



HIAF overview: Current status and future perspectives

Lijun Mao

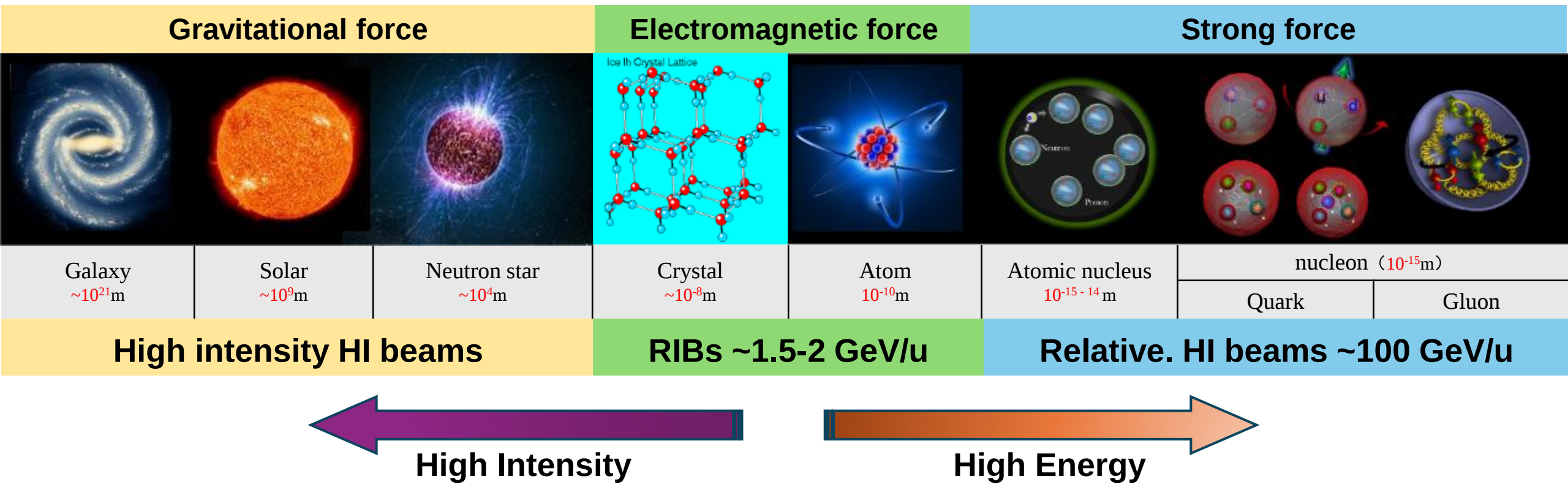
on behalf of the HIAF project group

Institute of Modern Physics, CAS

Introduction

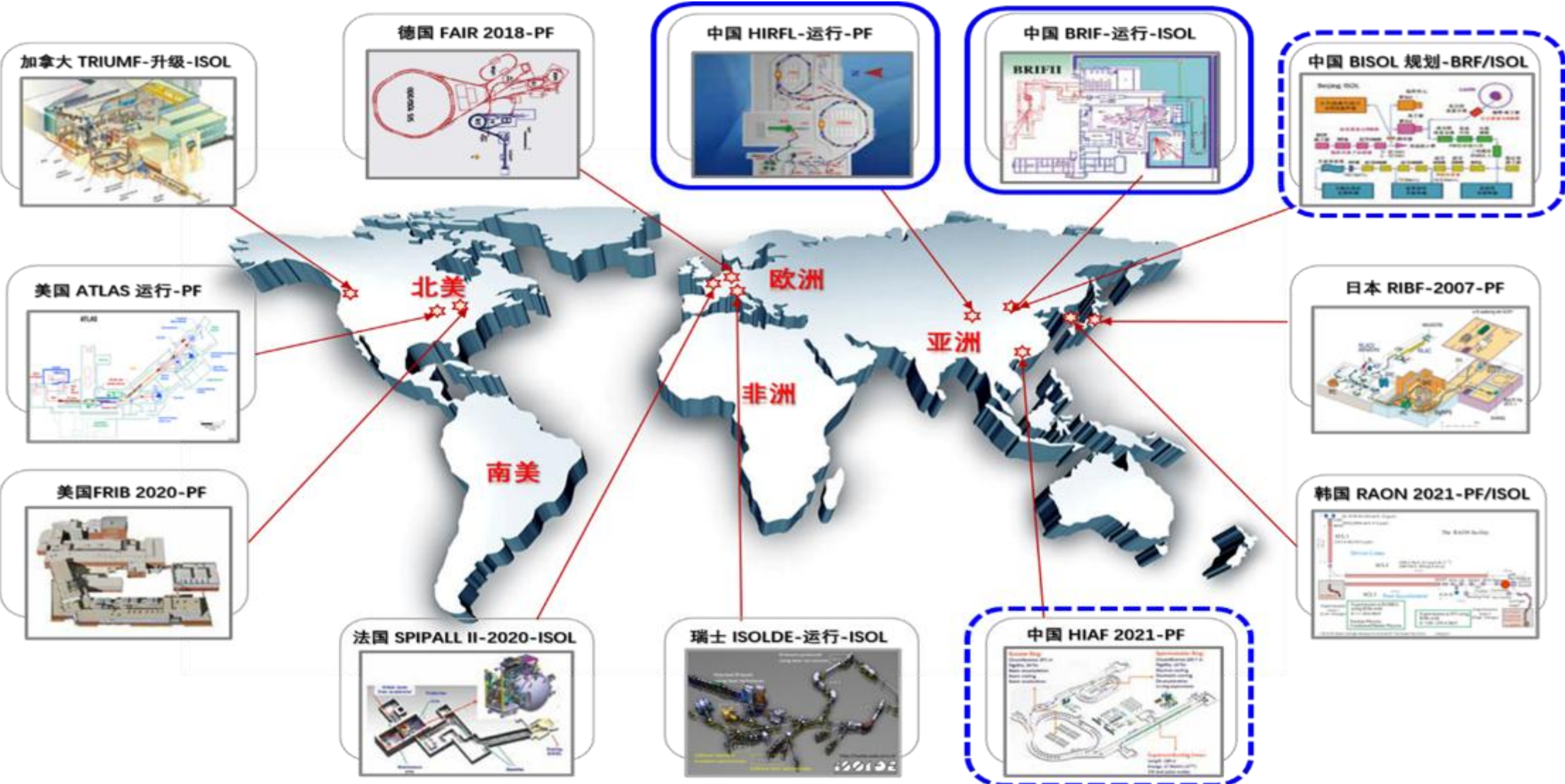
Particle accelerators are devices that speed up the particles that make up all matter in the universe and collide them together or into a target. This allows scientists to study those particles and the forces that shape them.

—DOE explains



Introduction

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



□ Introduction

Institute of Modern Physics (IMP CAS) the most important research center for heavy ion science and technologies



Lanzhou campus

Heavy Ion Research Facility in Lanzhou, **HIRFL**



Huizhou campus

High Intensity heavy-ion Accelerator Facility, **HIAF**

□ 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

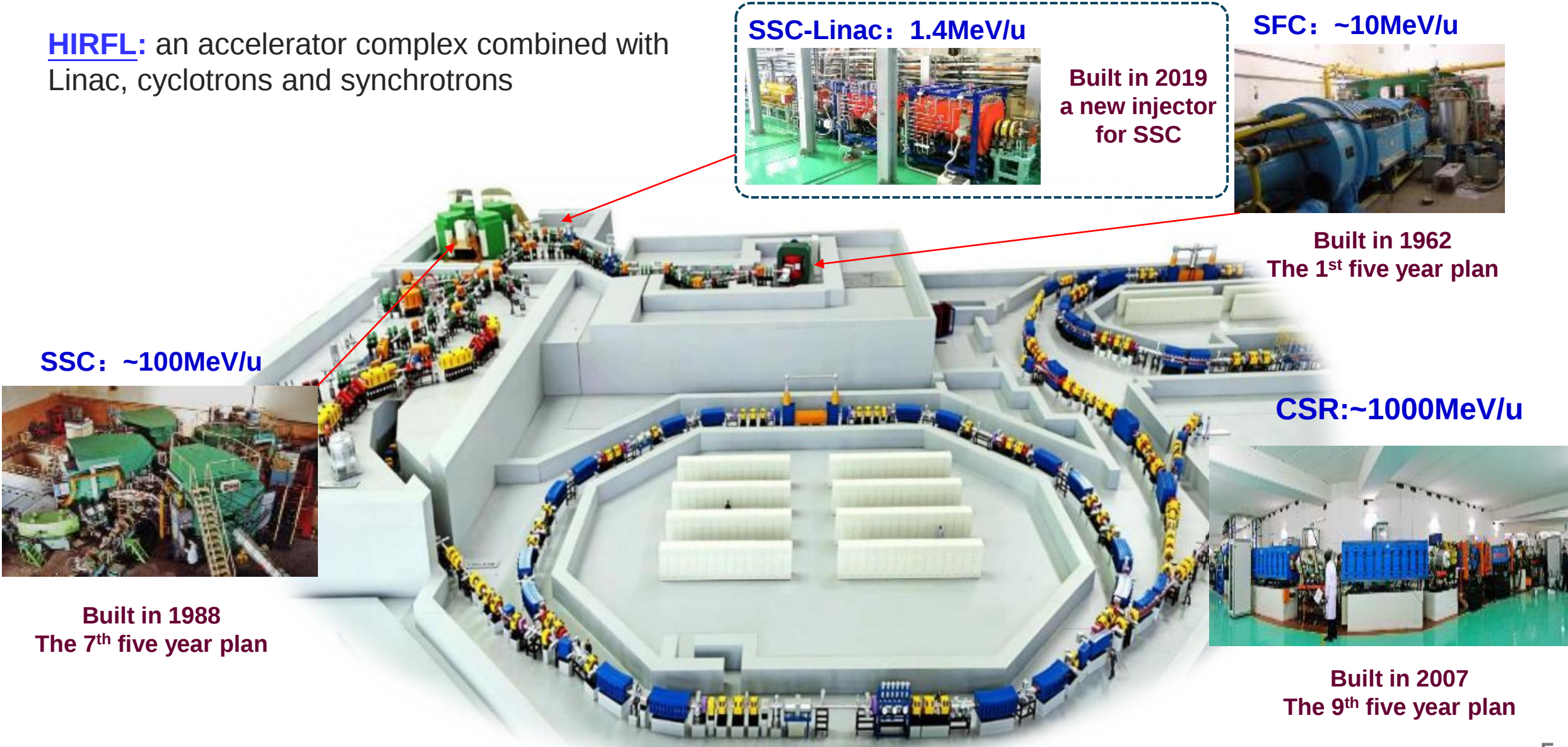


Built in 1988
The 7th five year plan

CSR: ~1000MeV/u



Built in 2007
The 9th five year plan



□ Introduction

CW beam provided by cyclotrons and pulsed beam provided by cooling synchrotron

	SFC	SSC	CSR	GANIL (FR)	SIS18 (DE)
Accelerator	Cyclotron	Cyclotron	Cooling synchrotron	Cyclotron	Cooling synchrotron
	K=69	K=450	BR=12Tm	K=380	BR=18 Tm
Ion species		H ₂ ⁺ to U		C to U	p to U
Energies	1~10MeV/u	6~100MeV/u	1.1GeV (C ⁶⁺) 500MeV/u (U ⁷⁴⁺)	1~95MeV/u	2GeV (C ⁶⁺) 1000MeV/u (U ⁷³⁺)
Current	30uA(C ⁶⁺) 1uA(U ³²⁺)	12uA(Xe ²²⁺) 8uA(U ⁴⁶⁺) **	~10 ¹⁰ ppp (C ⁶⁺) 1×10 ⁸ ppp (U ⁷⁴⁺)	18uA(C ⁶⁺) 0.2uA(²³⁸ U)	4×10 ¹⁰ ppp (C ⁶⁺) 2×10 ⁹ ppp (U ⁷³⁺)

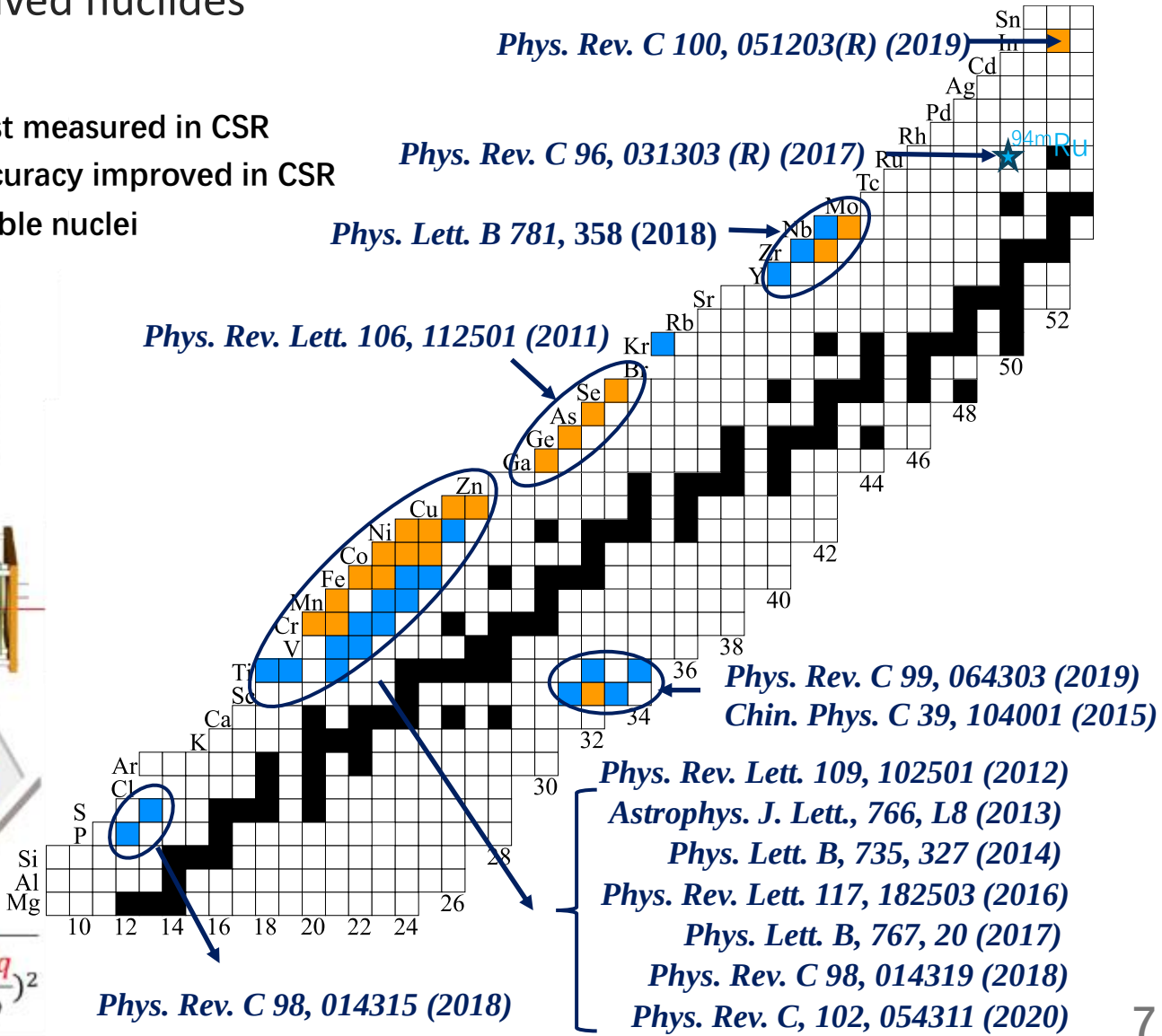
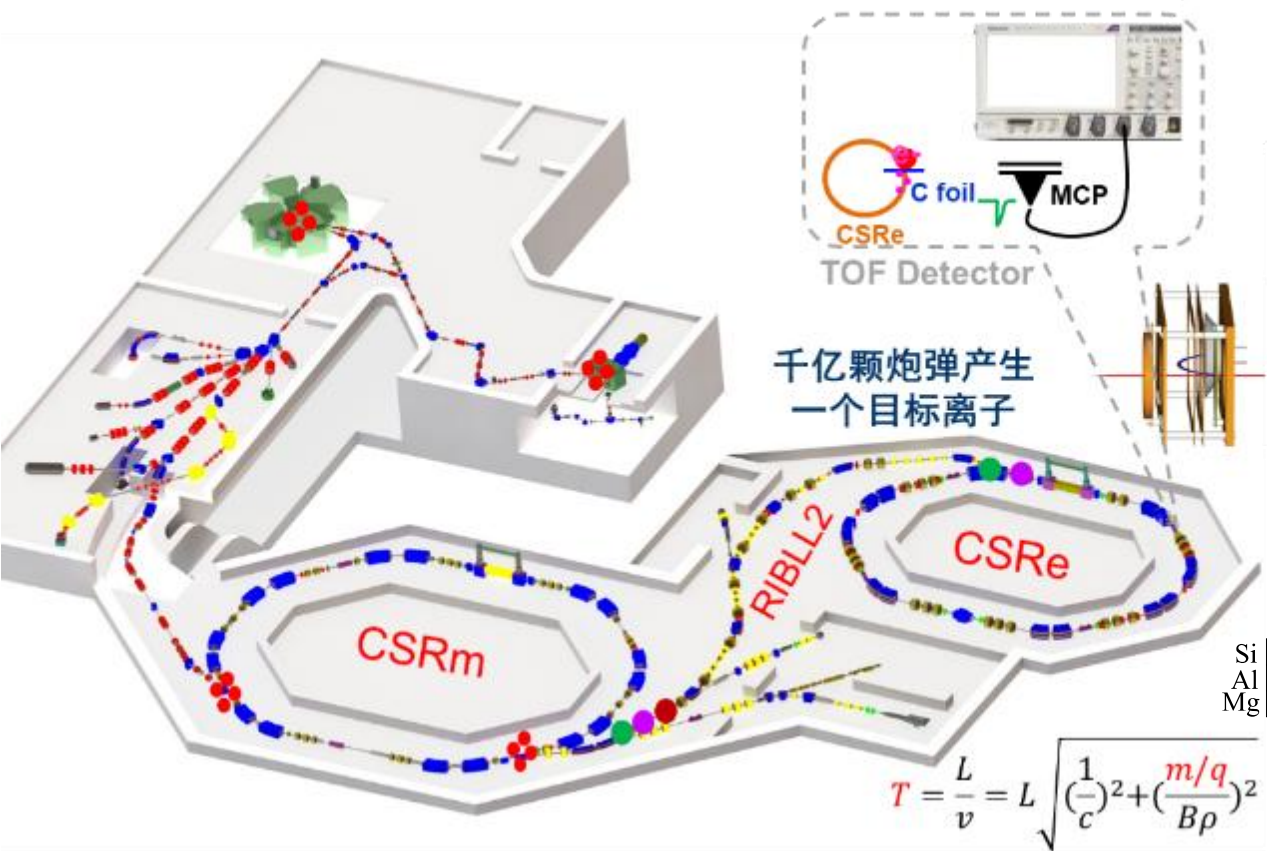
**With Linac injection, pulsed beam

