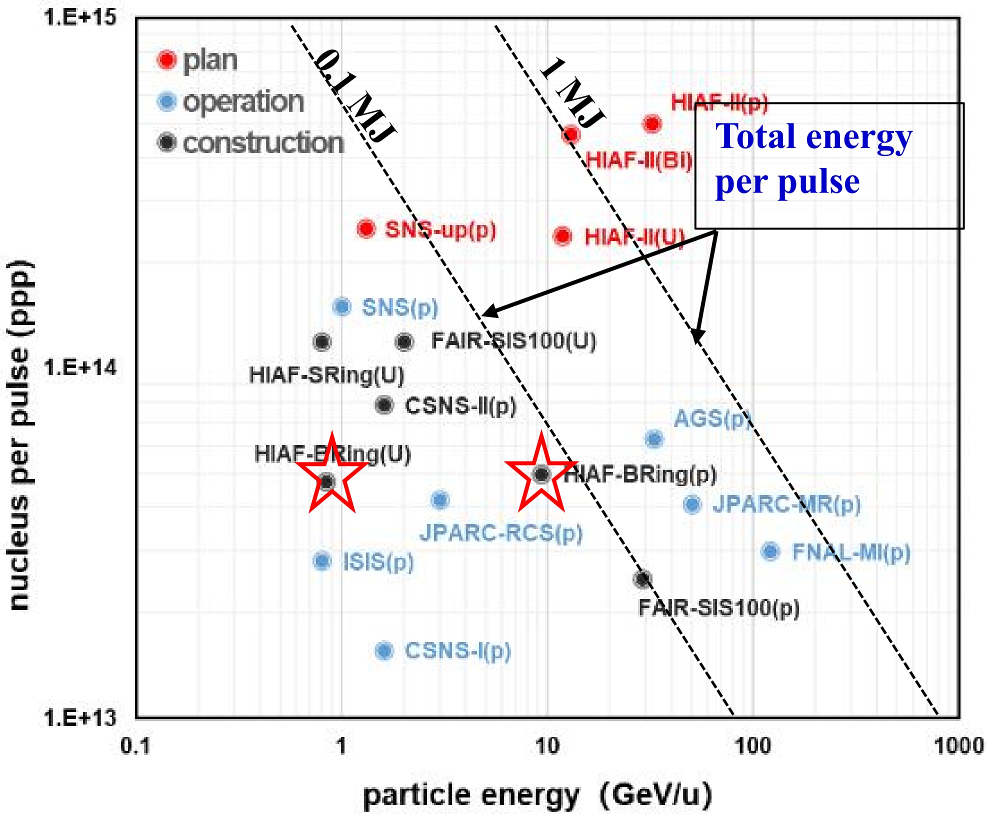
① Low energy nuclear structure terminal
② High energy experimental terminal
③ High energy fragment separator **HFRS**
④ High precision spectrometer ring **SRing**
⑤ Electron ion recombination terminal
⑥ Radioactive ion beam physics terminal



Introduction

- HIAF is aimed to provide the ultra-high intensity heavy ion bunches **(~10^{11} ppp)**
- Improve the average power as much as possible (operation cycle **~3 Hz**)

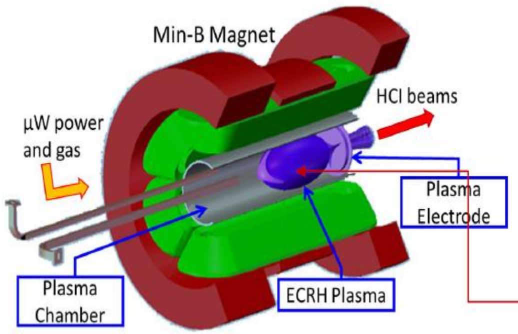
	iLinac	BRing	SRing	FAIR
Length / circumference (m)	114	569	277	*1080*
Final energy of U (MeV/u)	17 (U^{35+})	835 (U^{35+})	835 (U^{92+})	*2700 (U^{28+})*
Max. magnetic rigidity (Tm)	---	**34**	15	*100*
Max. beam intensity of U	28 pμA (U^{35+})	**1×10^{11}ppp (U^{35+})**	**$(2\sim4)\times10^{11}$ppp (U^{92+})**	*4×10^{11}ppp (U^{28+})*
Operation mode	CW or pulse	**fast ramping (12T/s, 3Hz)**	**DC**	*0.5*



How can we achieve this design goal?

Challenges and solutions

- **A powerful ion source is needed**



Plasma Magnet Microwave

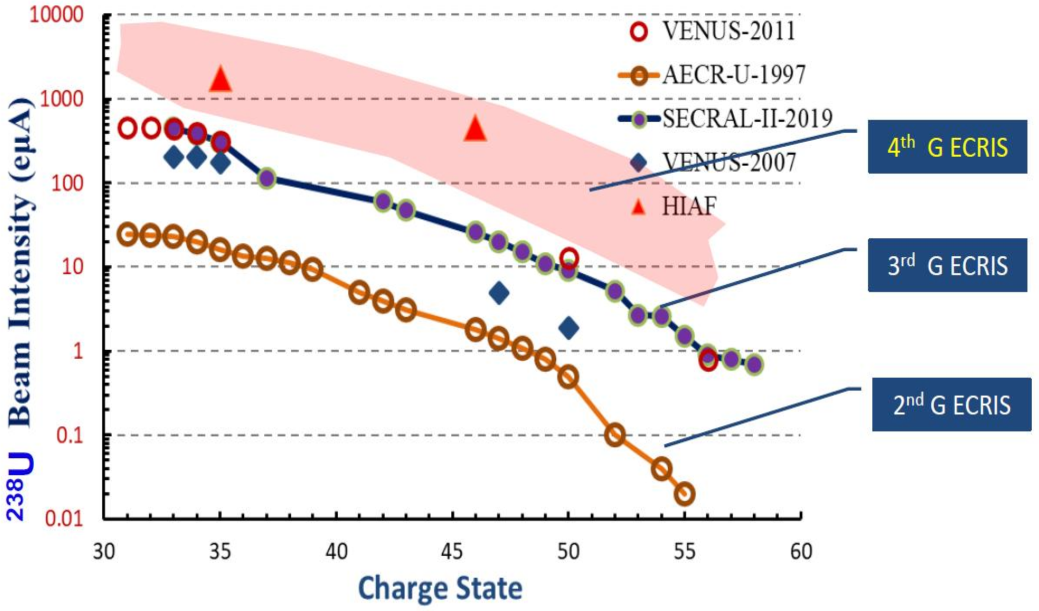
Electron Cyclotron Resonance

Ion Source

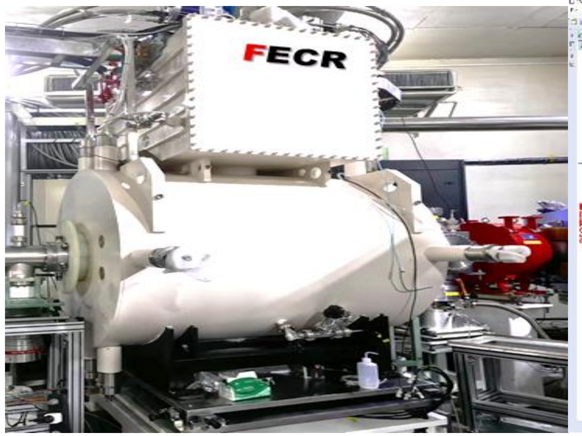
$$\omega_{ce} = \frac{e \cdot B_{ecr}}{m_e}$$

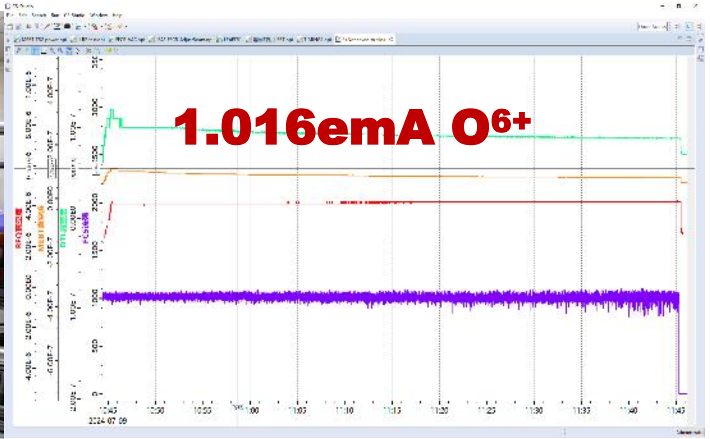
- ECR (electron cyclotron resonance) ion source, use a magnetic field and microwave to create, confine and heat a dense plasma, leading to the efficient production of highly charged ion
- Hot electrons collide with neutral gas atoms, knock out one or more electrons
- Longer an ion is confined in presence of the hot electrons, higher charge states become

A highly charged heavy ion could be created with high magnetic field and high microwave frequency



f=45 GHz, B=1.6 T, the 4th generation ECR ion source





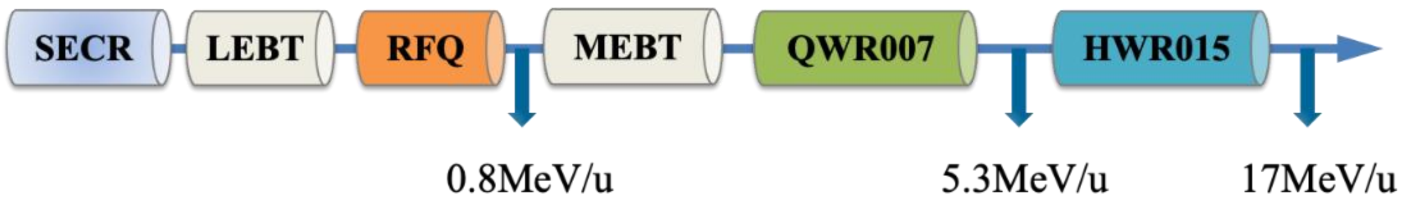
---L. Sun, ICIS'23

☐ Challenges and solutions

Goal:

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

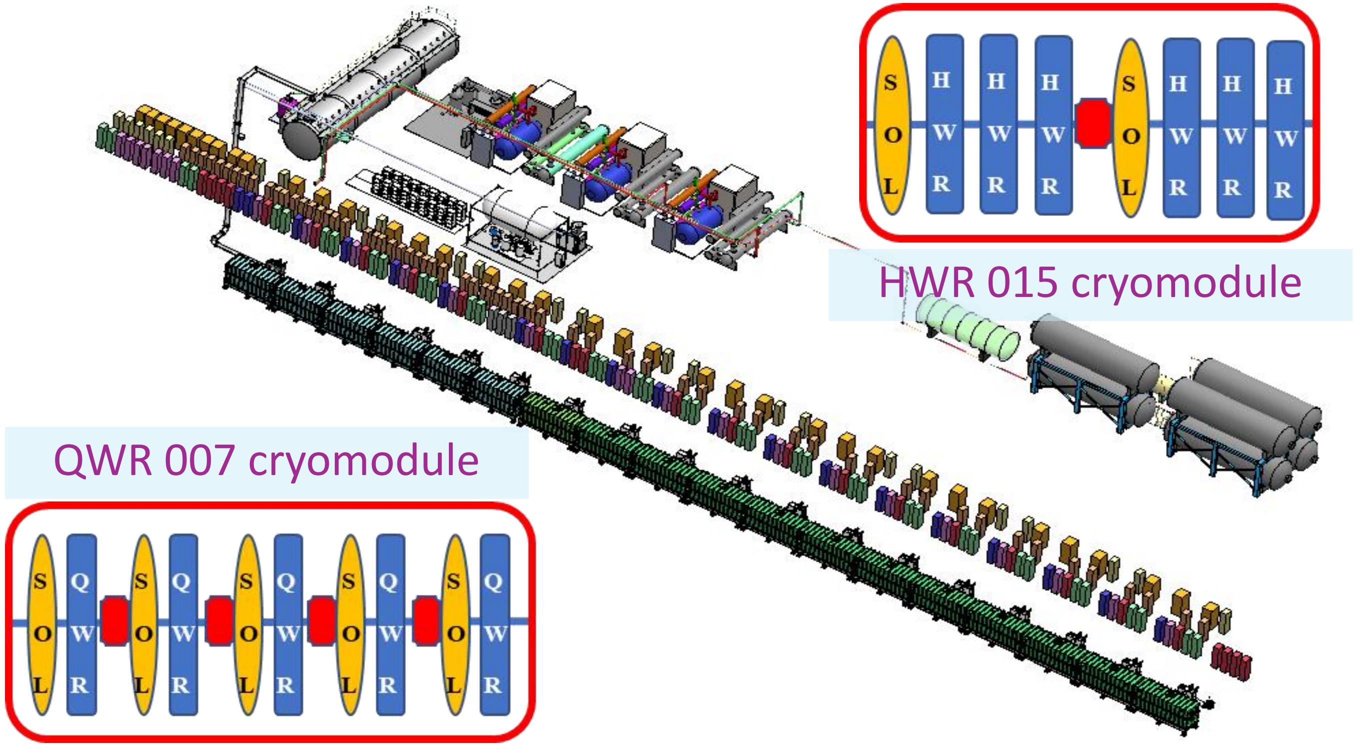
- **A CW superconducting linac is wonderful**