Introduction

Precise mass measurement spectrometry of short-lived nuclides

Principle of IMS
Isochronous Mass Spectrometry

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



□ 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



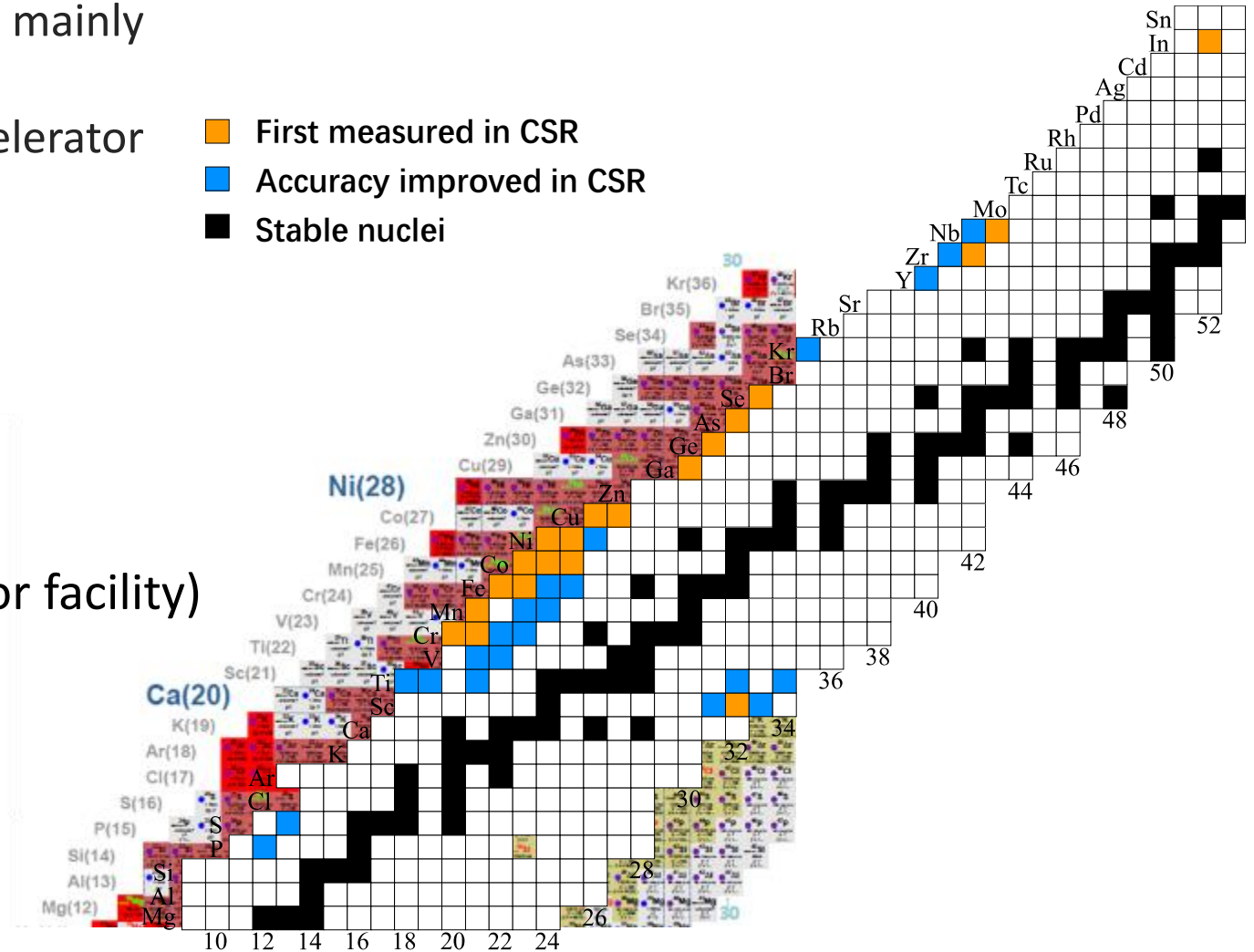
HIAF (High Intensity heavy-ion Accelerator facility)

---proposed in 2011

---approved in 2015

---construction from 2018

---beam commissioning in 2025



□ Introduction



Future Facility: HIAF

Budget planned: ~2.0B RMB (2013-2019)

Accelerator Components

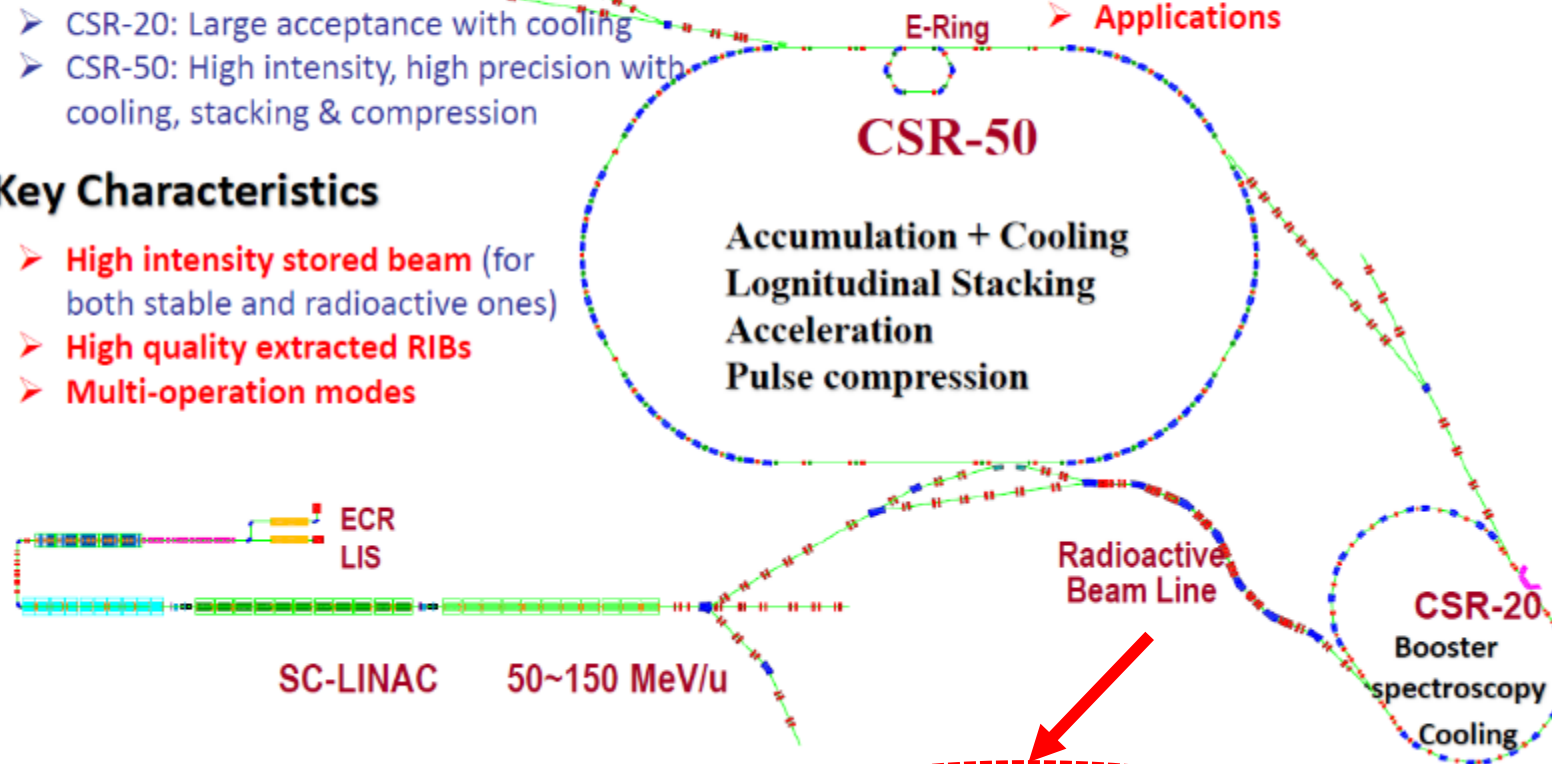
- Ion sources: High intensity
- SC-LINAC: High pulse intensity
- Radioactive beam line: Large acceptance
- CSR-20: Large acceptance with cooling
- CSR-50: High intensity, high precision with cooling, stacking & compression

Motivation

- Nuclear physics and astrophysics
- Atomic Physics
- High energy density physics
- Applications

Key Characteristics

- High intensity stored beam (for both stable and radioactive ones)
- High quality extracted RIBs
- Multi-operation modes



Introduction

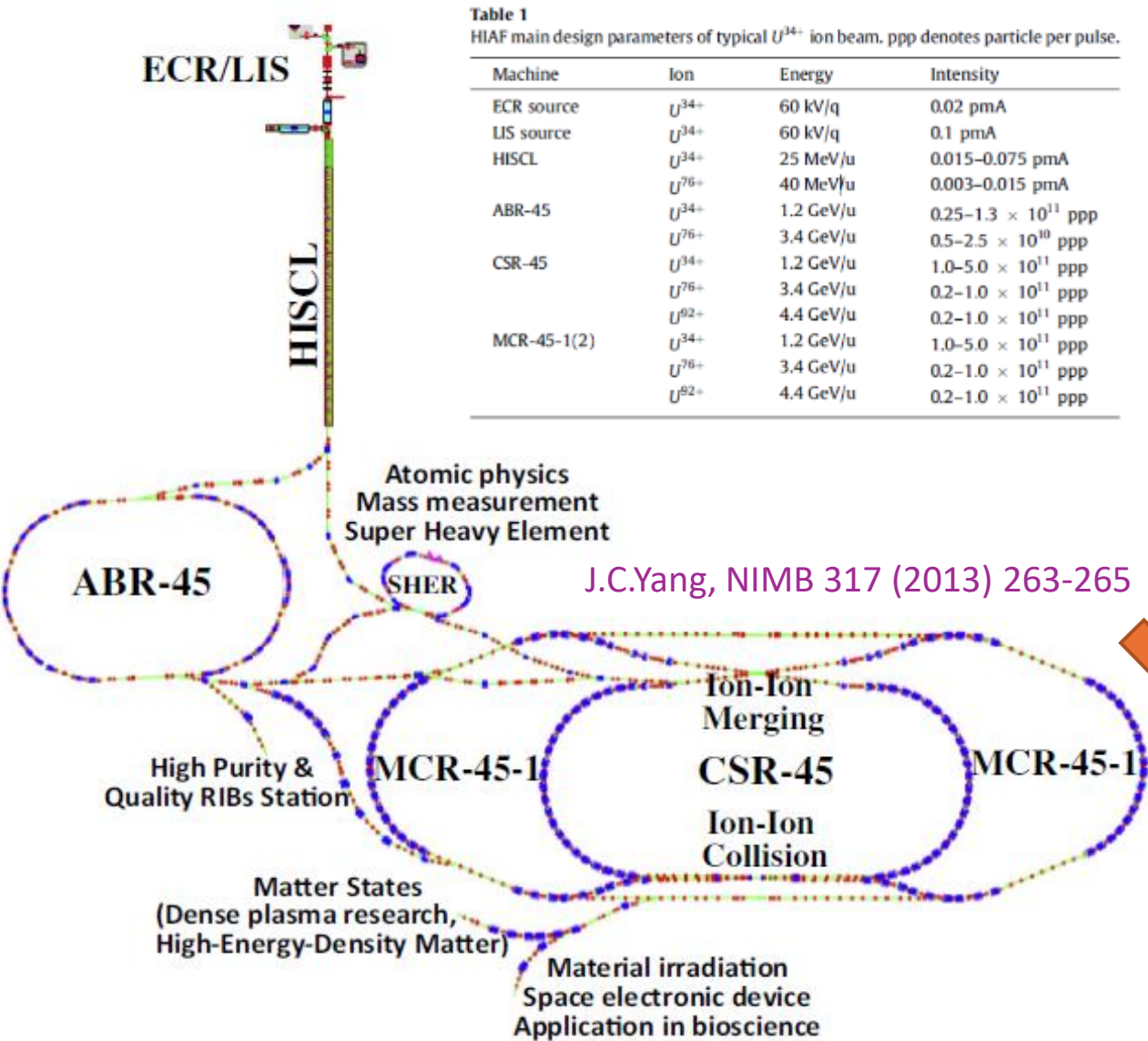


Table 1
HIAF main design parameters of typical U^{34+} ion beam. ppp denotes particle per pulse.

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

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.

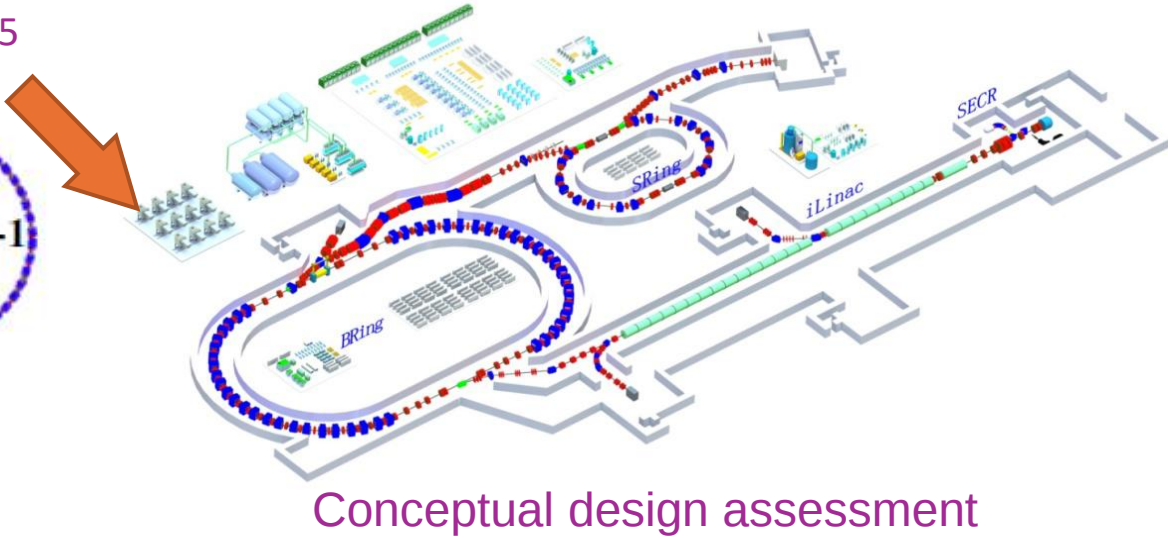


Fig. 1. Layout of the HIAF complex

□ Introduction

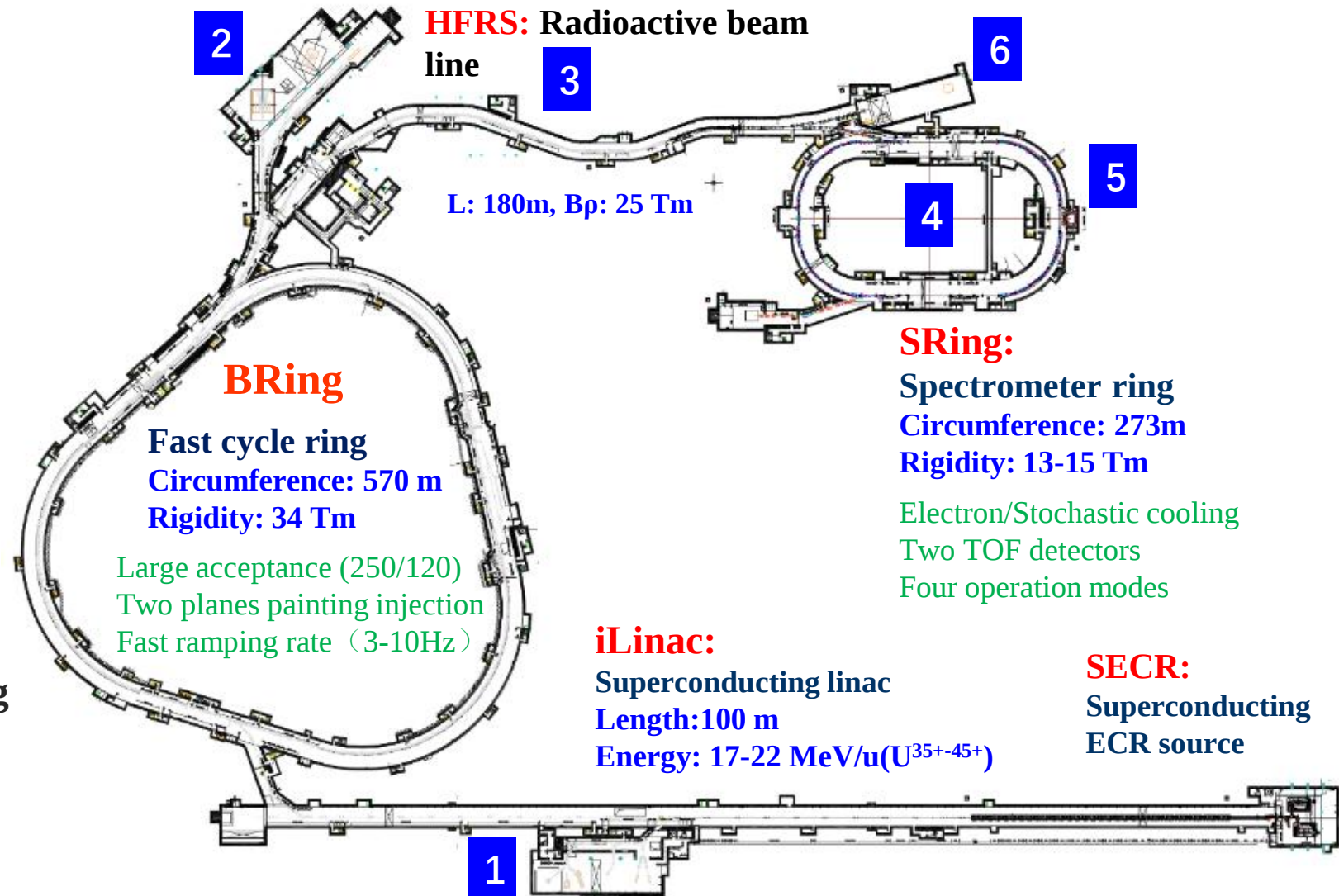
- **HIAF** (High Intensity heavy-ion Accelerator Facility)

- **Accelerators**

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

- **Terminals**

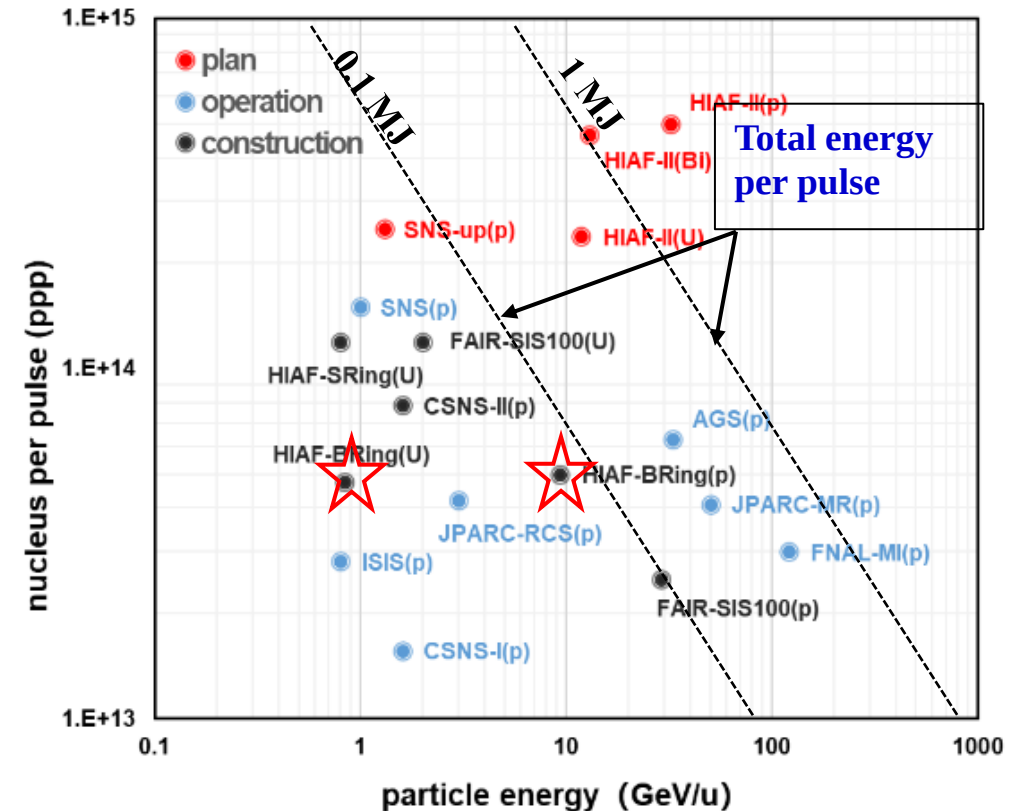
- ① Low energy nuclear structure terminal
 - ② High energy experimental terminal
 - ③ High energy fragment separator **HFRS**
 - ④ High precision spectrometer ring **SRing**
 - ⑤ Electron ion recombination terminal
 - ⑥ Radioactive ion beam physics terminal



□ Introduction

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

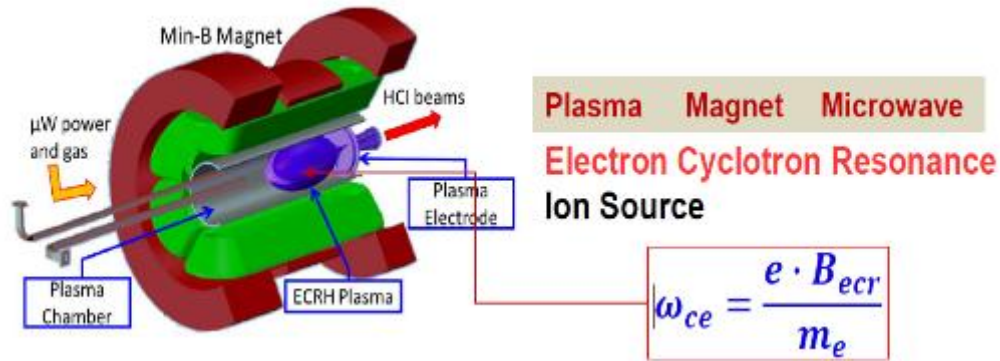
	iLinac	BRing	SRing	FAIR
Length / circumference (m)	114	569	277	1080
Final energy of U (MeV/u)	17 (U^{35+})	835 (U^{35+})	835 (U^{92+})	2700 (U^{28+})
Max. magnetic rigidity (Tm)	---	34	15	100
Max. beam intensity of U	28 pμA (U^{35+})	1×10^{11} ppp (U^{35+})	$(2 \sim 4) \times 10^{11}$ pp p (U^{92+})	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?

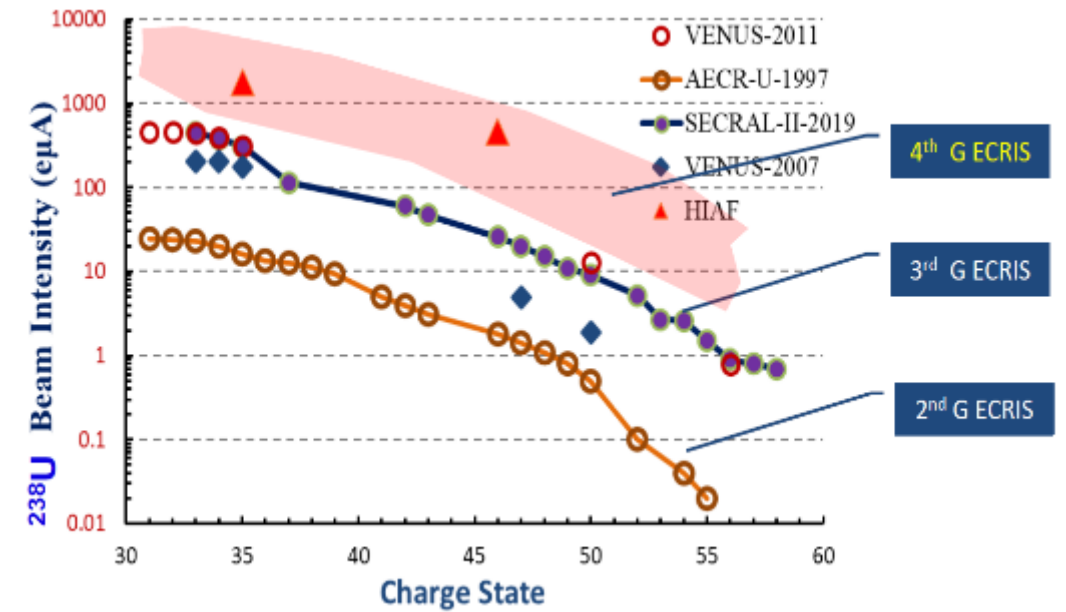
□ Challenges and solutions

- A powerful ion source is needed

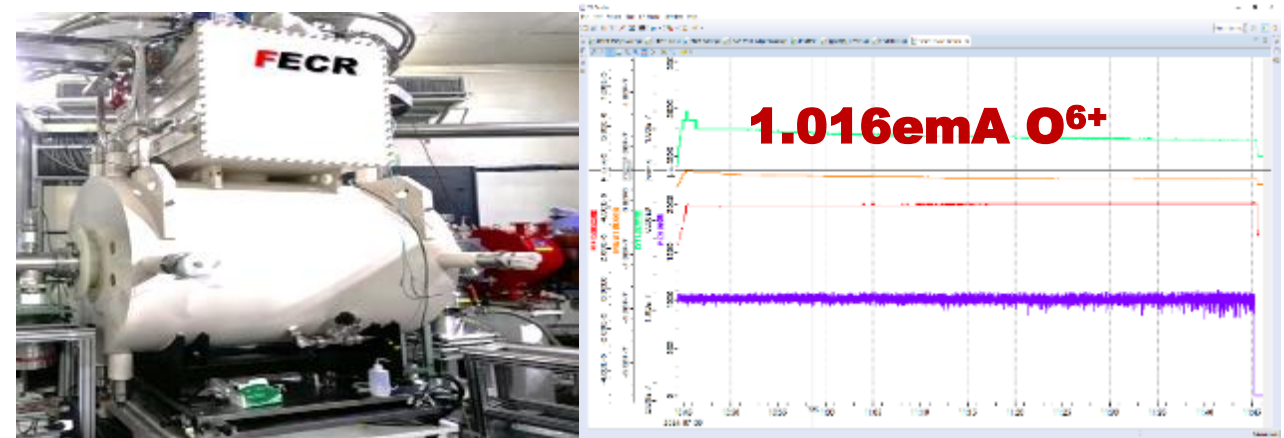


- ECR (electron cyclotron resonance) ion source, use a magnetic field and microwave to create, confine and heat a dense plasma, leading to the efficient production of highly charged ion
- Hot electrons collide with neutral gas atoms, knock out one or more electrons
- Longer an ion is confined in presence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