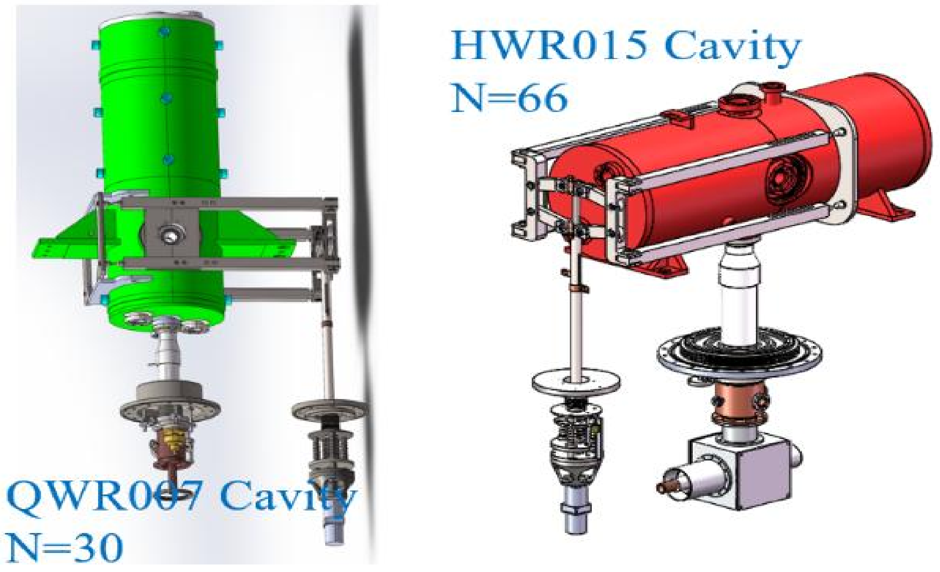
To BRing with 3 Hz pulsed beam

To low energy terminal with CW beam

Linac consists of 6 QWR 007 cryomodules and 11 HWR 015 cryomodules

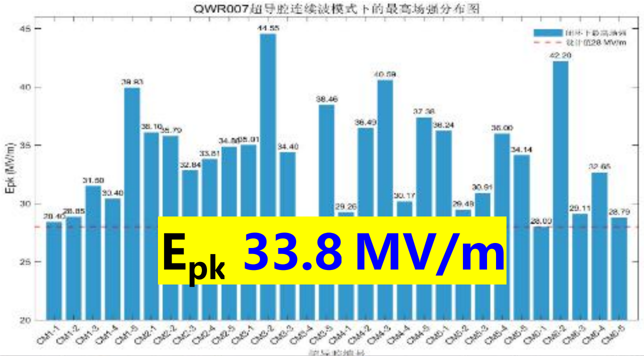


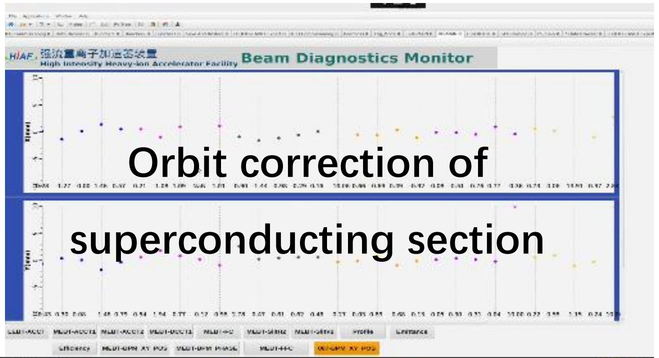
2 types of cavities: QWR 007 and HWR 015

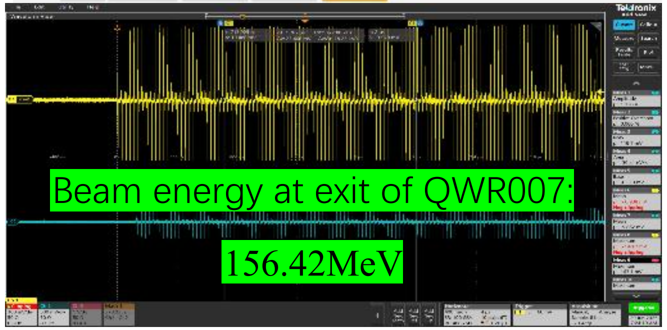


Challenges and solutions

- It only takes 12 months from QWR007 cavity processing to stable operation
- The average E_{pk} of QWR007 at CW mode achieves 33.8 MV/m, 20.7% higher than the designed parameter. It verifies the new process, new method and new route
- Initial beam commissioning for QWR007 section has been completed with $^{16}O^{6+}$. HWR015 will be cool down in the middle of Oct., followed by beam commissioning



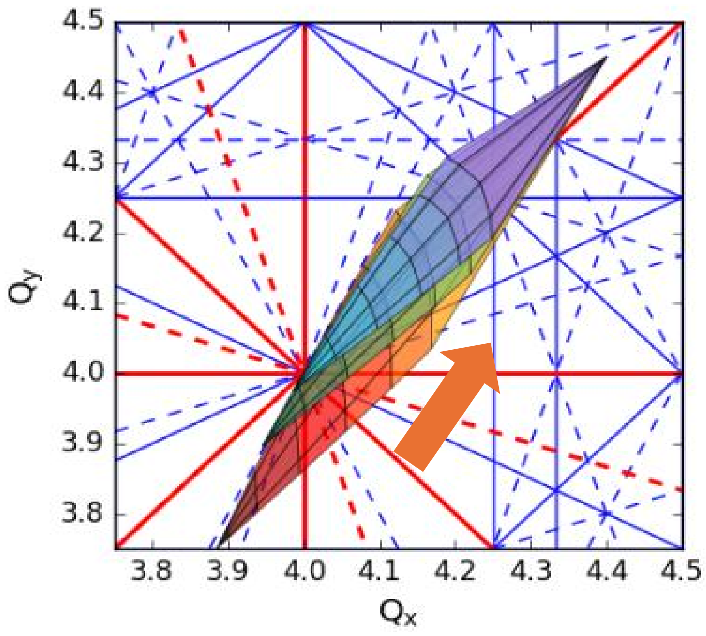




Challenges and solutions

- **A fast ramping synchrotron is necessary**

- Working point (oscillation frequency) for each particle is different
- Beam loss due to resonance or dynamic vacuum effect
- **Fast ramping acceleration** is a possible way to avoid the beam loss



0.6T/s @ HIRFL

↓

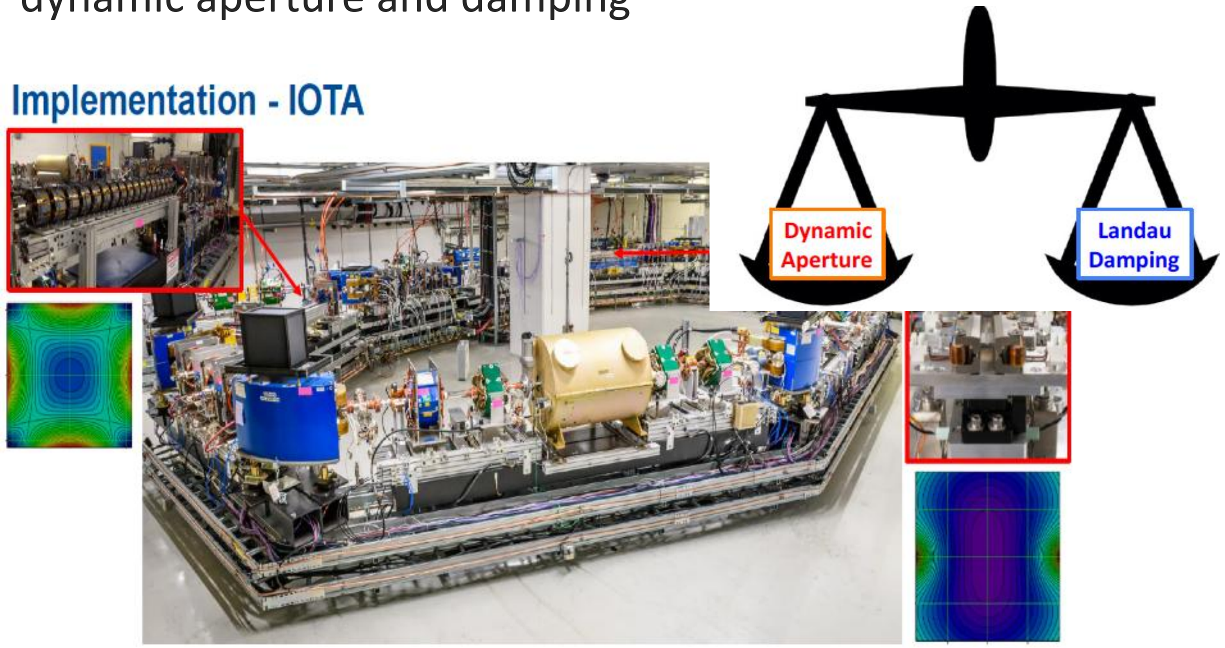
10T/s @ SIS 18

↓

12T/s @ BRing

Tune spread depends on space charge effect, with the normalized factor γβ

Nonlinear integrable optics to find a balance between dynamic aperture and damping

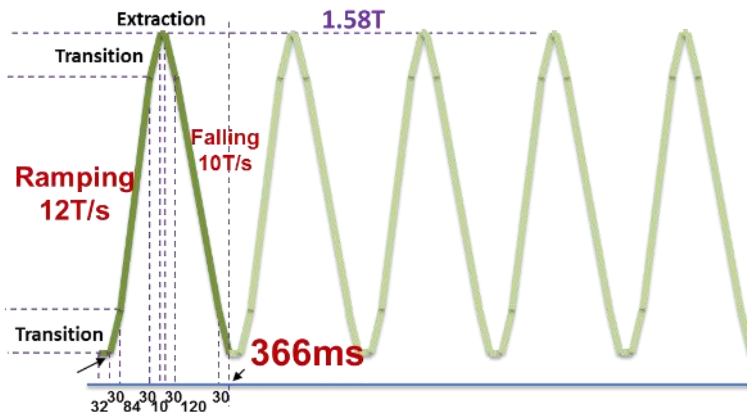


☐ Challenges and solutions

- Challenges

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

Acceleration before instabilities

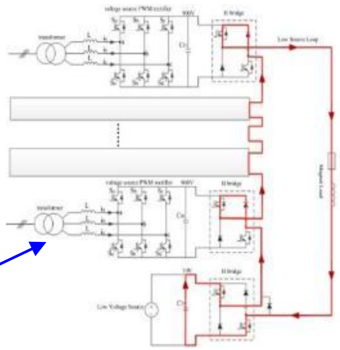
The highest ramping rate for heavy ion synchrotron, challenges for power supply、RF cavities and vacuum chamber

- Very high current ramping rate up to **38 kA/s** for dipole PS, drive 12 T/s magnetic field ramping rate
- High acceleration voltage up to **240 kV/turn**, satisfy to energy gain
- Thin wall vacuum chamber less than **0.3 mm**, avoid distortion with eddy current

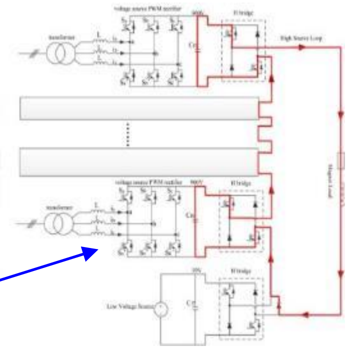
Challenges and solutions

- **Fast ramping rate full energy storage power supply for dipoles and quadrupoles**

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

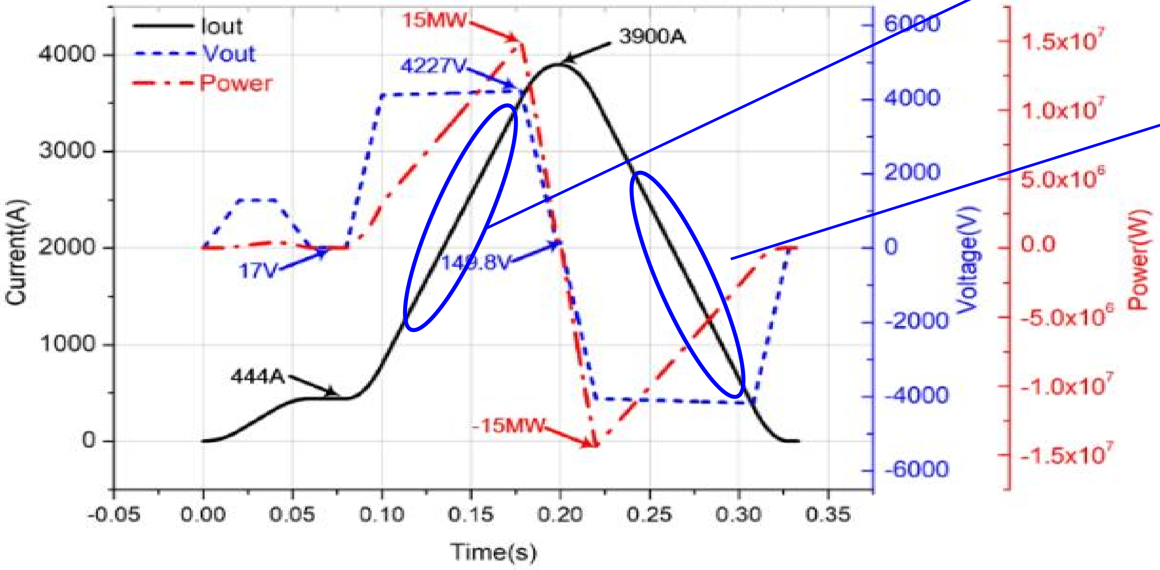


Energy from capacitor tank to magnet load



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!

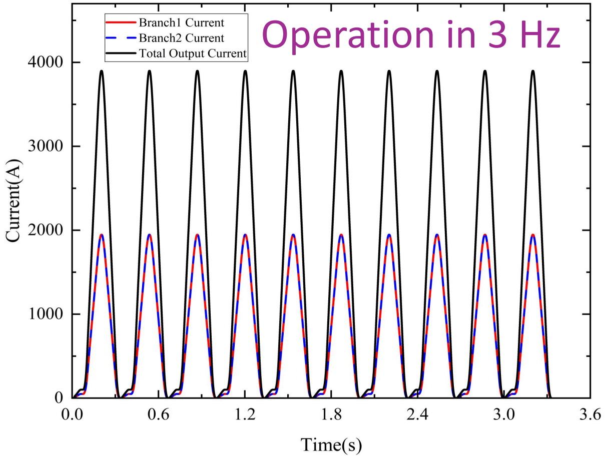
☐ Challenges and solutions

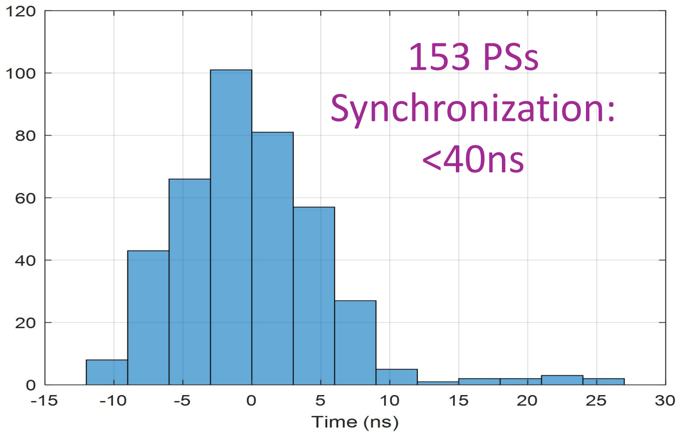
- Reduce the power consumption

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

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

PS of dipoles and quadrupoles in the hall



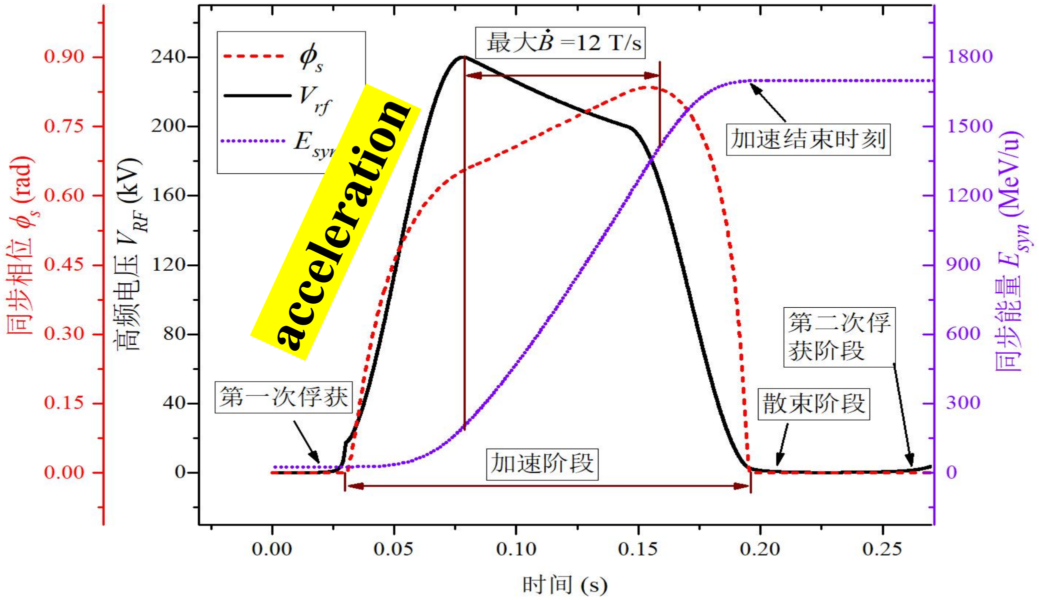


621 power supplies have been installed and debugged successfully. The test results of the power supplies meet the specified requirements.

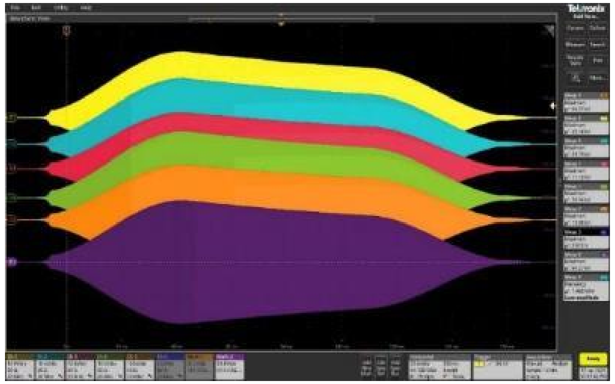
◻ Challenges and solutions

- **Magnetic ally core loaded RF system**

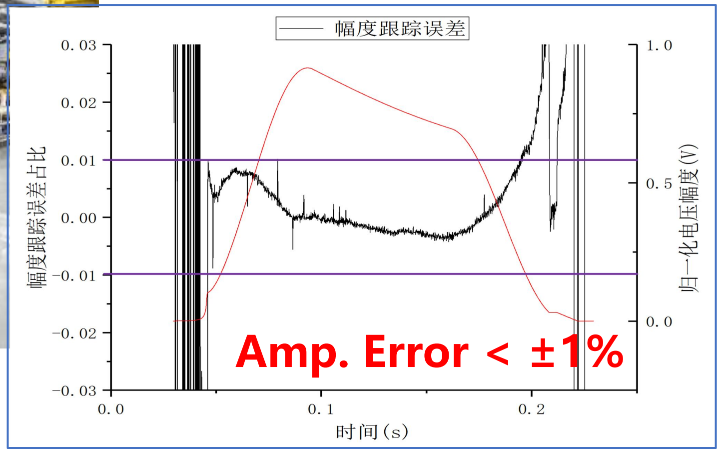
To satisfy fast acceleration, the voltage for total RF system should be **240 kV**



Gradient of traditional ferrite is only **~10kV/m**, long dispersion-free space is needed, challenges for beam optical design



Cavities in tunnel



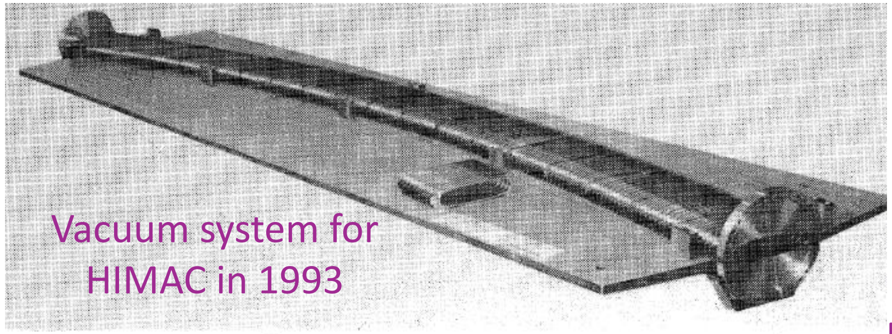
Facilities	Voltage (kV)	Length (m)	Gradient (kV/m)
JPARC-RCS	41	1.78	23
JPARC-MR	46.7	1.78	26.2
SIS18	50	2	25
HIAF-BRing	**70**	**2**	**35**

◻ Challenges and solutions

- **Titanium alloy-lined thin-walled vacuum chamber**

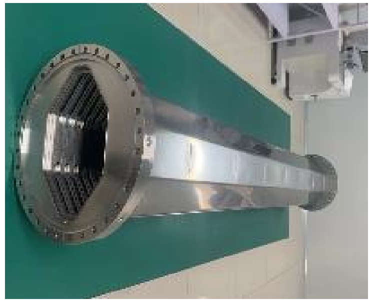
Problem: fast ramping of the magnets induces eddy currents:

- The chamber walls are heated
- Generation of additional harmonics in field

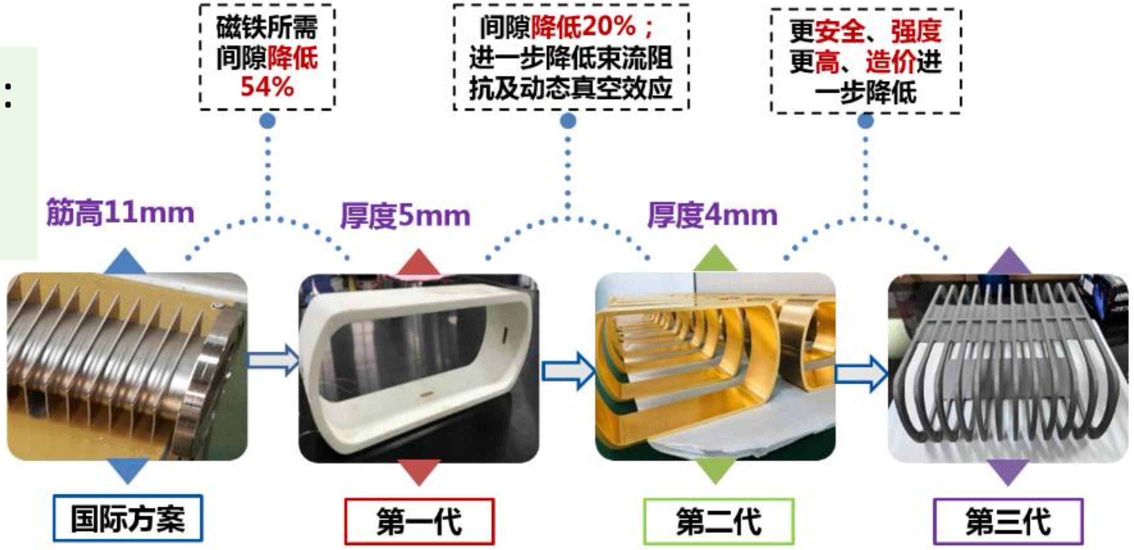


Vacuum system for HIMAC in 1993

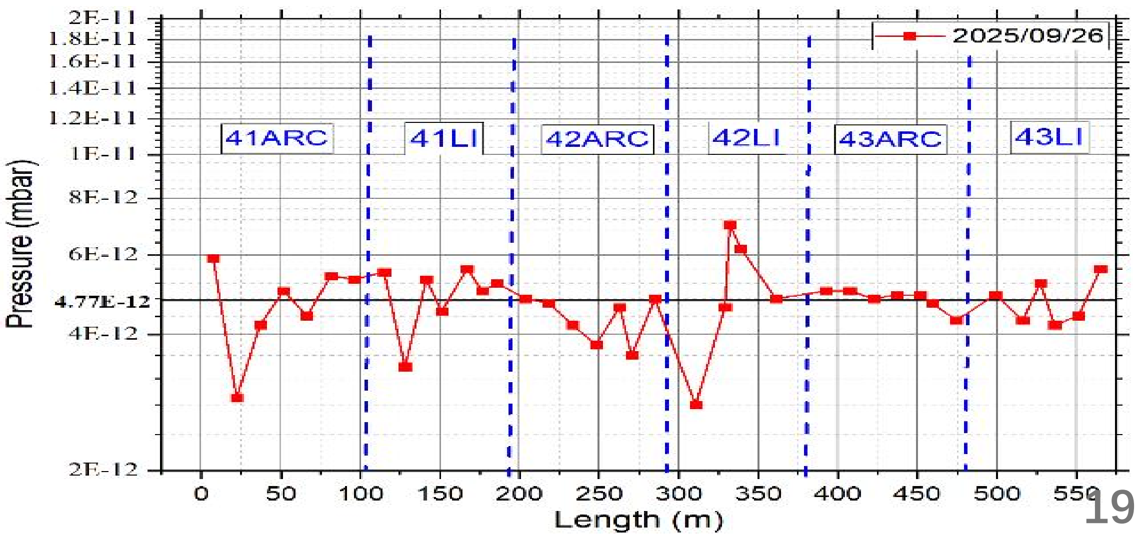
Figure 1a. One section of vacuum chamber set on a steel plate with the same curvature as the bending magnet.