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



$f=45\text{ GHz}$, $B=1.6\text{ T}$, the 4th generation ECR ion source

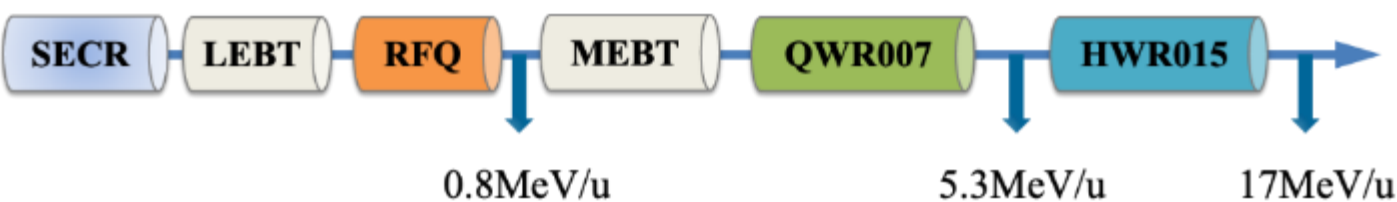


---L. Sun, ICIS'23

Challenges and solutions

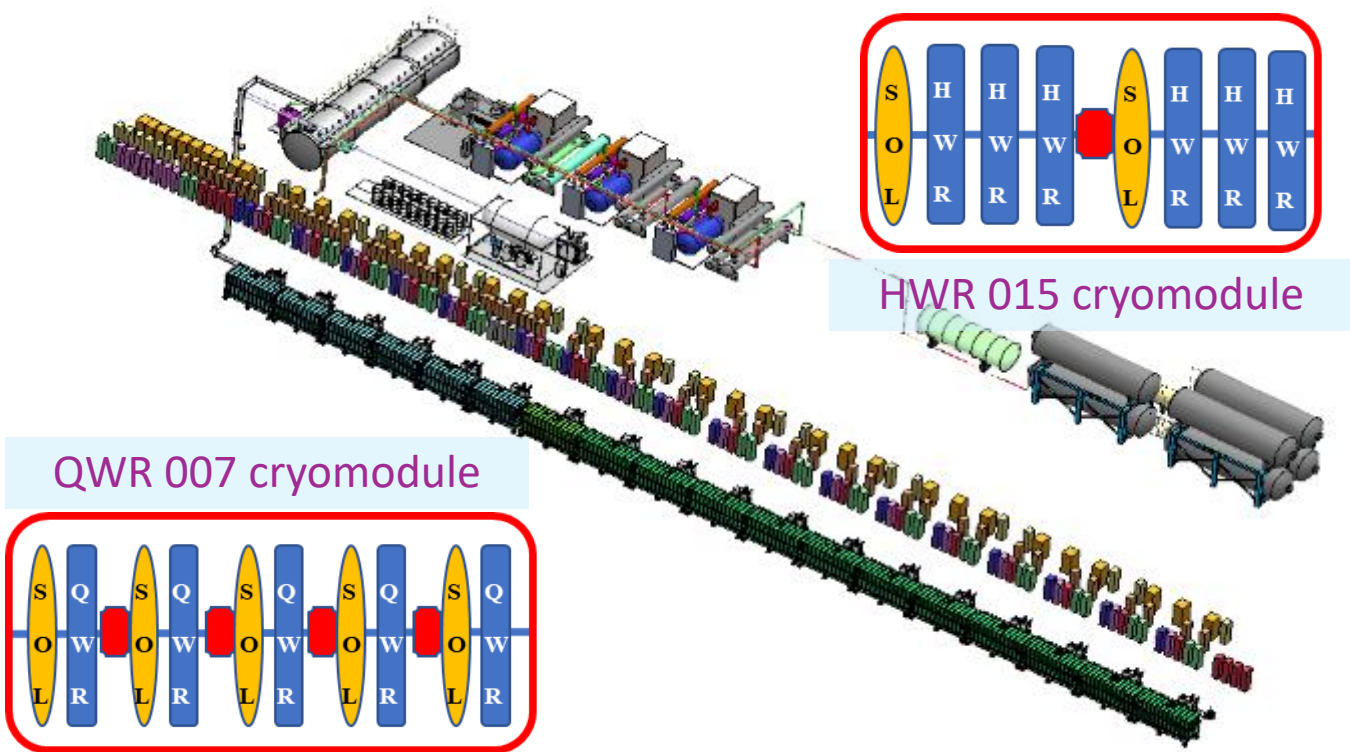
- A CW superconducting linac is wonderful

- Goal:
- Pulsed, 28 pμA U³⁵⁺
 - CW, 15 pμA U³⁵⁺

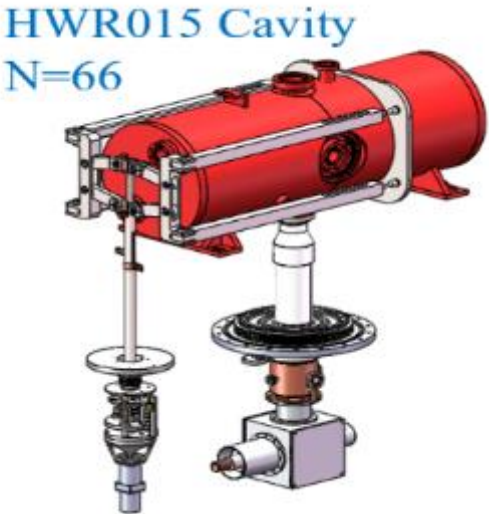


To BRing with 3 Hz pulsed beam
To low energy terminal with CW beam

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

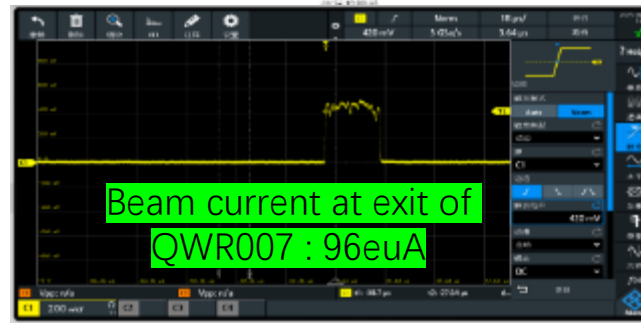
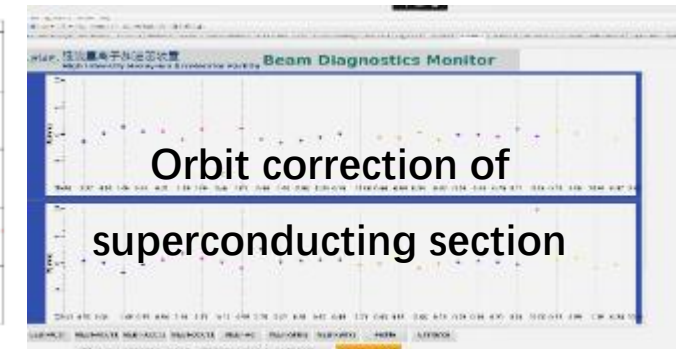
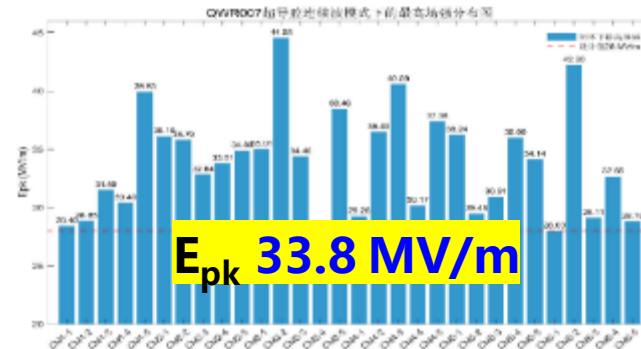


2 types of cavities: QWR 007 and HWR 015



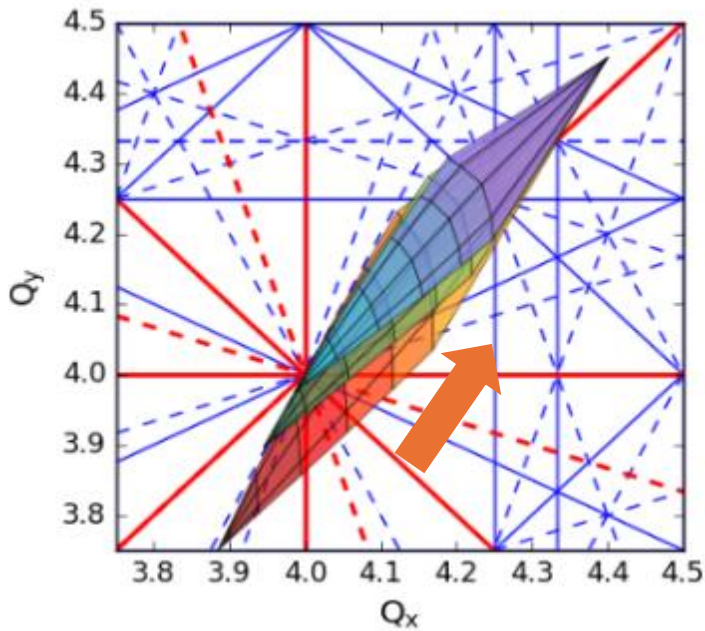
□ Challenges and solutions

- 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 $^{16}\text{O}^{6+}$. 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

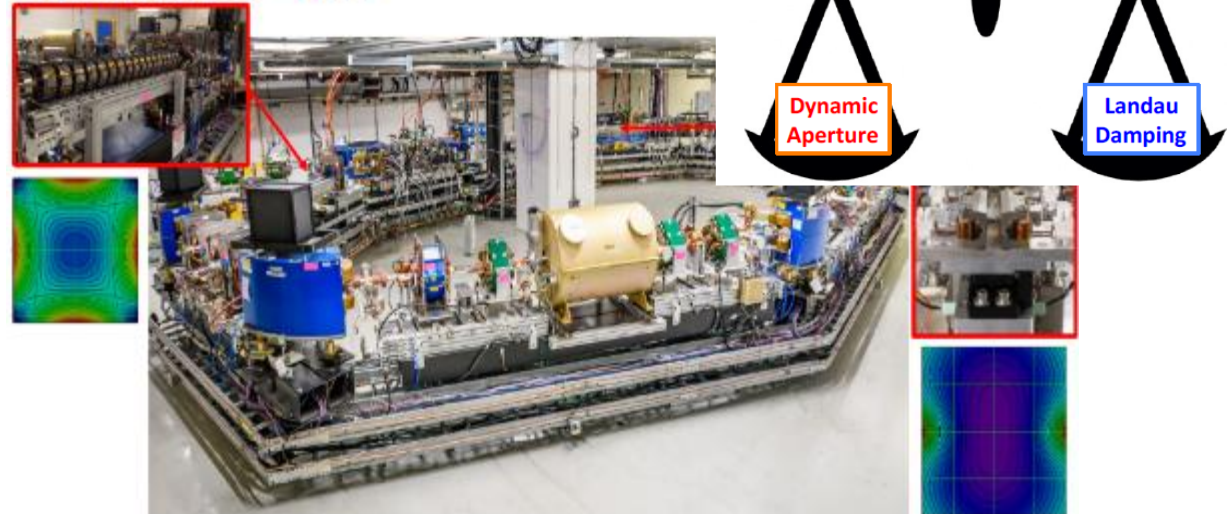


12T/s @ BRing

Tune spread depends on space charge effect, with the normalized factor $\gamma\beta$

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

Implementation - IOTA

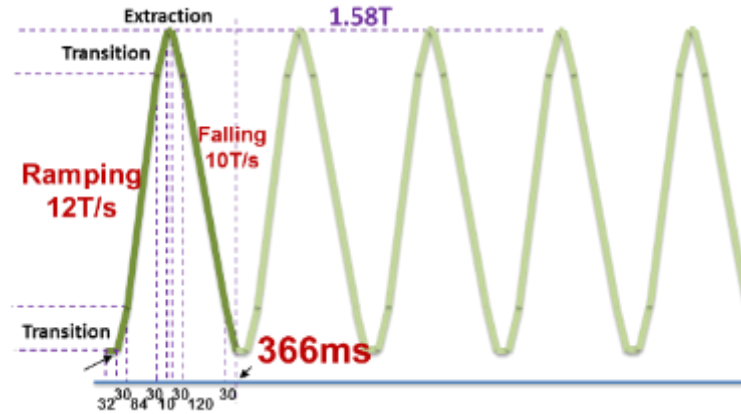


□ Challenges and solutions

- 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

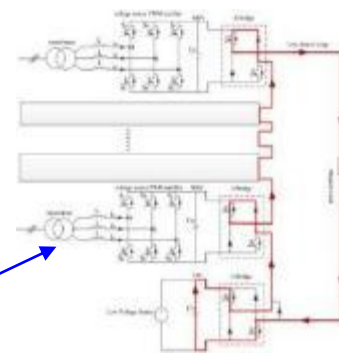
The highest ramping rate for heavy ion synchrotron, challenges for **power supply**、**RF cavities** and **vacuum chamber**

- 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

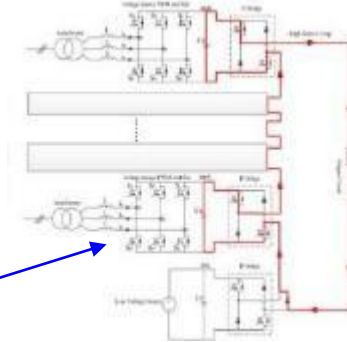
□ Challenges and solutions

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

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

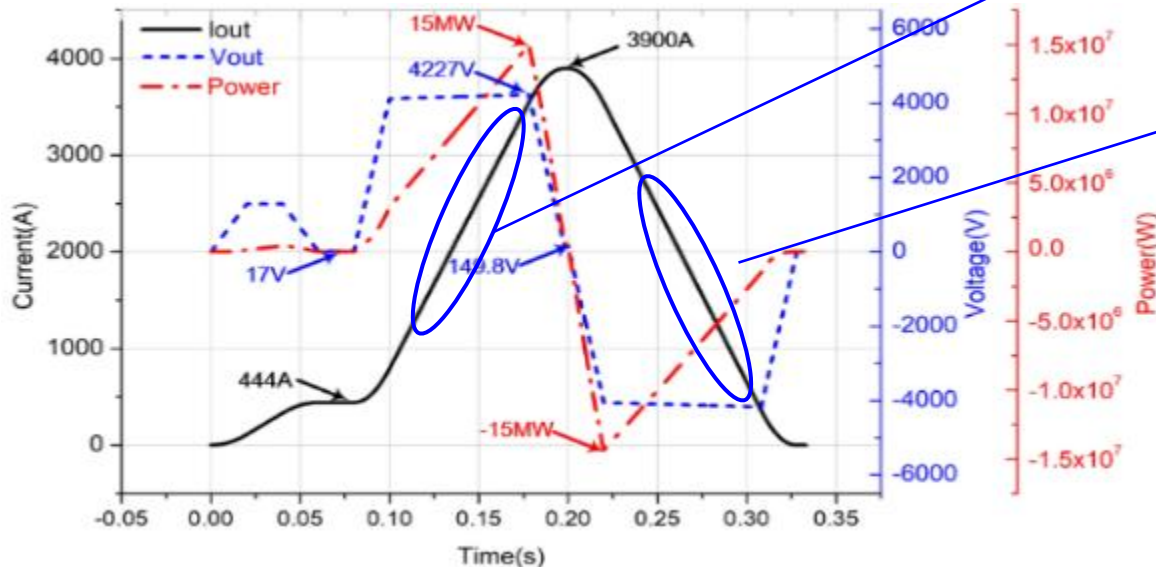


Energy from capacitor tank to magnet load



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

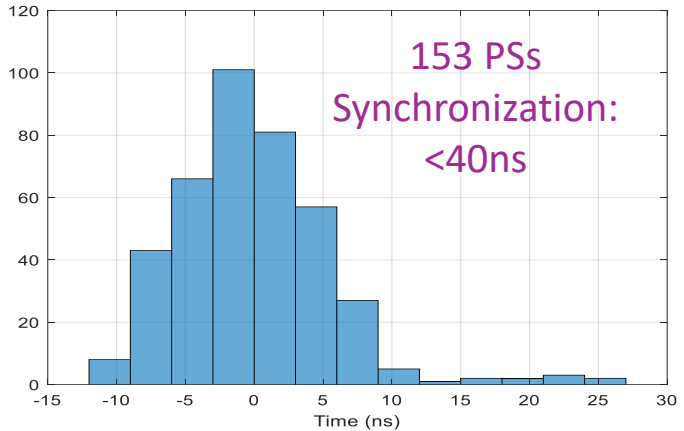
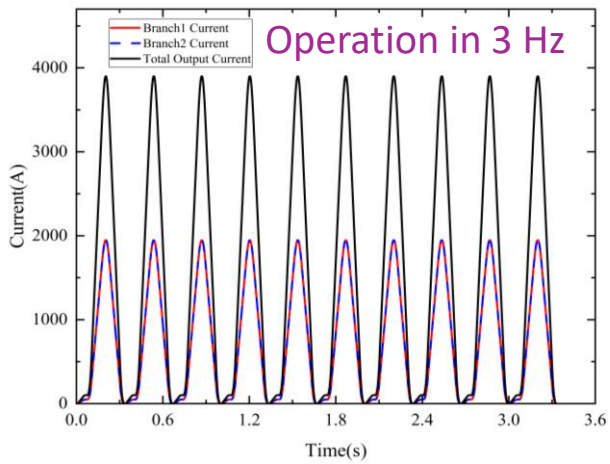
- Reduce the power consumption