Rings inside @ IMP



average vacuum better than 5×10^{-12}mbar



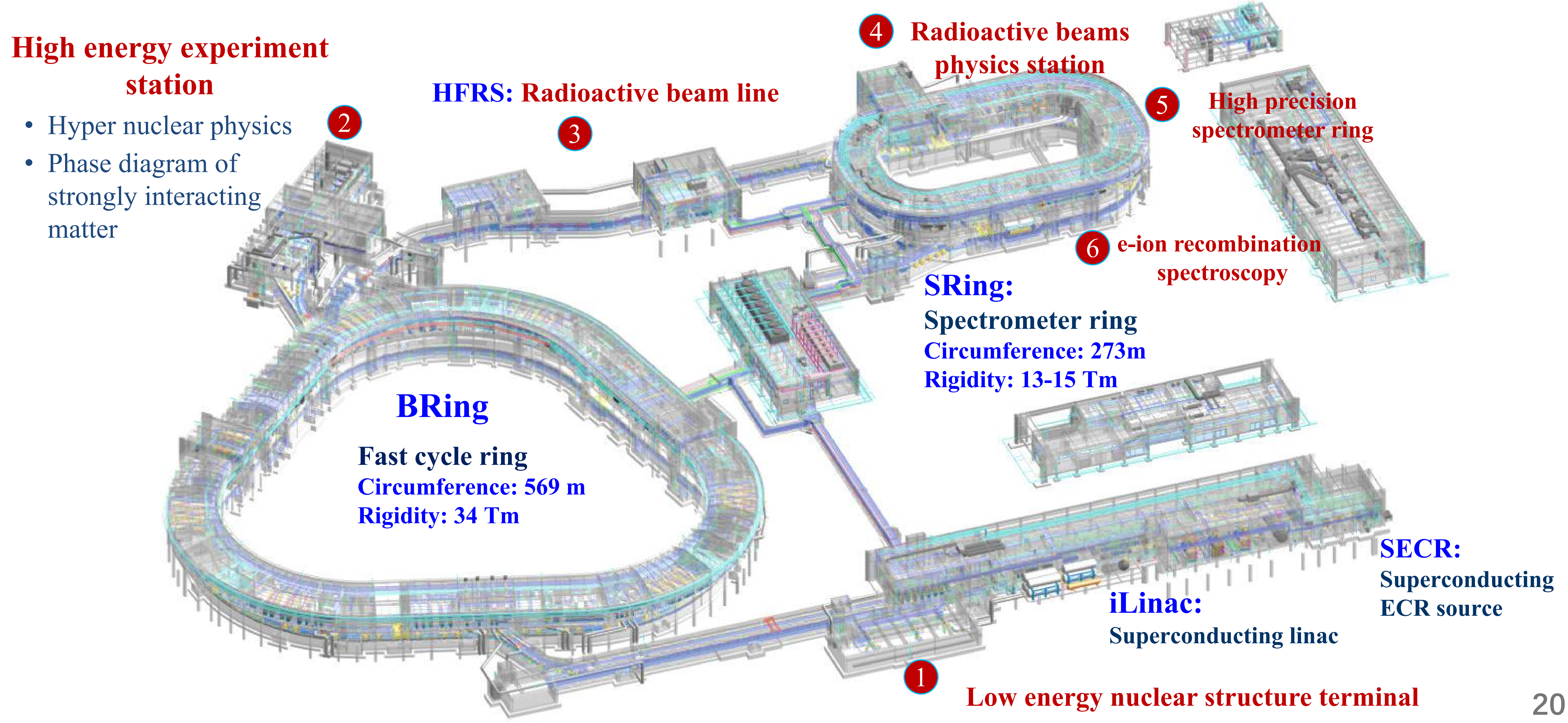
Solution from GSI

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

Quadrupole Chamber

Experimental terminals

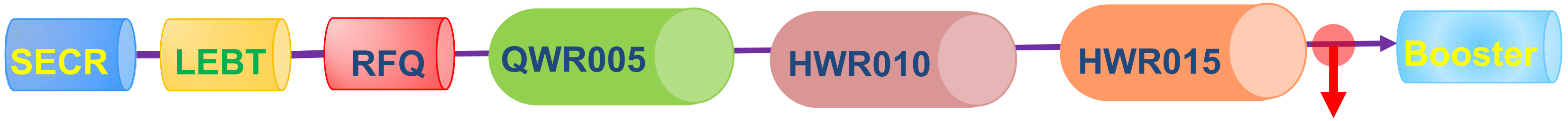
- Distribution of 6 experimental terminals



☐ Experimental terminals

- Low energy nuclear structure terminal

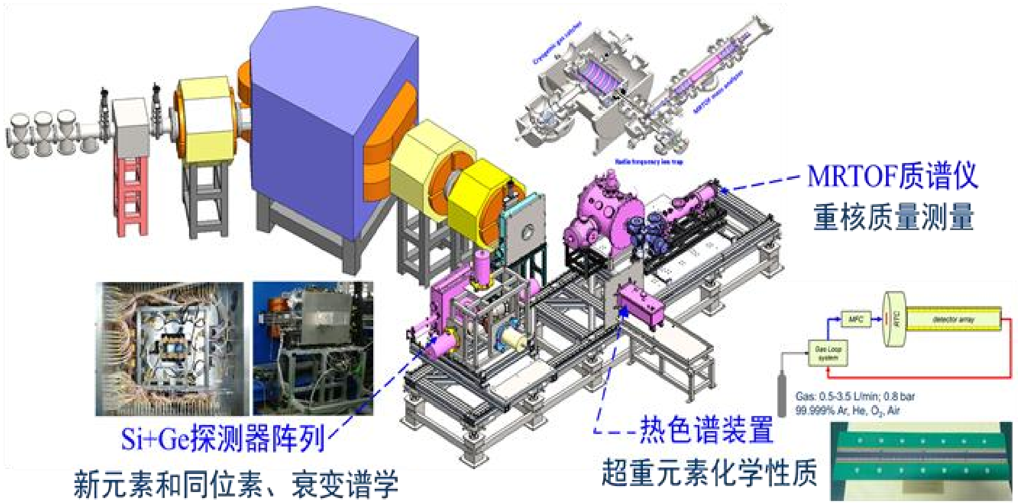
Use the CW beam provided by iLinac for **new element discovery**



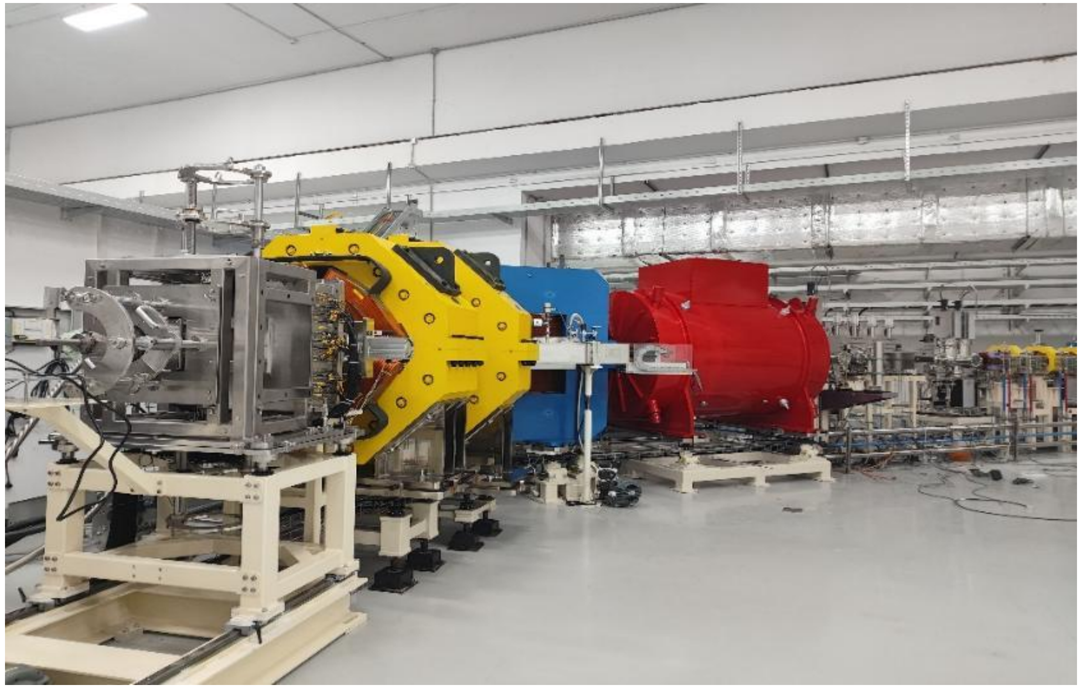
Energy Adjustable

CW mode:

10 pμA beams with A/Q=2~5



Gas-filled recoil separator

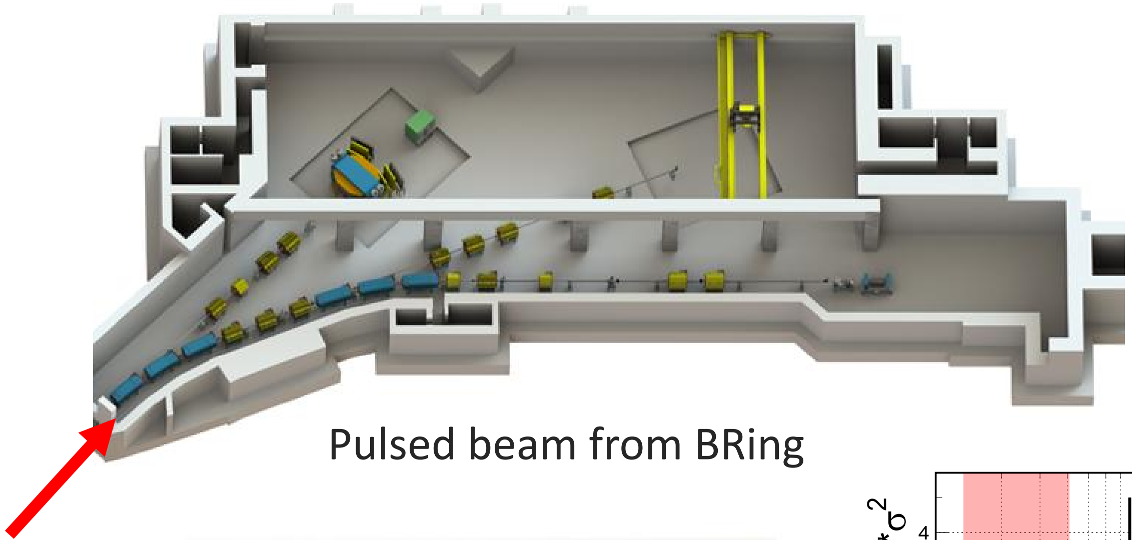


Experimental terminals

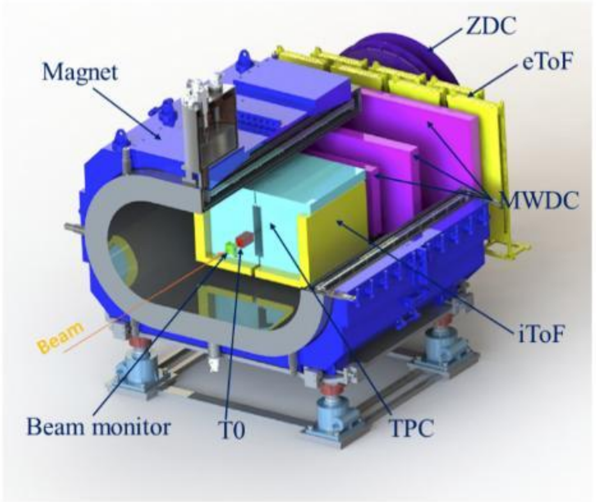
- High energy experimental station

Typical beam parameters from the Booster Ring

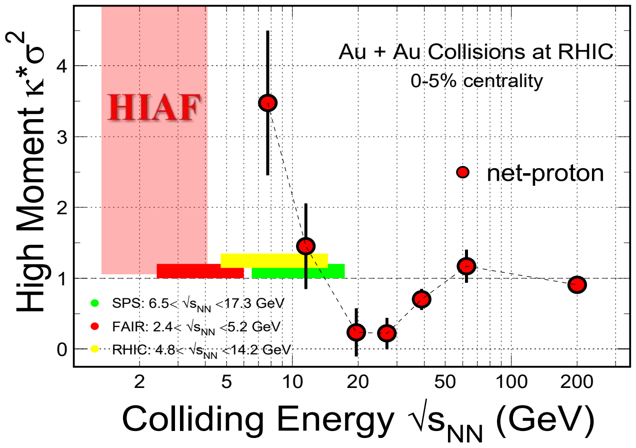
Ions	Energy(GeV/u)	Intensity (ppp)
p	9.3	2.0×10^{12}
$^{18}O^{6+}$	2.6	6.0×10^{11}
$^{78}Kr^{19+}$	1.7	3.0×10^{11}
$^{209}Bi^{31+}$	0.85	1.2×10^{11}
$^{238}U^{34+}$	0.8	1.0×10^{11}



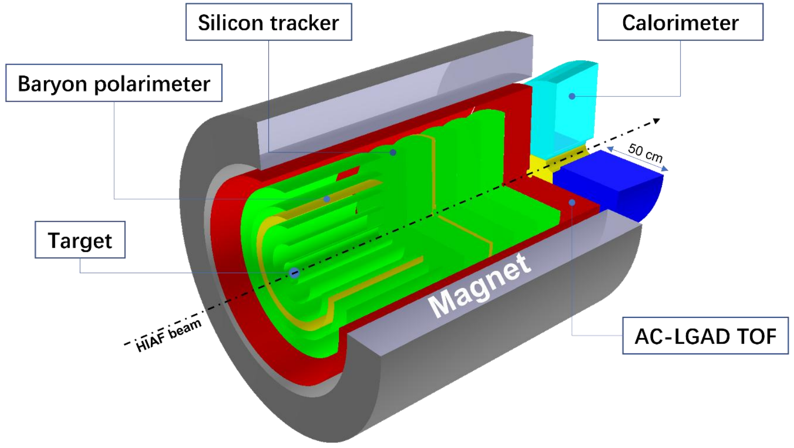
Pulsed beam from BRing



The External Target Experiment Setup



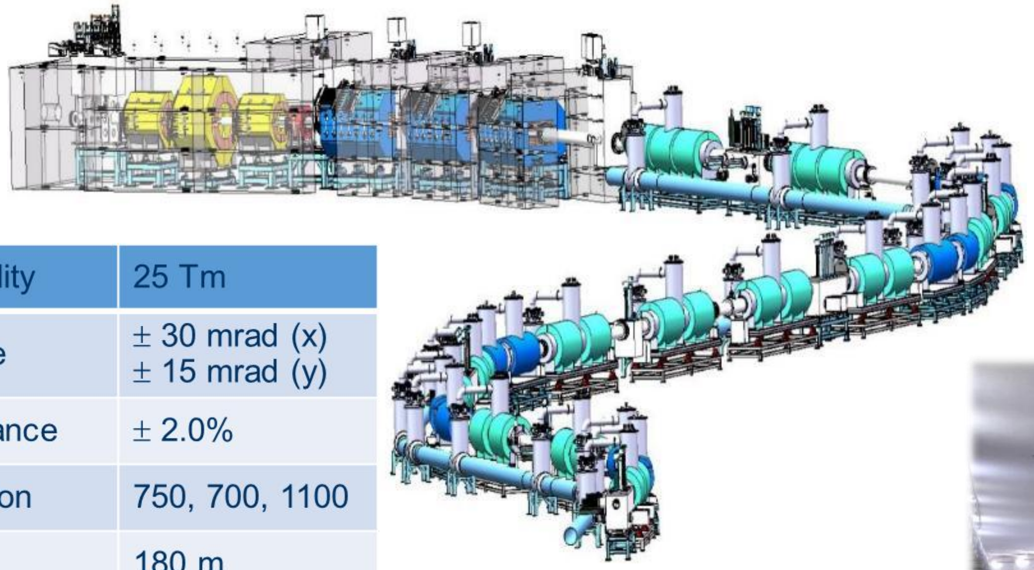
Study of the QCD Phase Structure



Hyperon-Nucleon Spectrometer (H-NS)

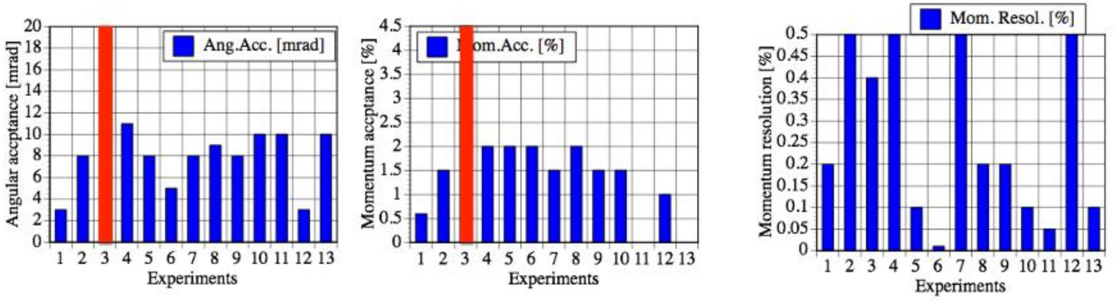
Experimental terminals

- **High Energy Fragment Separator (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



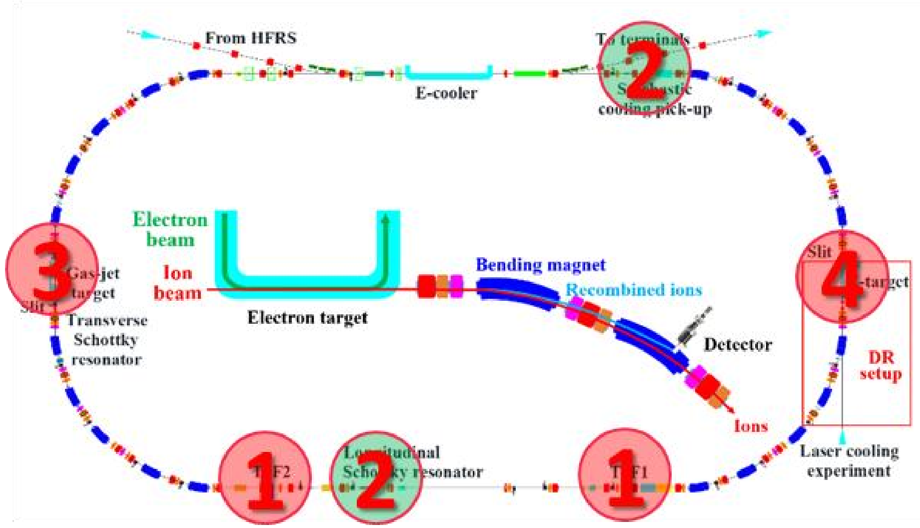
Acceptance, and Momentum Resolution

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) …

◻ Experimental terminals

- **Spectrometer Ring: Multi Working Modes of Storage Ring**



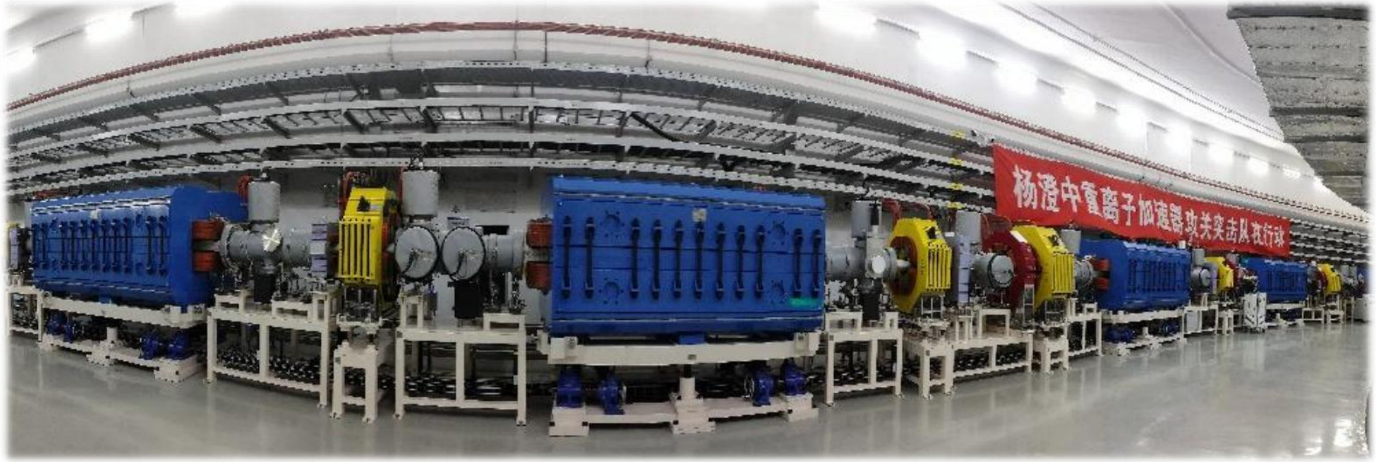
With fast extracted projectiles from the Booster, HFRS produces, separates and injects the isotopes of interests into the Spectrometer Ring

Experiments:

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

Spectrometer Ring:

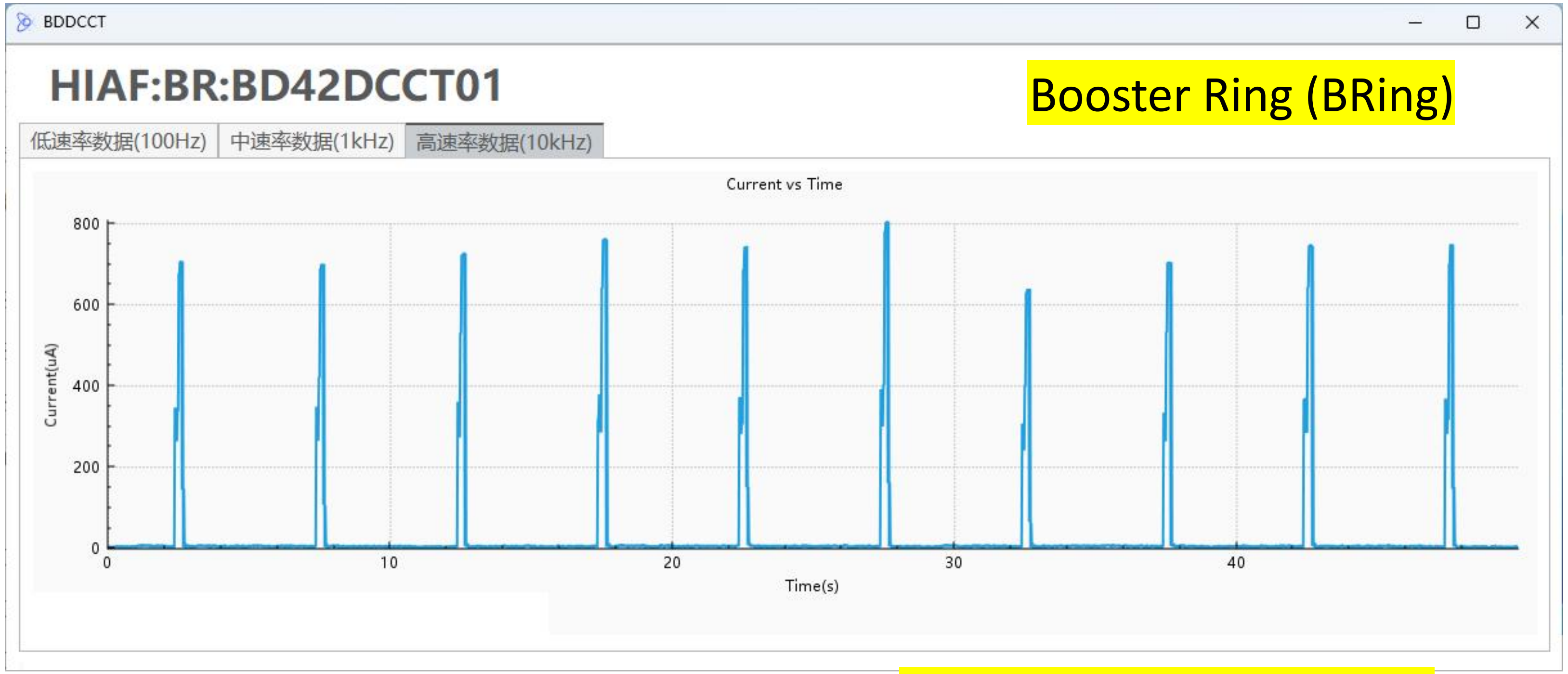
- Circumference:273 m
- Rigidity: 15 Tm
- Electron cooler
- Stochastic cooler

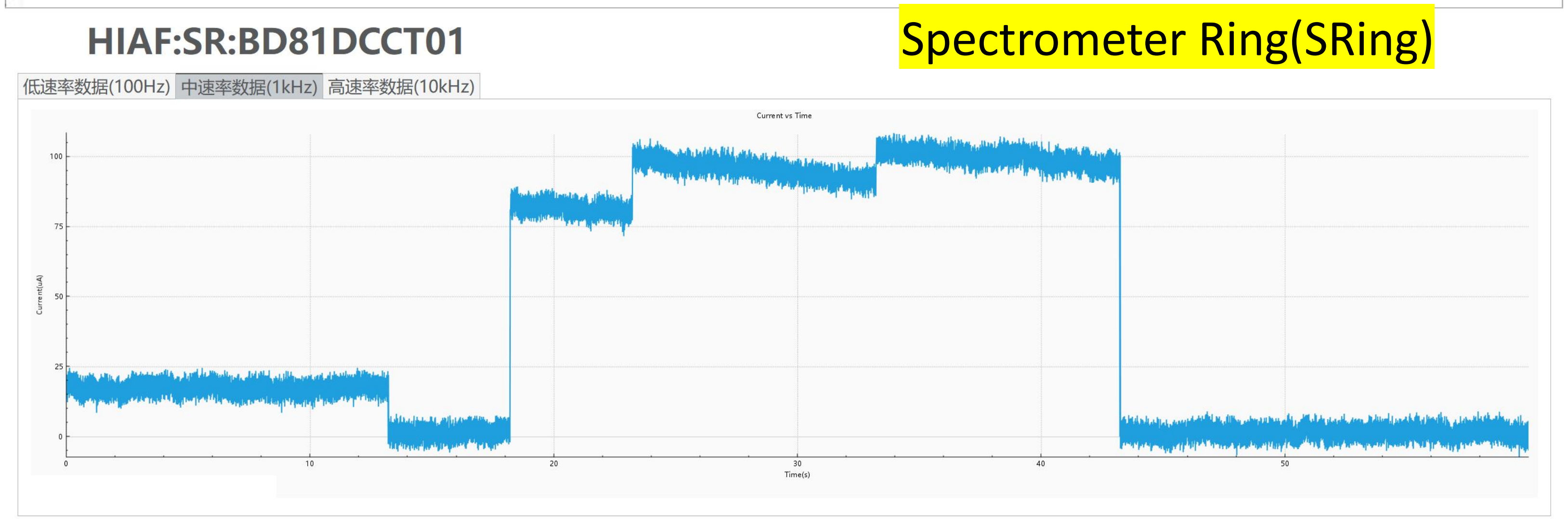


☐ Current status

- The first dipole was moved into the tunnel in 27^{th} March, 2024
- The first beam was injected, accelerated in BRing in 27^{th} October, 2025