Items	
Excitation current/voltage	3900A/4300V
load inductance	116mH
Load Resistance	36.4mΩ
Current changing rate	$\leq \pm 38000\text{A/s}$
tracking error	$\leq \pm 0.2\text{A}$

Power requirement (MVA)	Conventional	Energy storage
BRing bending 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

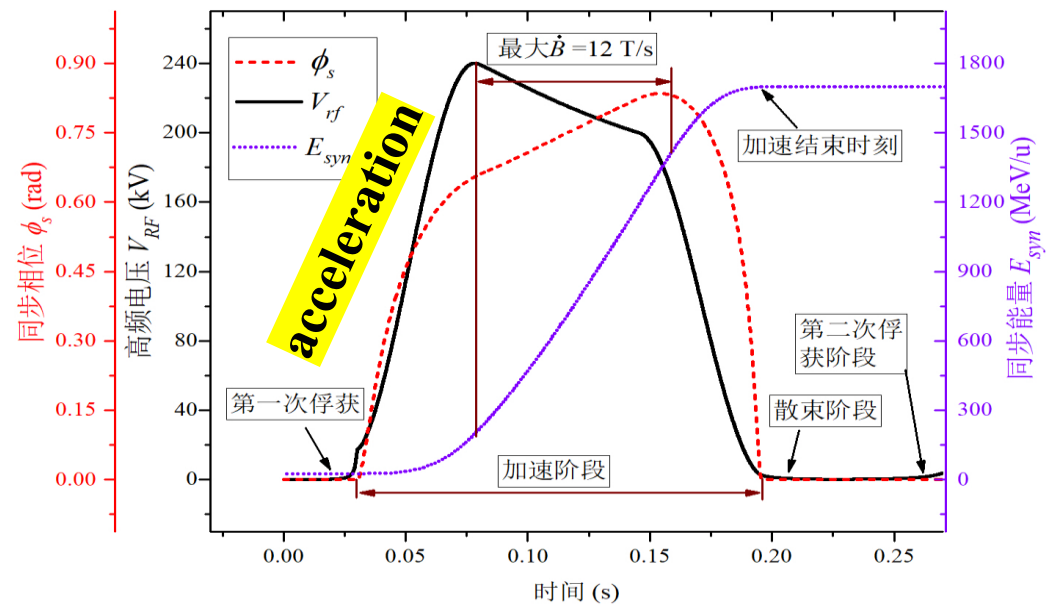


621 power supplies have been installed and debugged successfully. The test results of the power supplies meet the specified requirements.

Challenges and solutions

- Magnetic ally core loaded RF system

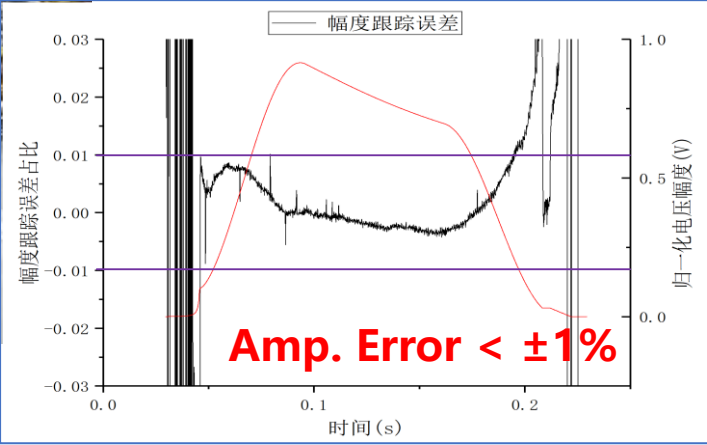
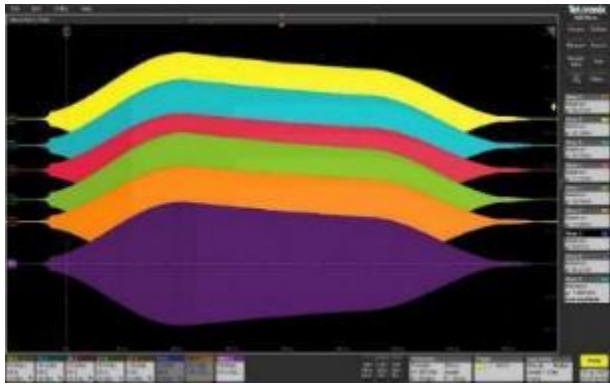
To satisfy fast acceleration, the voltage for total RF system should be **240 kV**



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

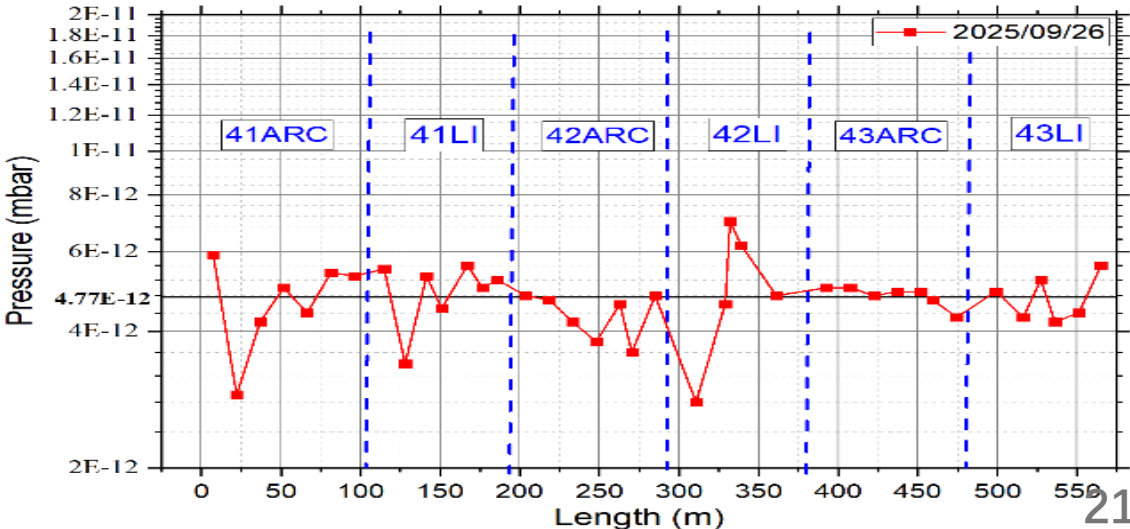
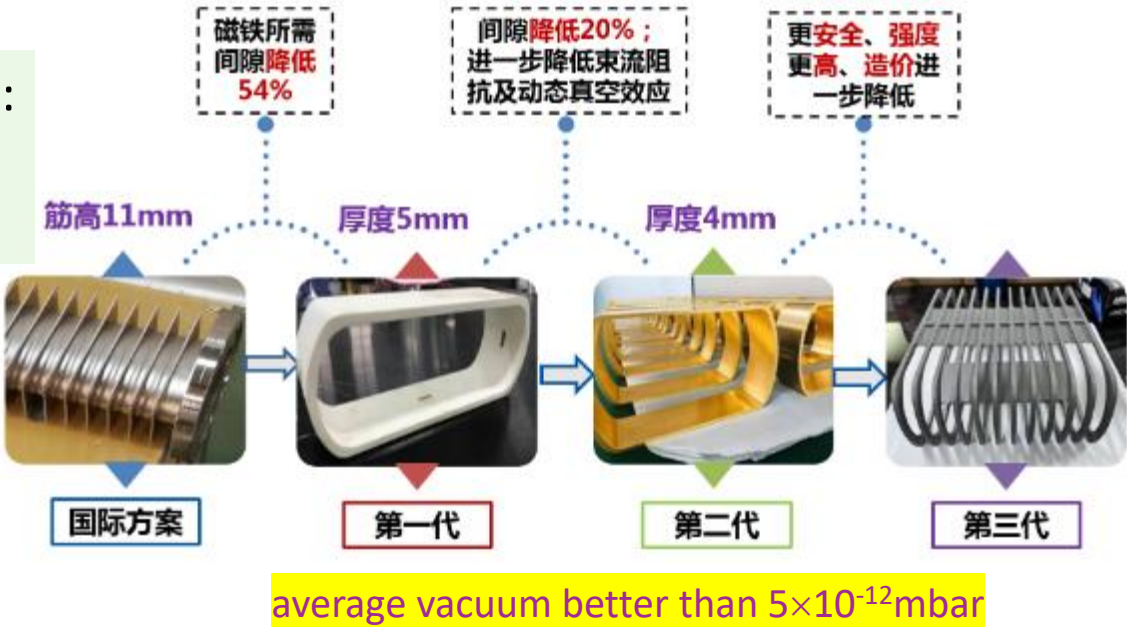
Titanium alloy-lined thin-walled vacuum chamber

Problem: fast ramping of the magnets induces eddy currents:

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

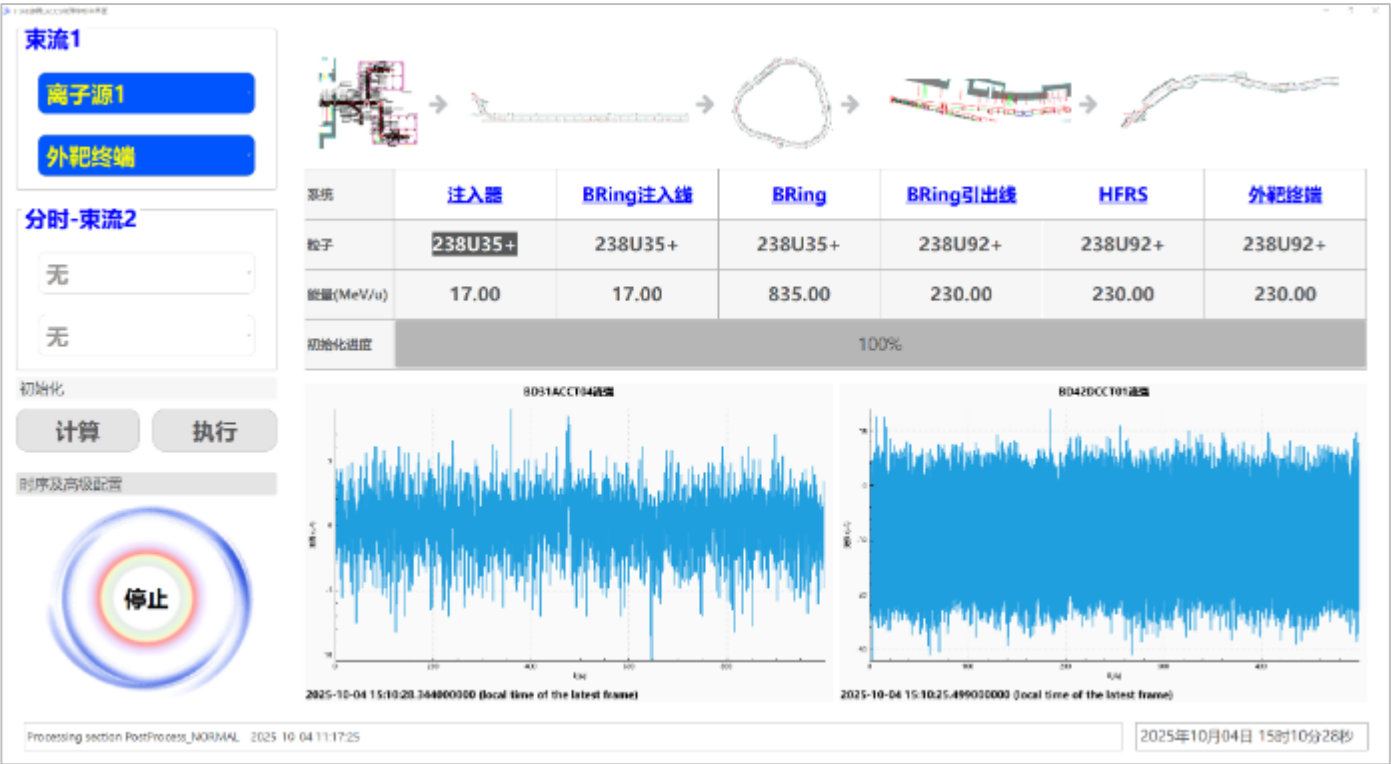


Figure 1a. One section of vacuum chamber set on a steel plate with the same curvature as the bending magnet.

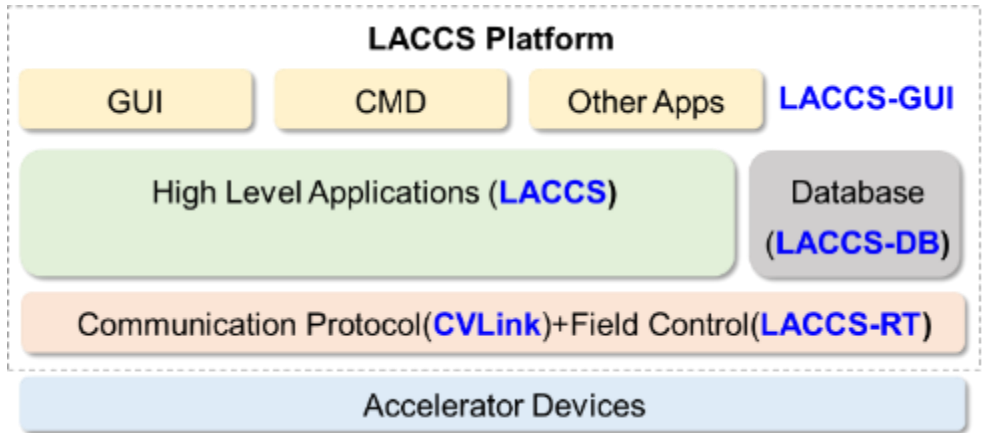


Challenges and solutions

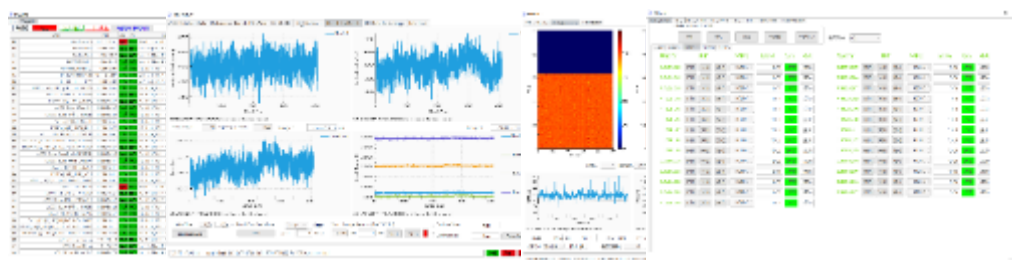
- Integrate, process, store ~210k control variables in >500 computing nodes in real-time to perform coupling control of 141 beam dynamics and related ~2000 devices.
- The whole LACCS system is online and ready for HIAF beam commissioning.