□ Current status

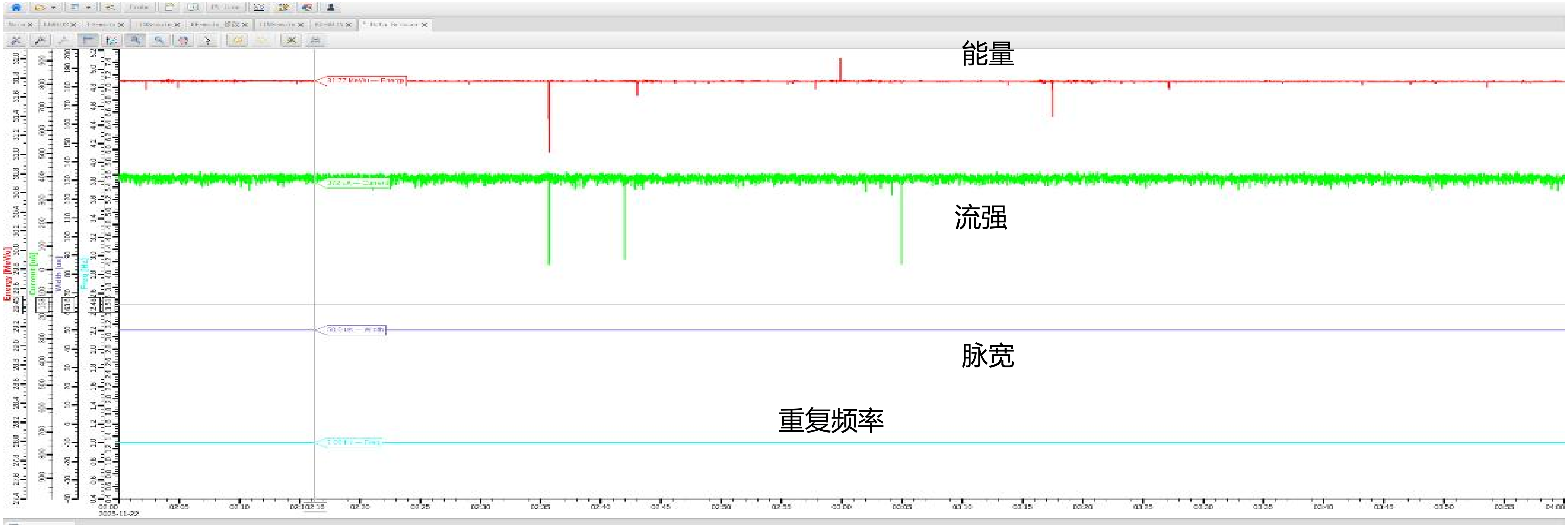




☐ Current status

- iLinac commissioning results

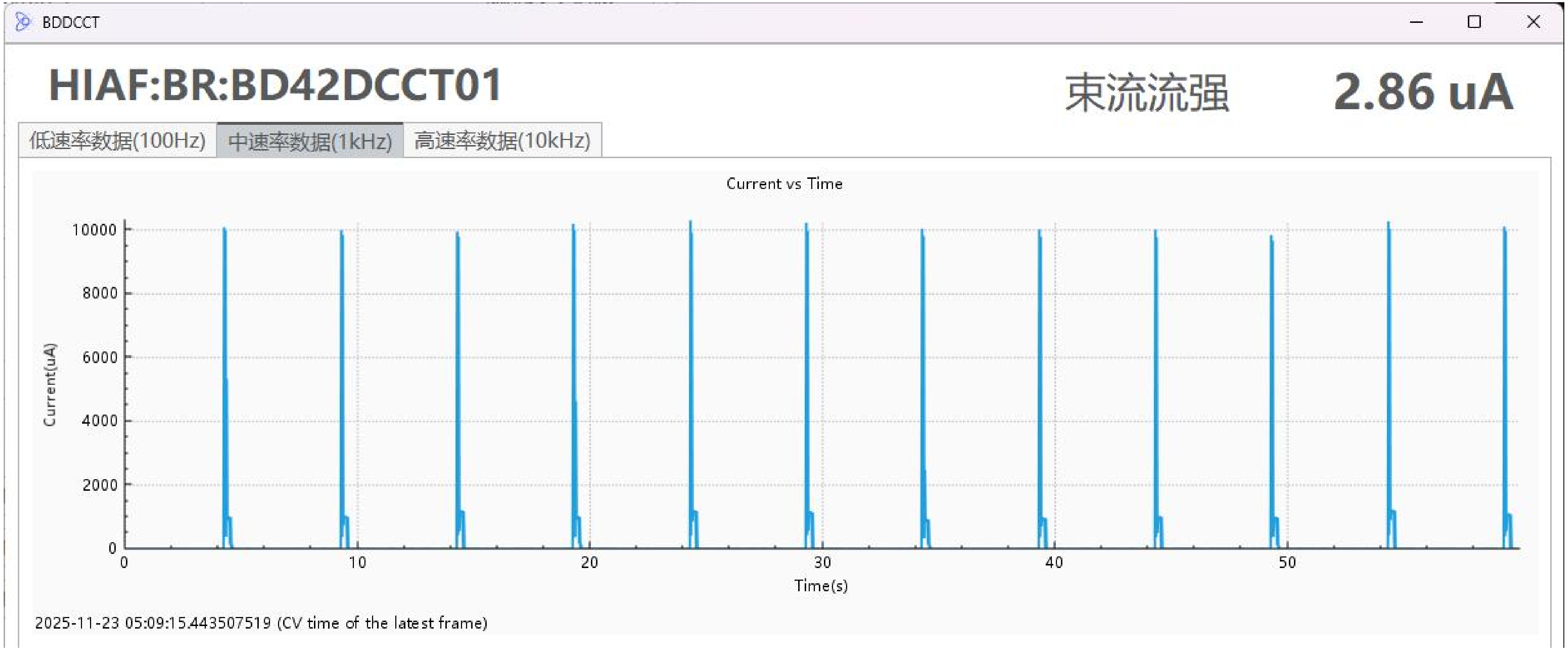
- ion: ${}^{18}_{8}O^{6+}$
- energy: ≤33.20±0.01MeV/u
- current: ~400uA
- frequency: 0.2-5Hz
- pulse width: 20-800us



☐ Current status

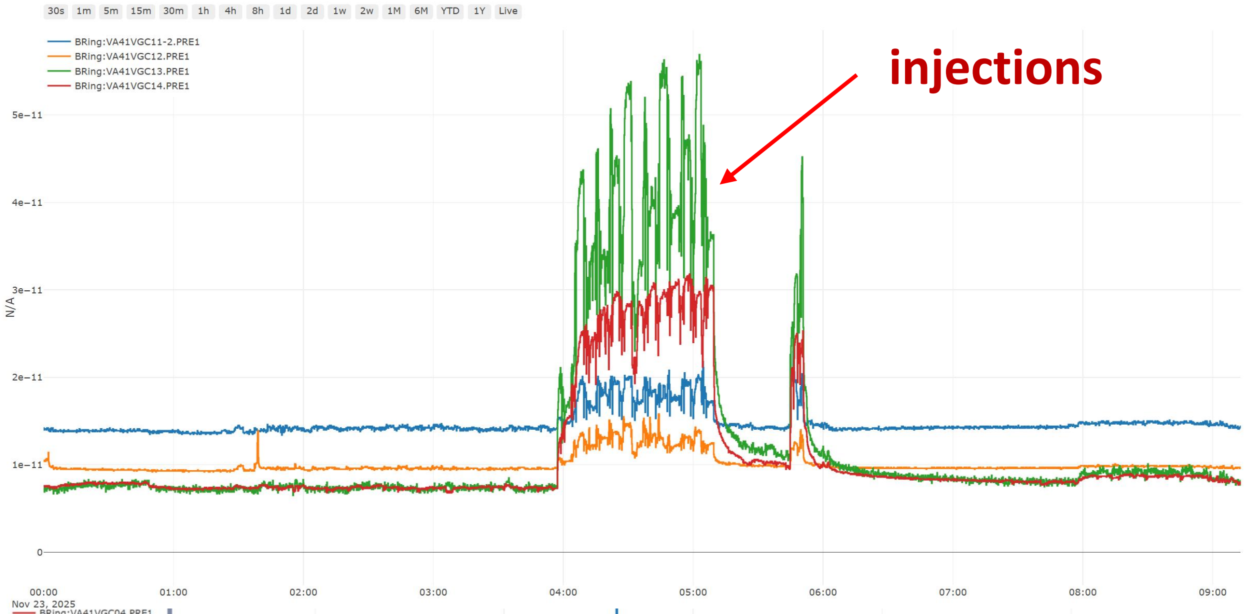
- BRing commissioning results

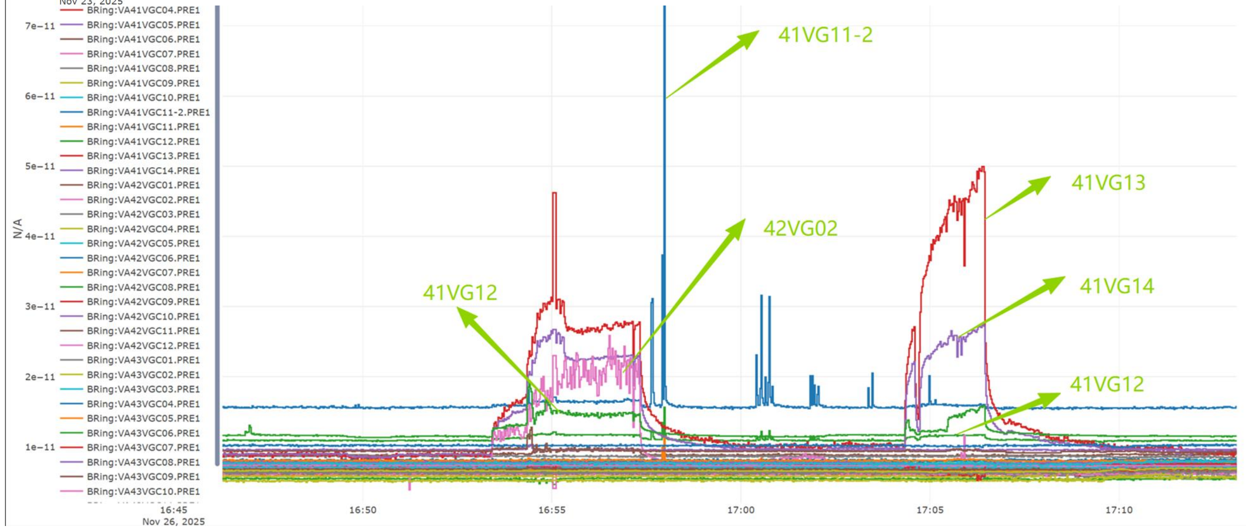
- ion: ${}^{18}_{8}O^{6+}$
- current: ~10 mA
- particle number: 8×10^{10} ppp

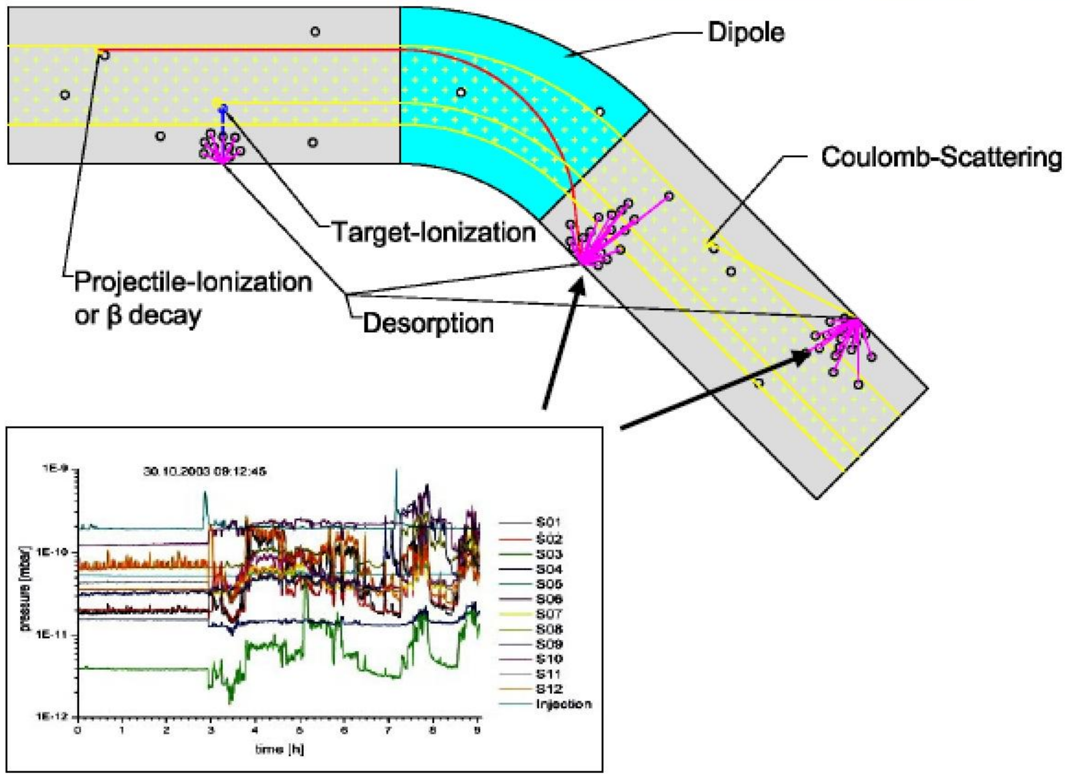


☐ Current status

- Dynamic vacuum effect???

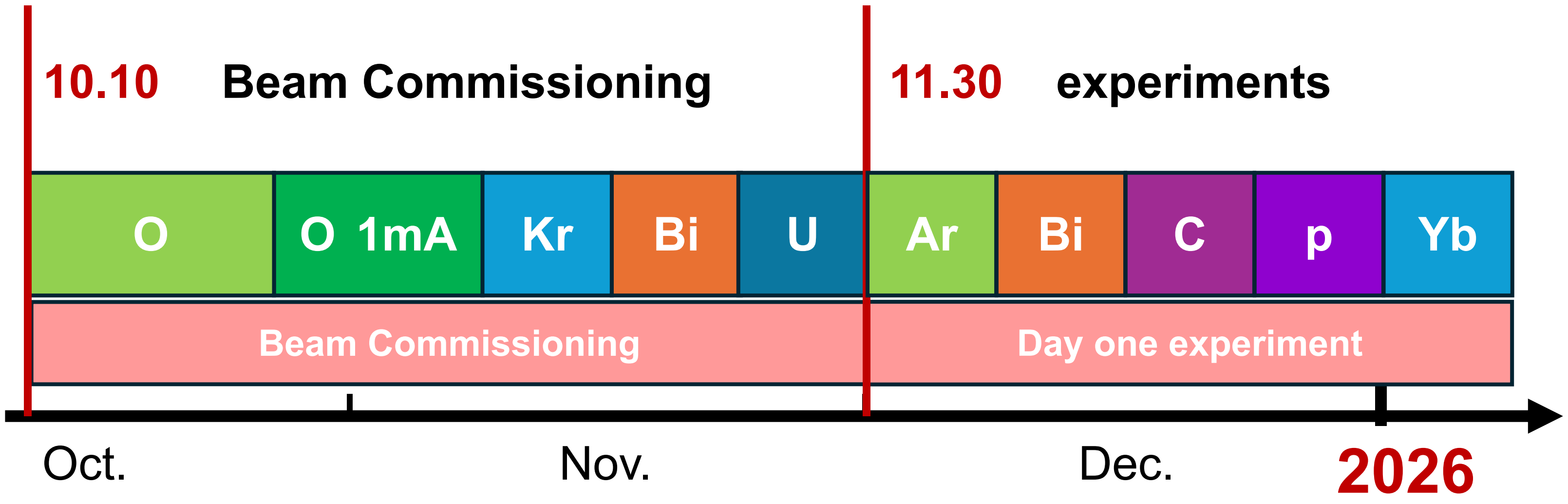






- Ion induced gas desorption increases the local pressure
- Life time depends strongly on the residual gas pressure

☐ Current status



	Ion	iLinac Energy (MeV/u)	iLinac Intensity (eμA)	BRing Energy (MeV/u)	BRing Intensity (ppp)
Phase I	$^{18}O^{6+}$	33	100	830	1×10^{10}
				2600	
Phase II	$^{18}O^{6+}$	33	1000	2600	4×10^{11}
Phase III	$^{78}Kr^{19+}$	25	300	1700	5×10^{10}
	$^{209}Bi^{31+}$	17	400	850	5×10^{10}
	$^{238}U^{35+}$	17	400	835	5×10^{10}

☐ Protons

The Energy Transition Factor denoted by γ_t is a fundamental parameter that describes the relationship between a particle's momentum and its revolution frequency in a circular accelerator.

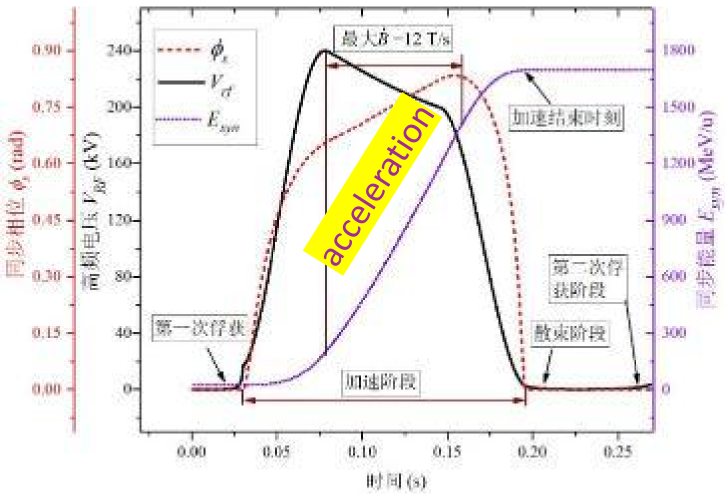
$\gamma < \gamma_t$

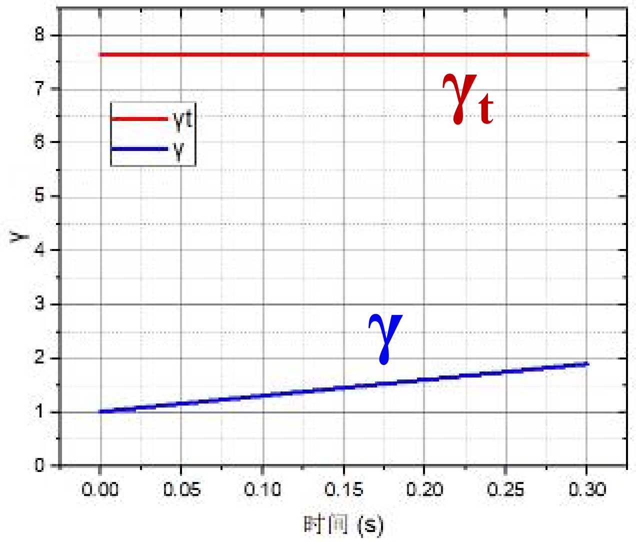
Higher energy particles move “**faster**” than lower energy particles

$\gamma > \gamma_t$

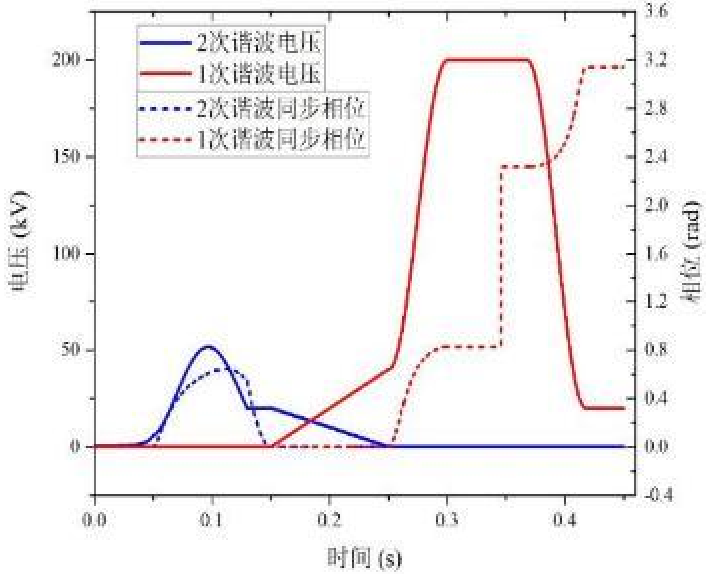
Higher energy particles move “**slowly**” than lower energy particles

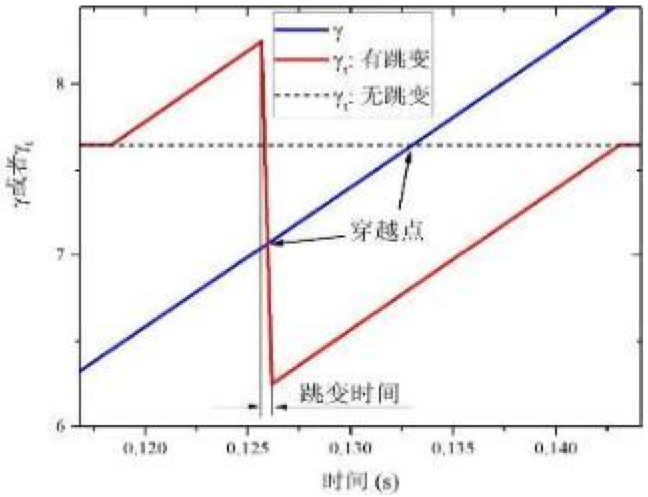
- Heavy ion acceleration





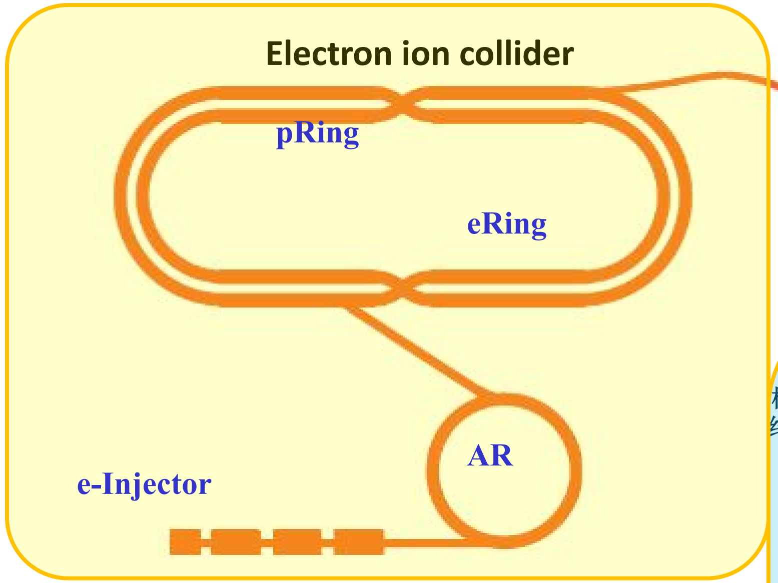
- Proton acceleration





☐ Future plan

CNUF-China advanced NUclear physics research Facility

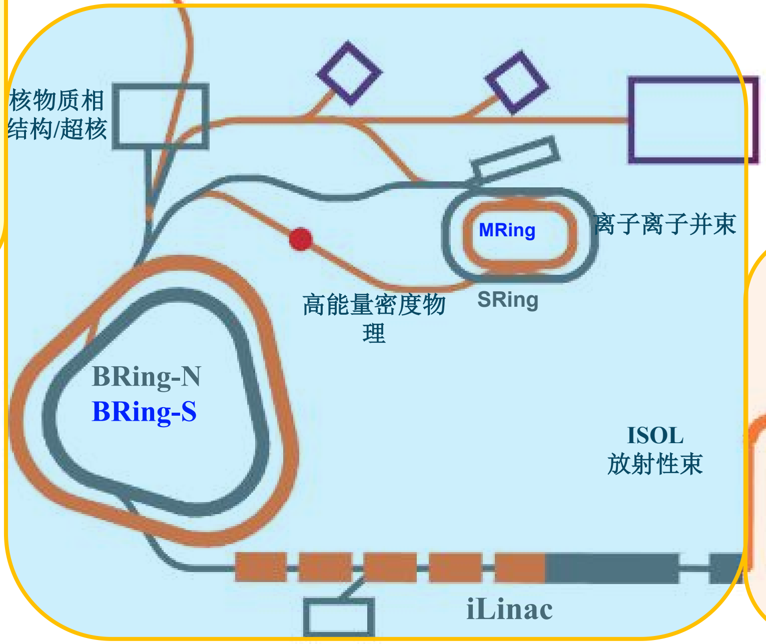


☐ Electron ion collider in China (EicC)

Precision measurements of the structure of the nucleon in the sea quark region

☐ Upgrade of the HIAF (HIAF-U)

Improve the energy up to 25 GeV (p) and 9 GeV (U)



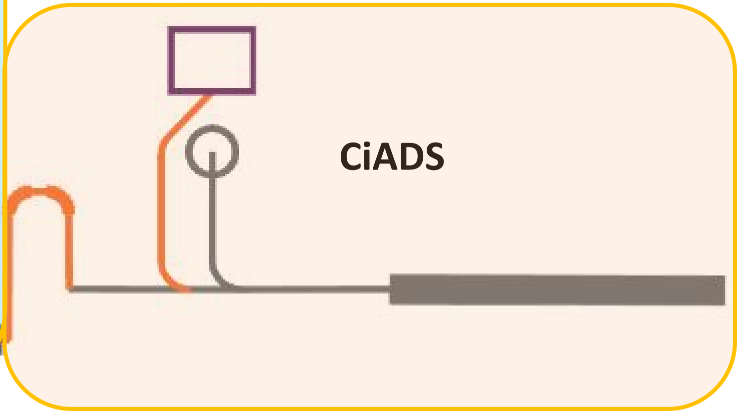
New accelerators

Under construction

New terminal

☐ Isotope Separation On-Line (ISOL)

Provide MW beam for stable high atomic number elements



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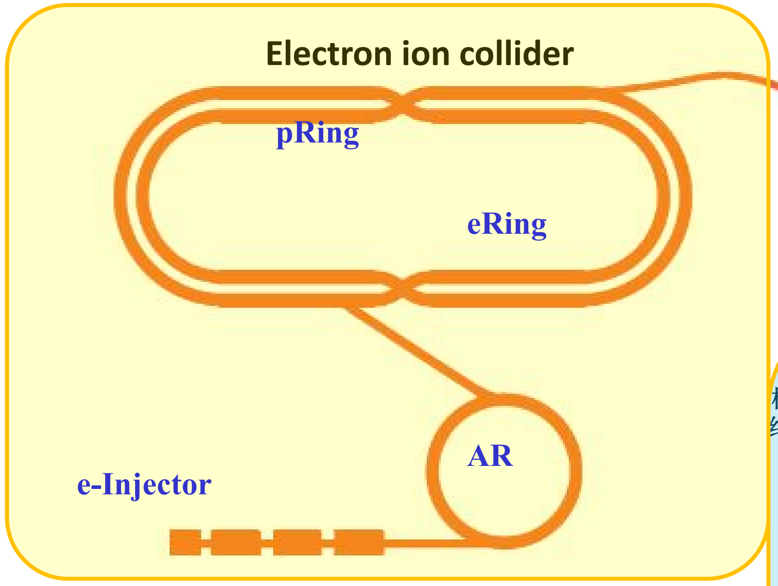
CNUF-China advanced NUclear physics research Facility