Automatic Control of the Whole Beam Manipulation Process in the HIAF



Full-featured LACCS Software Ecosystem



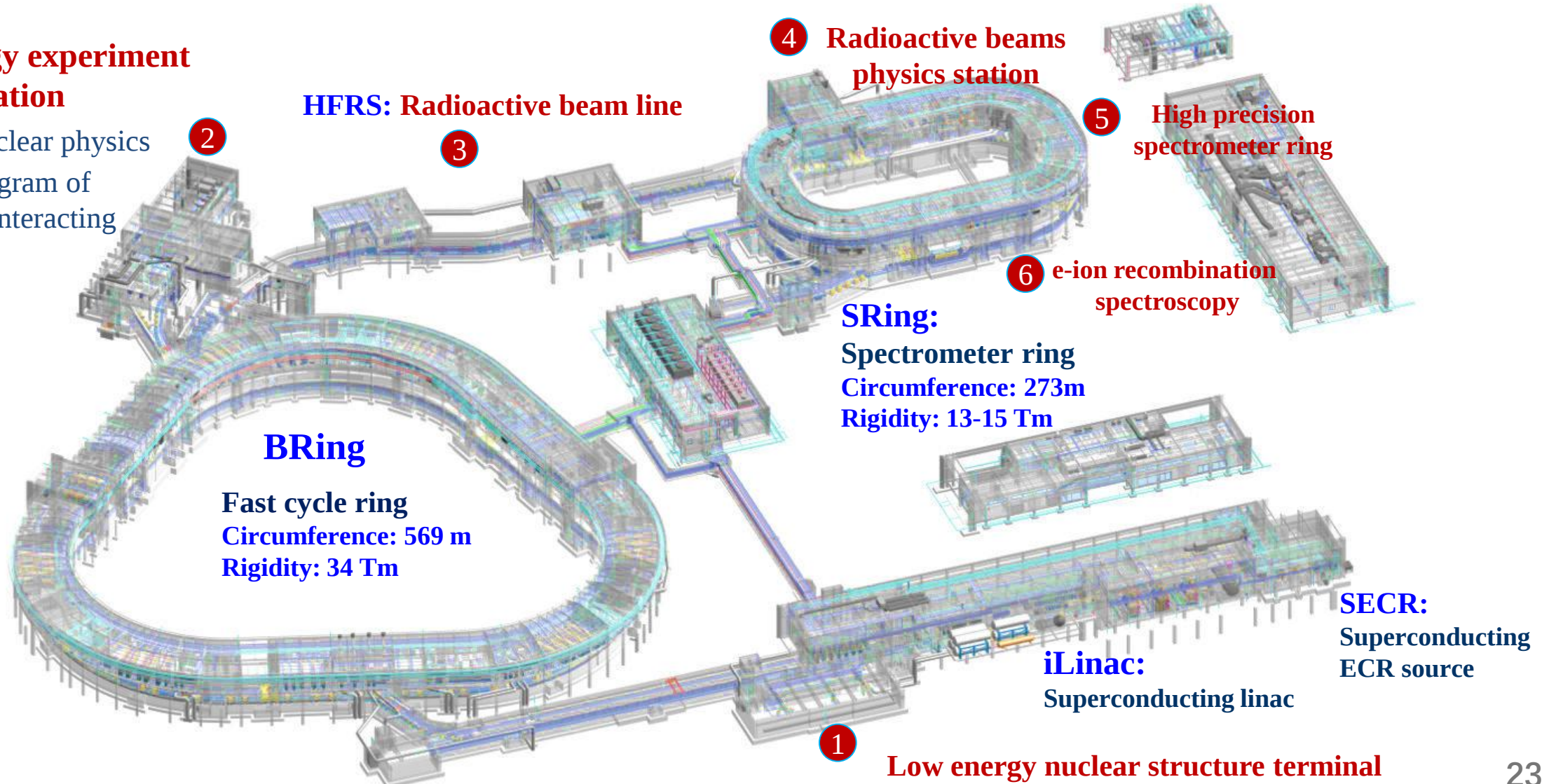
Diverse GUIs for Control and Management

□ Experimental terminals

- Distribution of 6 experimental terminals

High energy experiment station

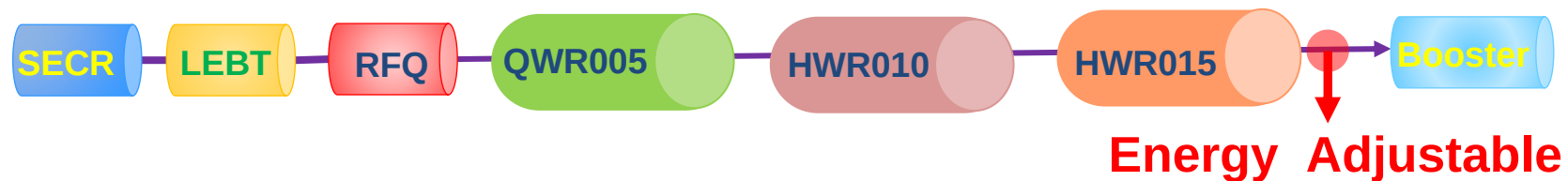
- Hyper nuclear physics
- Phase diagram of strongly interacting matter



□ Experimental terminals

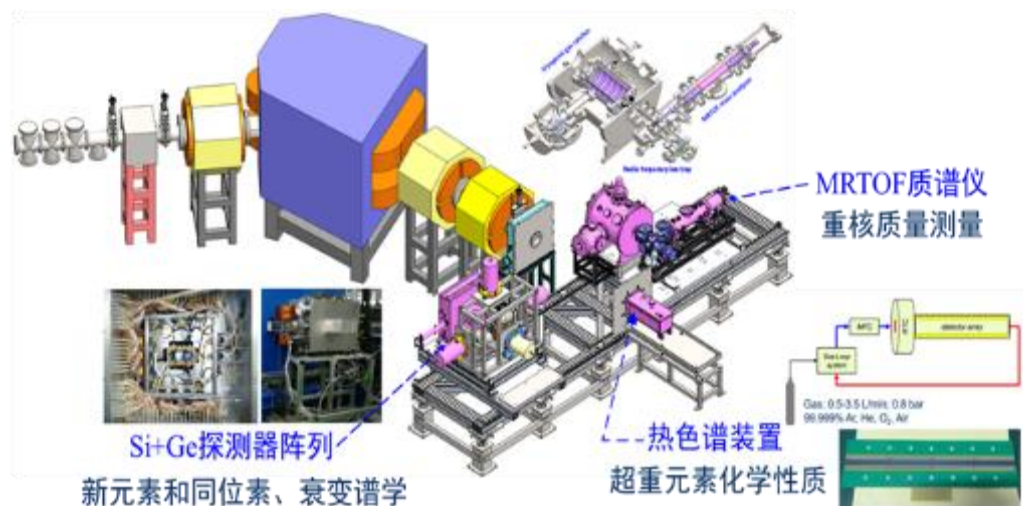
- Low energy nuclear structure terminal

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



CW mode:

10 pμA beams with $A/Q=2\sim5$



Gas-filled recoil separator



□ Experimental terminals

Typical beam parameters from the Booster Ring

- High energy experimental station

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



Pulsed beam from BRing



The External Target Experiment Setup



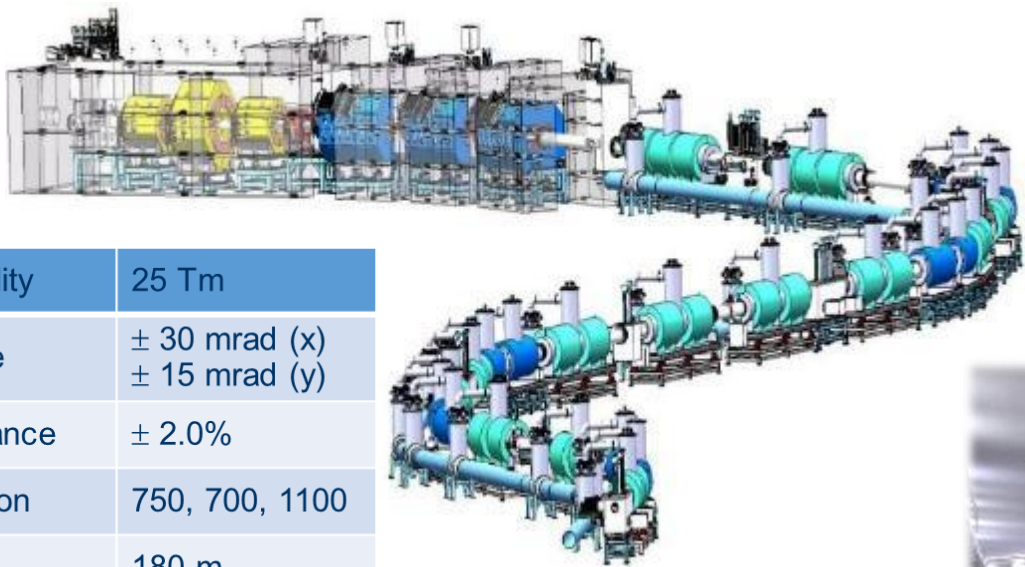
Study of the QCD Phase Structure



Hyperon-Nucleon Spectrometer (H-NS)

Experimental terminals

- High Energy Fragment Separator (HFRS)

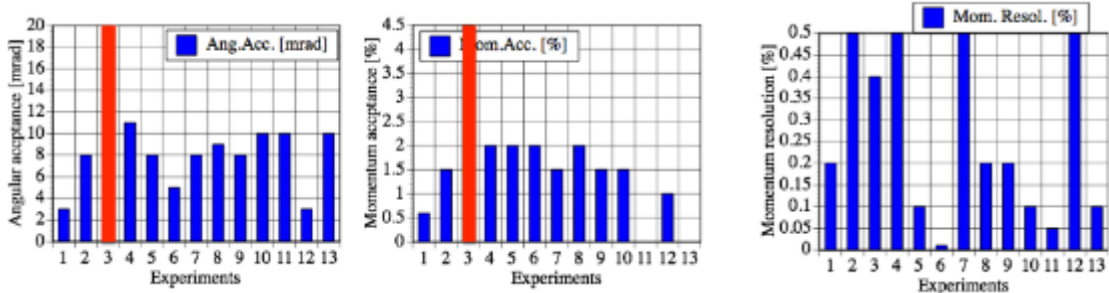


Max. magnetic rigidity	25 Tm
Angular acceptance	± 30 mrad (x) ± 15 mrad (y)
Momentum acceptance	$\pm 2.0\%$
Momentum resolution	750, 700, 1100
Total length	180 m

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)
- ...

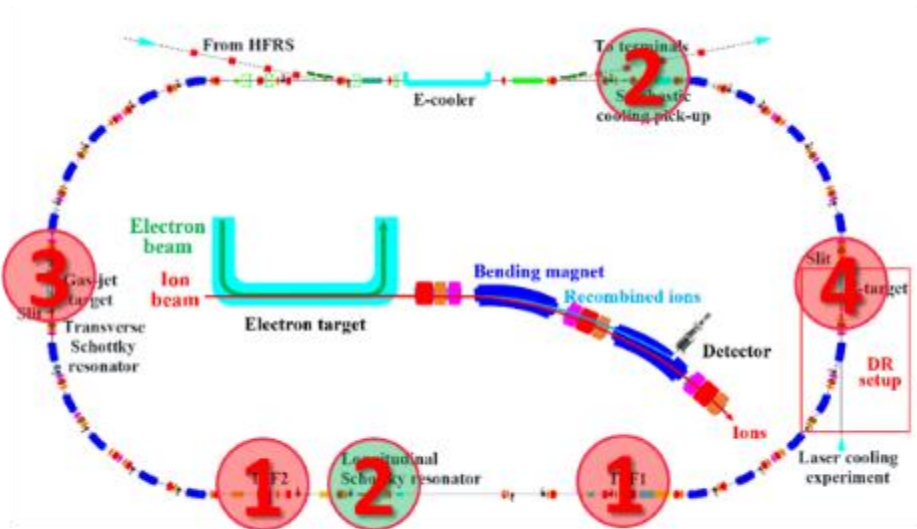
Requirements from Physics



Acceptance, and Momentum Resolution

□ Experimental terminals

- Spectrometer Ring: Multi Working Modes of Storage Ring



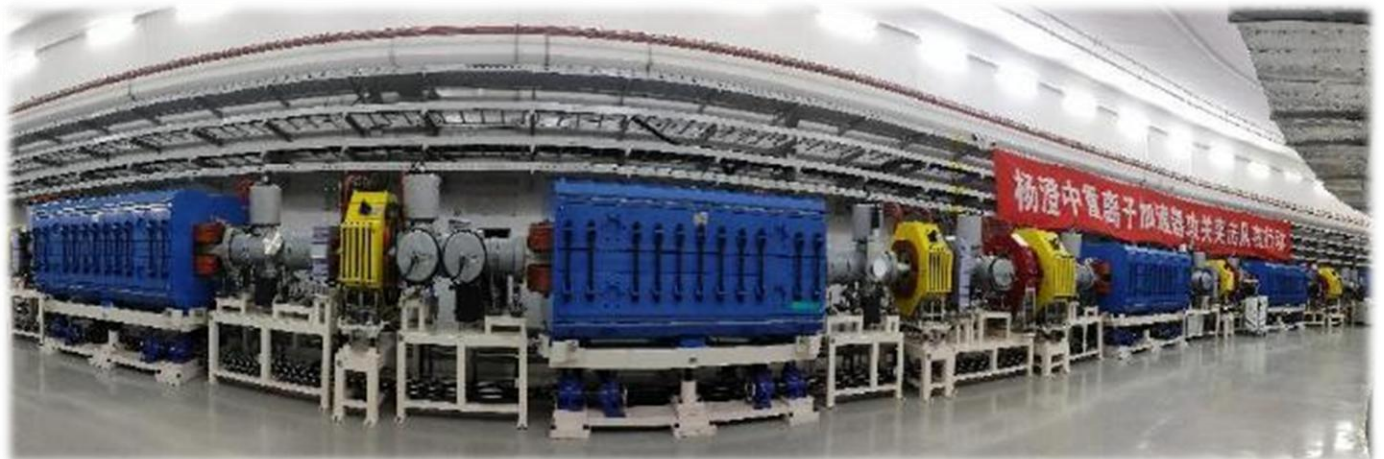
With fast extracted projectiles from the Booster, HFRS produces, separates and injects the isotopes of interests into the Spectrometer Ring

Experiments:

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

Spectrometer Ring:

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

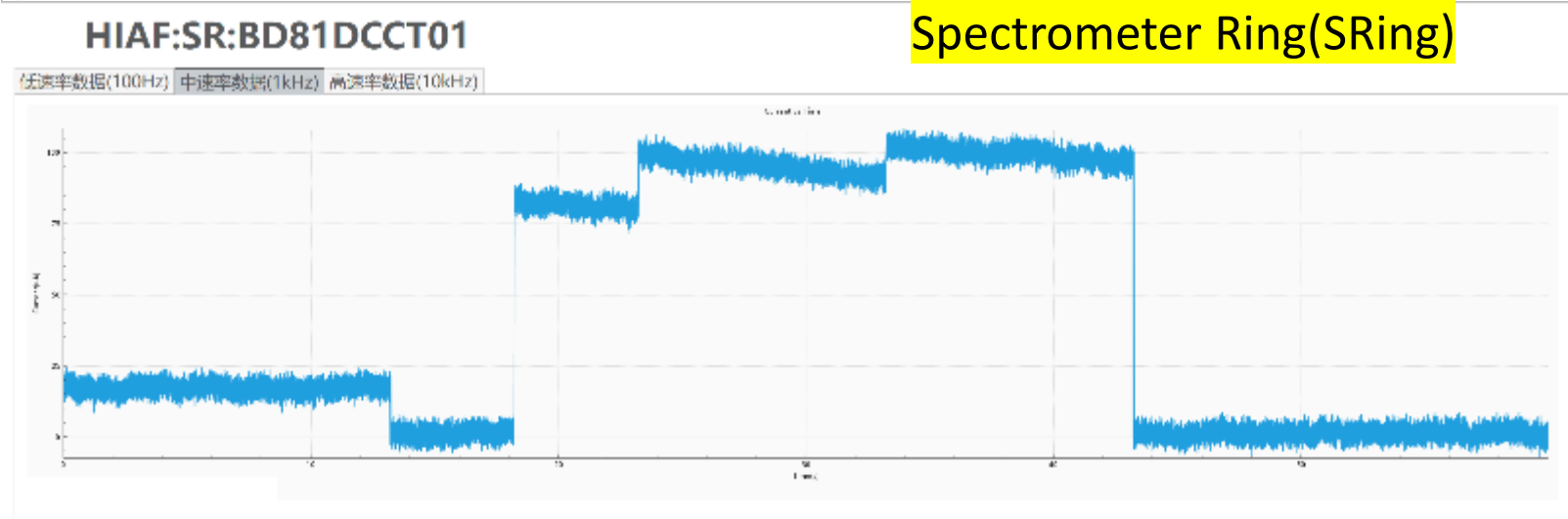
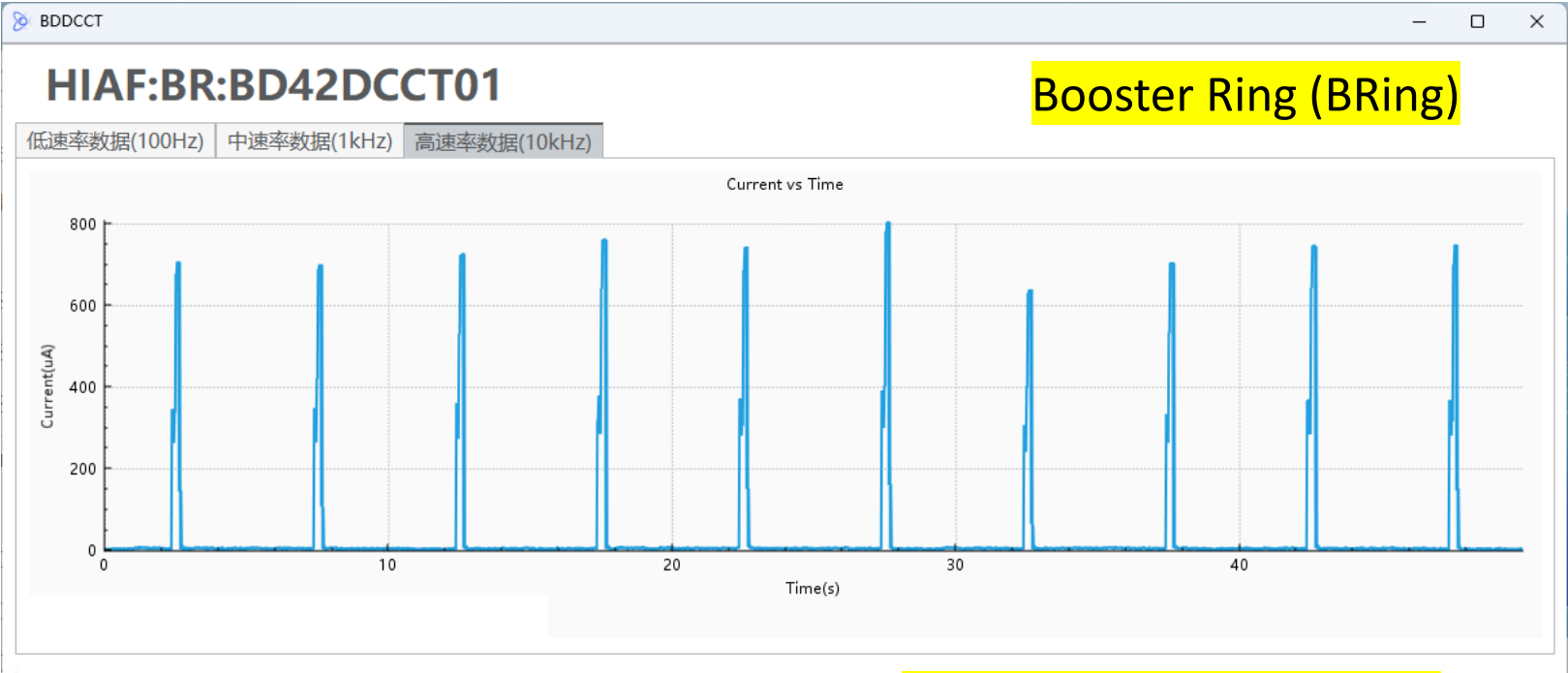


□ Current status

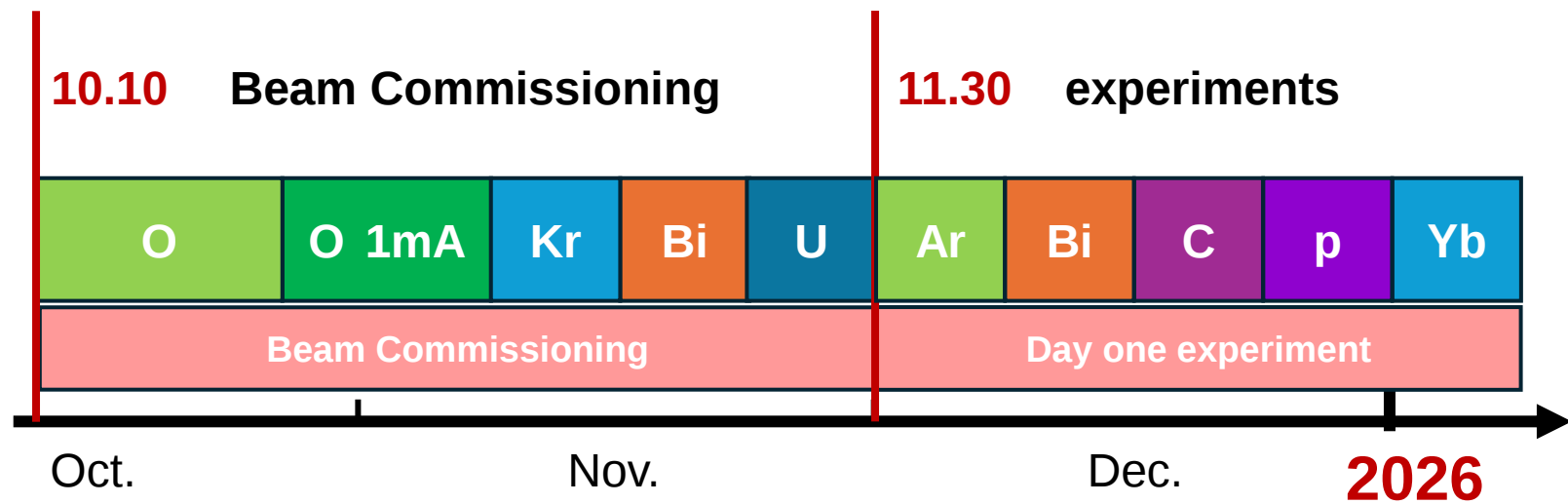
- The first dipole was moved into the tunnel in 27th March, 2024
- **The first beam was injected, accelerated in BRing in 27th October, 2025**



□ Current status



□ Current status



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

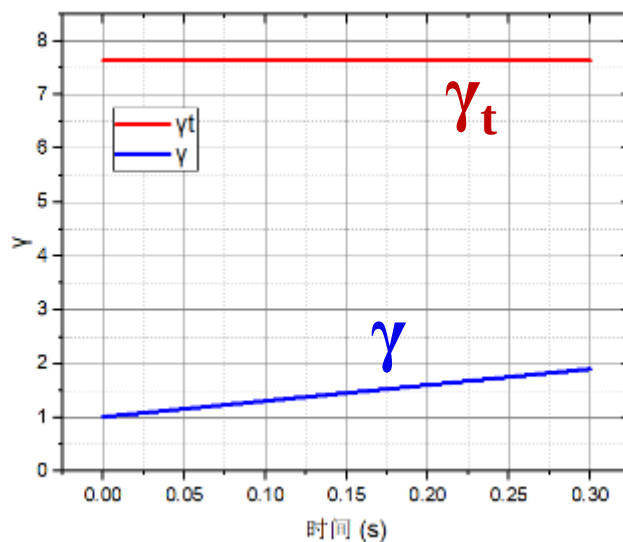
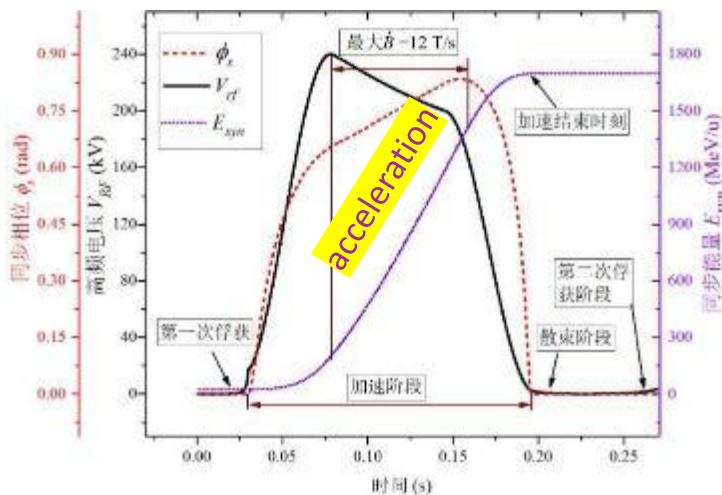
$$\gamma < \gamma_t$$

Higher energy particles move “faster” than lower energy particles

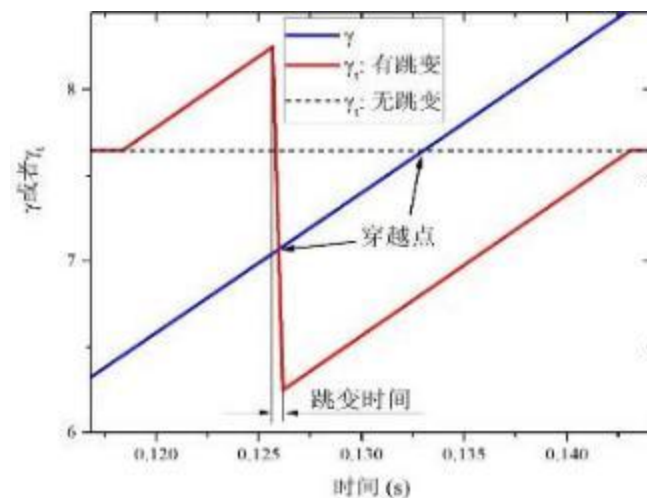
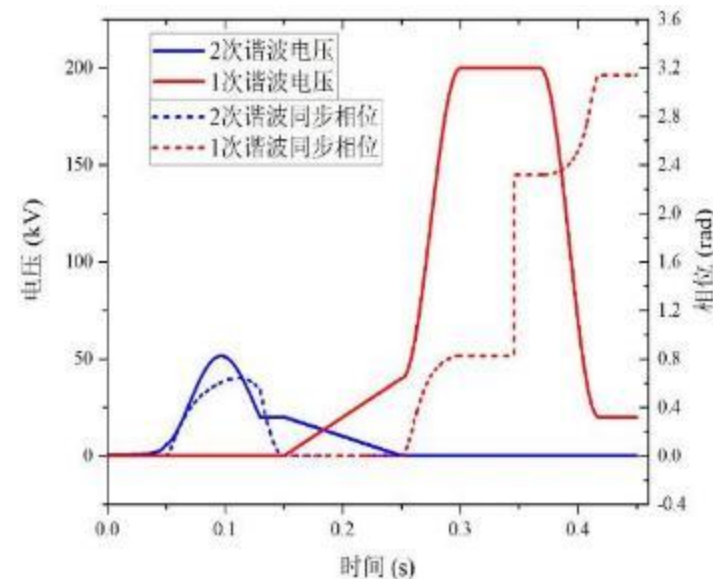
$$\gamma > \gamma_t$$

Higher energy particles move “slowly” than lower energy particles

- Heavy ion acceleration



- Proton acceleration



□ 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.

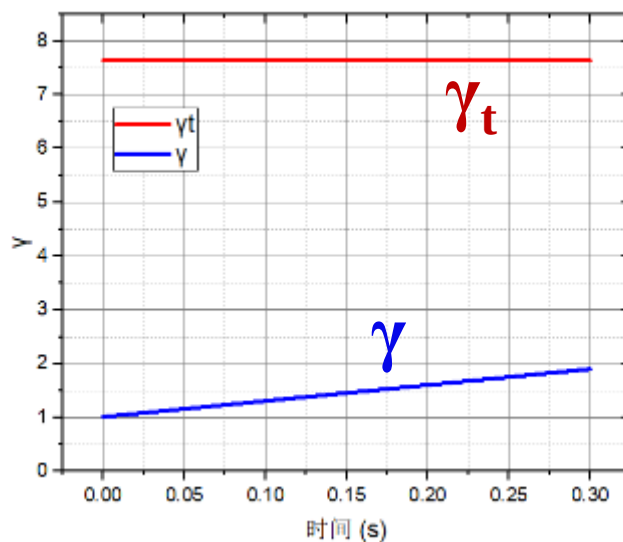
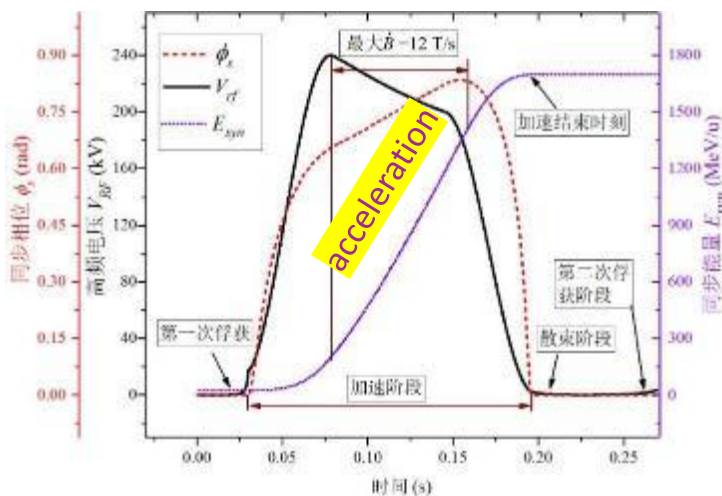
$$\gamma < \gamma_t$$

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

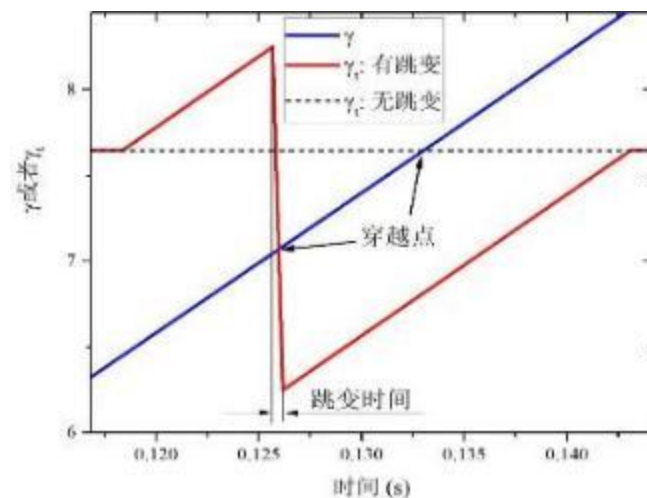
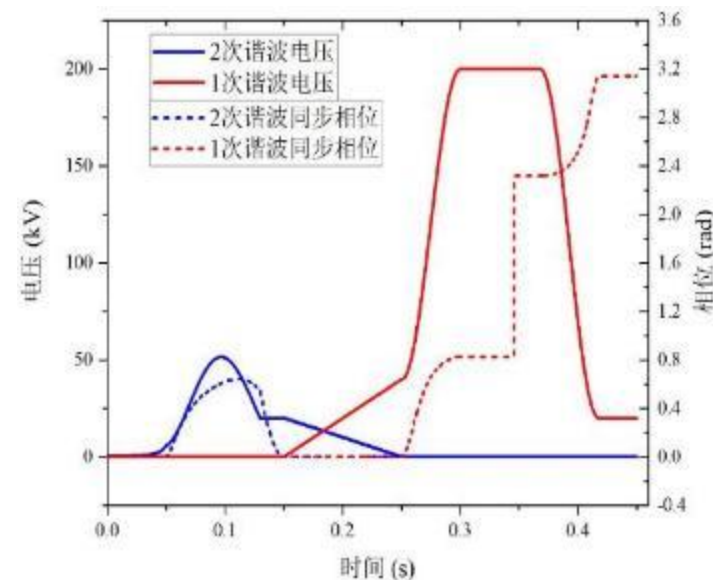
$$\gamma > \gamma_t$$