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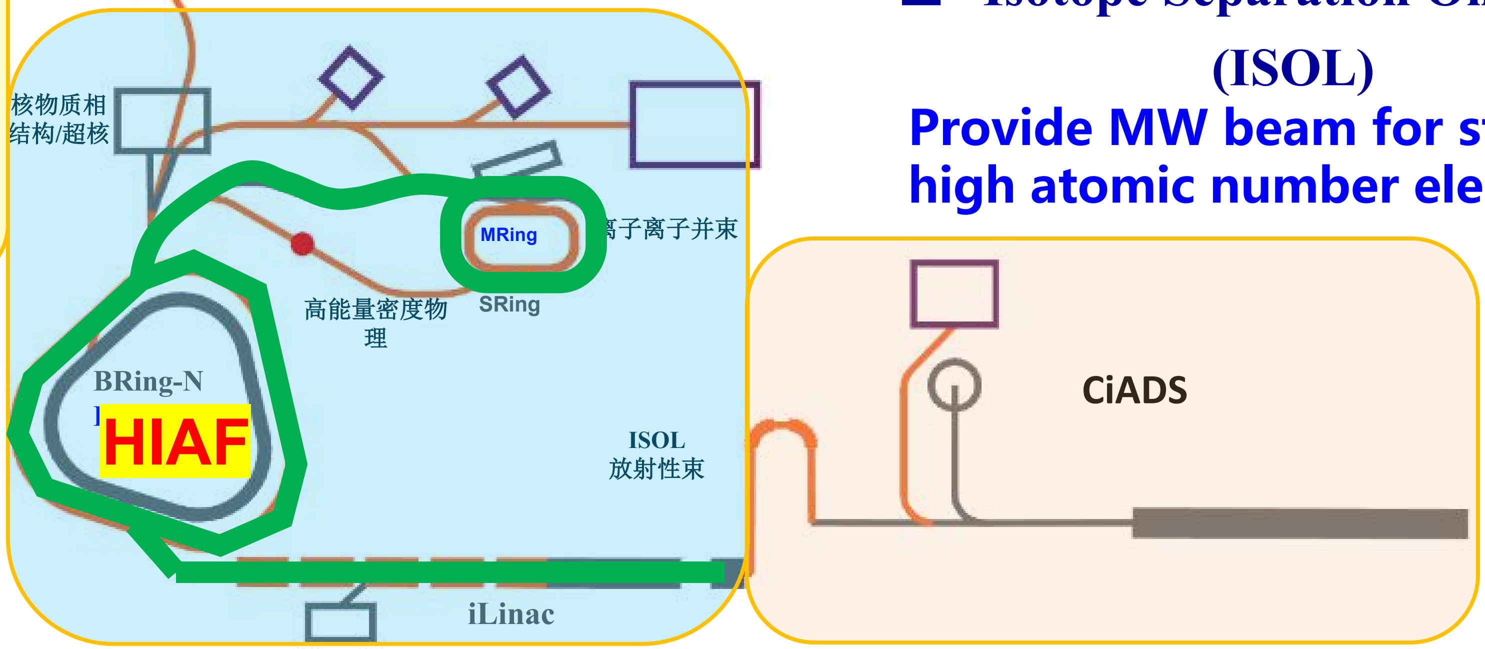

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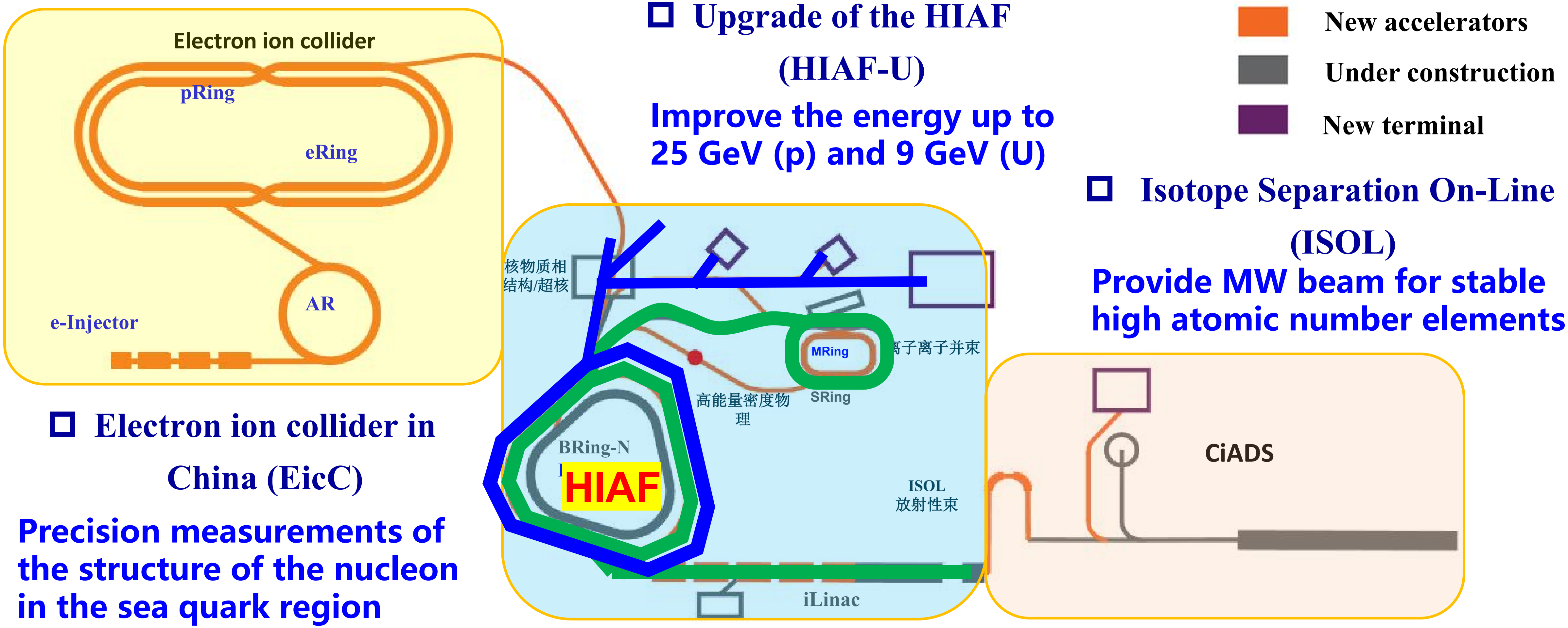

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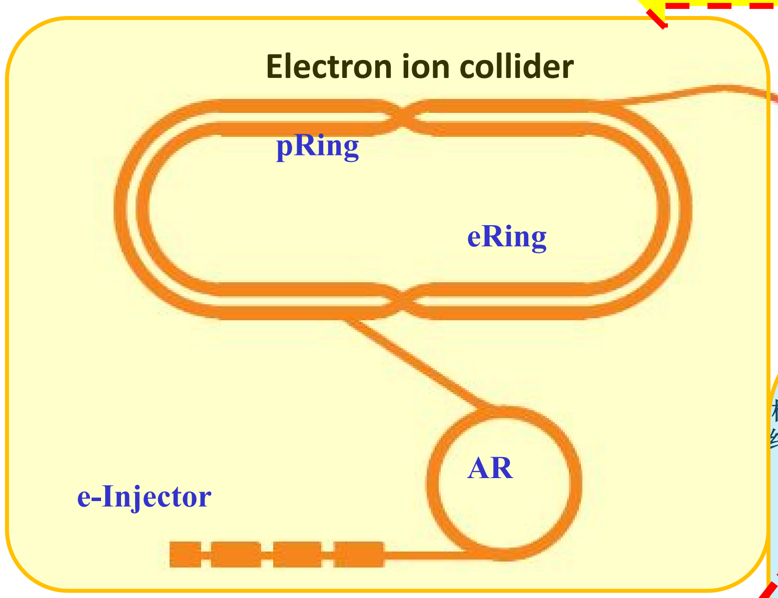

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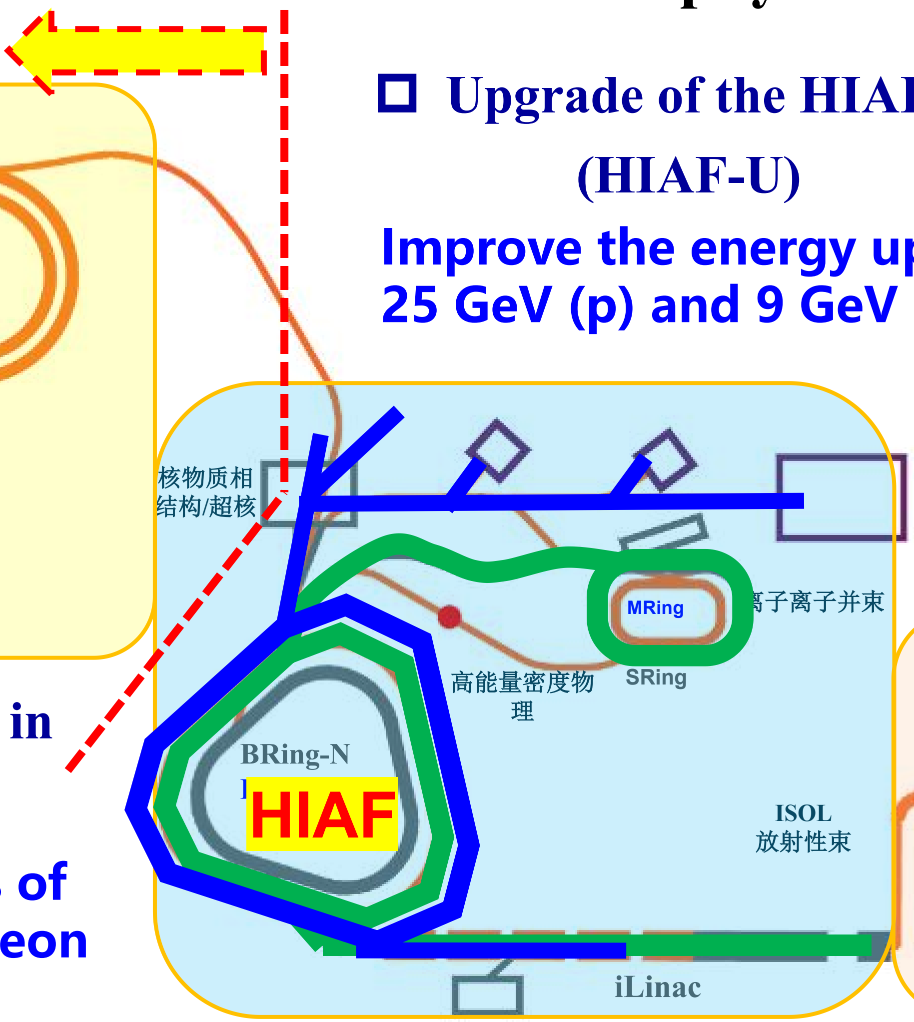

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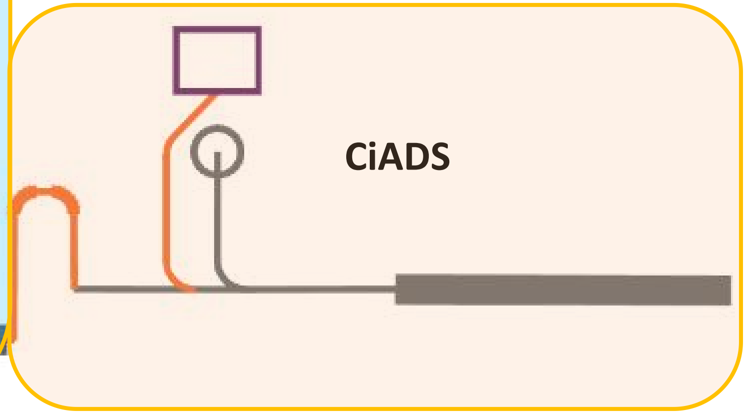

Future plan

Institution	Facilities	Time	Reference ion	Energy	Intensity or power
GSI	FAIR SIS100	2025	$^{238}U^{28+}$	2. 7 GeV/u	5×10^{11} ppp
MSU	FRIB	2021	$^{238}U^{76-80+}$	200 MeV/u	CW 13 pμA
JINR	NICA-Booster	2023	$^{197}Au^{32+}$	4. 5 GeV/u	4×10^{9} ppp
IMP	HIAF	2025-2027	$^{238}U^{35+}$	0. 8 GeV/u	1.0-2. 0×10^{11} ppp
			$^{238}U^{76+}$	2. 45 GeV/u	0.5-1.0×10^{11} ppp
			p	**9.3 GeV/u**	**5×10^{13}**
	HIAF-U BRing-S	2027-2032	**$^{238}U^{35+}$**	**2. 95 GeV/u**	**2. 0×10^{12} ppp**
			$^{238}U^{76+}$	**7. 3 GeV/u**	**1.0×10^{12} ppp**
			$^{238}U^{92+}$	**9. 1 GeV/u**	**1.0×10^{12} ppp**
			p	**25.0 GeV/u**	**1.0×10^{14}**
	HIAF-U MRing	2027-2032	$^{238}U^{92+}$	4. 4 GeV/u	2×10^{12} ppp
	HIAF-U iLinac	2027-2032	$^{238}U^{46+}$	150-200 MeV/u	1 emA
	HIAF-ISOL	2027-2032	**H^-, H^+**	**0. 5-1. 0 GeV/u**	**5-10 mA (2.5~10 MW)**

Thanks for your attention!