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

- Heavy ion acceleration

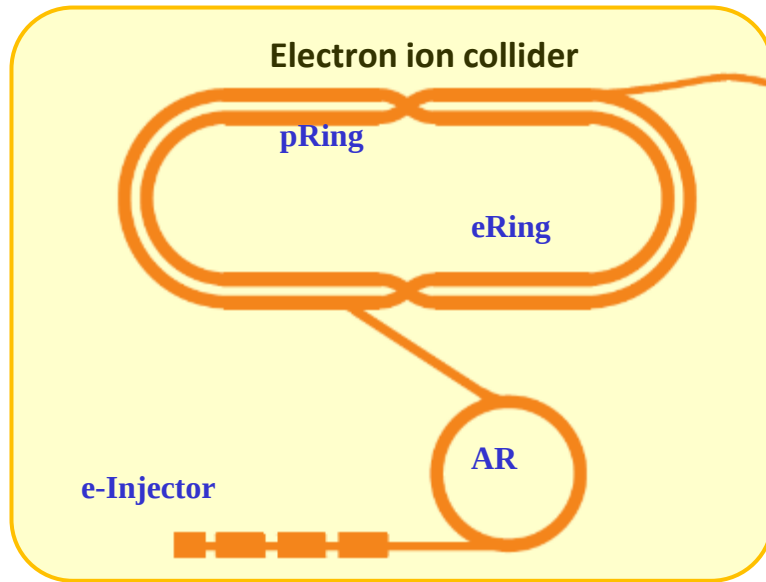


- Proton acceleration



□ Future plan

CNUF-China advanced **NU**clear physics research **F**acility

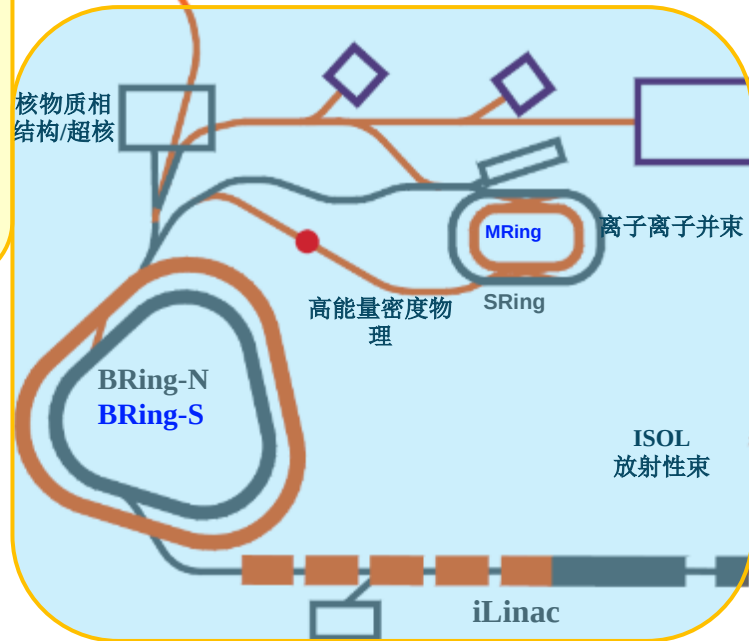


□ Electron ion collider in China (EicC)

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

□ Upgrade of the HIAF (HIAF-U)

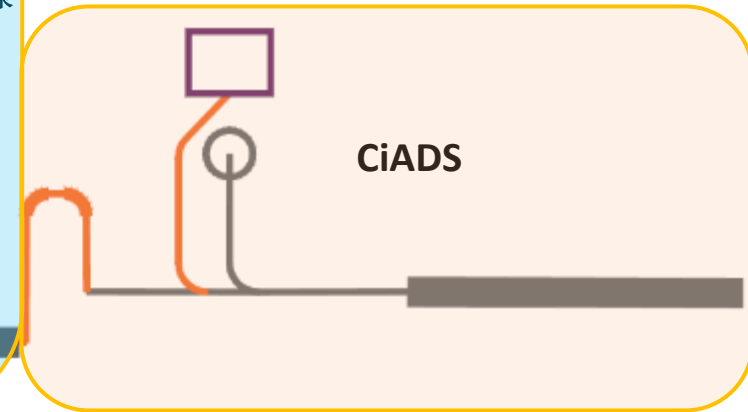
Improve the energy up to 25 GeV (p) and 9 GeV (U)



- New accelerators
- Under construction
- New terminal

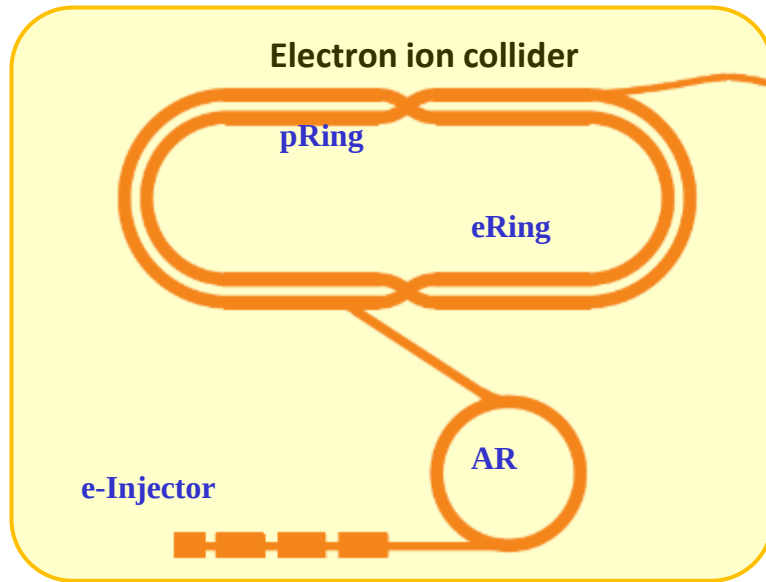
□ Isotope Separation On-Line (ISOL)

Provide MW beam for stable high atomic number elements



□ Future plan

CNUF-China advanced **NU**clear physics research **F**acility



□ 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)

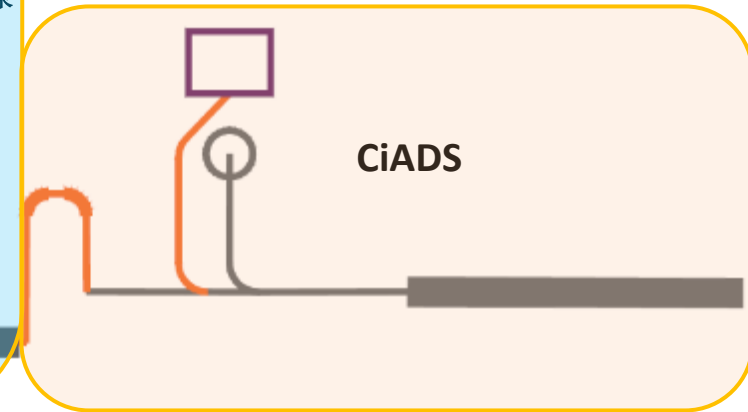
Improve the energy up to 25 GeV (p) and 9 GeV (U)



- New accelerators
- Under construction
- New terminal

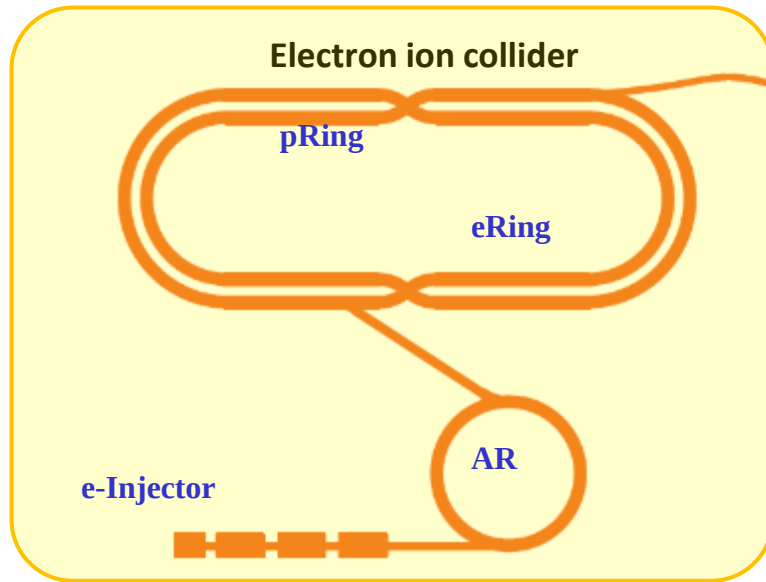
□ Isotope Separation On-Line (ISOL)

Provide MW beam for stable high atomic number elements



□ Future plan

CNUF-China advanced **NU**clear physics research **F**acility

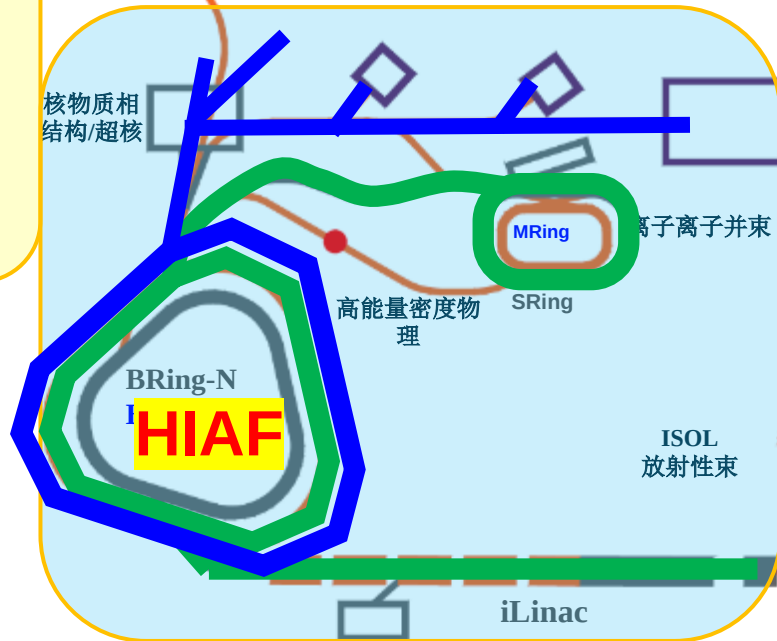


□ Electron ion collider in China (EicC)

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

□ Upgrade of the HIAF (HIAF-U)

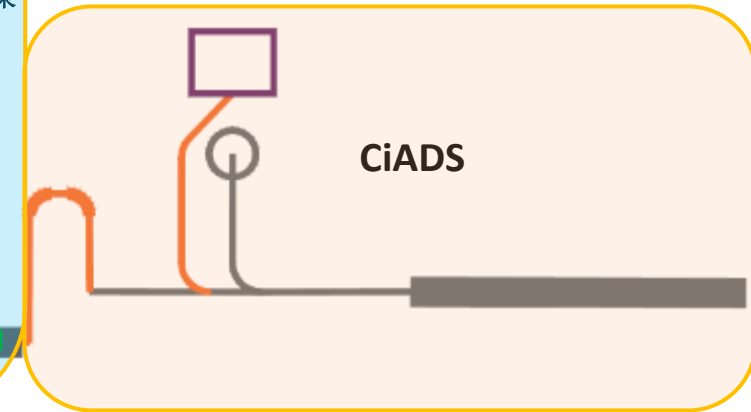
Improve the energy up to 25 GeV (p) and 9 GeV (U)



- New accelerators
- Under construction
- New terminal

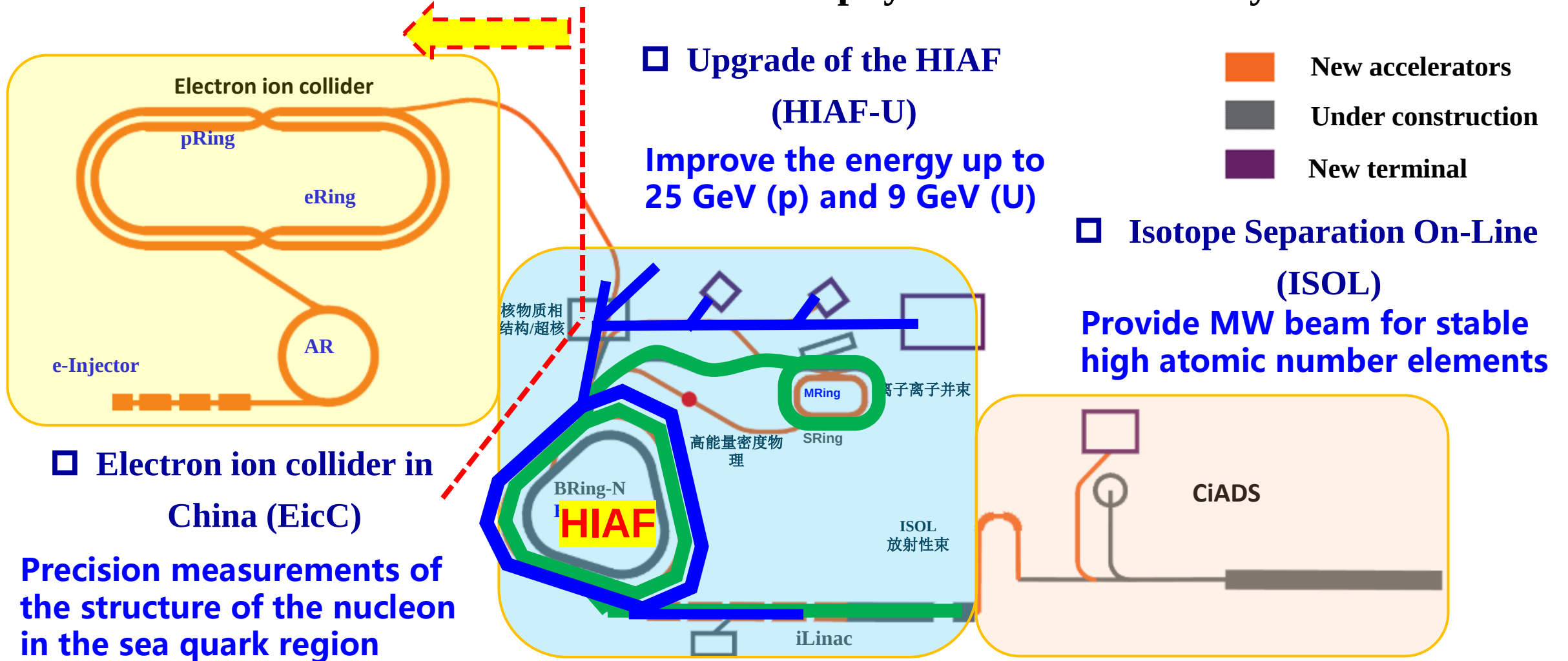
□ Isotope Separation On-Line (ISOL)

Provide MW beam for stable high atomic number elements



□ Future plan

CNUF-China advanced **NU**clear physics research **F**acility



□ Future plan

Institution	Facilities	Time	Reference ion	Energy	Intensity or power
GSI	FAIR SIS100	2025	$^{238}\text{U}^{28+}$	2.7 GeV/u	5×10^{11} ppp
MSU	FRIB	2021	$^{238}\text{U}^{76-80+}$	200 MeV/u	CW 13 pμA
JINR	NICA-Booster	2023	$^{197}\text{Au}^{32+}$	4.5 GeV/u	4×10^9 ppp
IMP	HIAF	2025-2027	$^{238}\text{U}^{35+}$	0.8 GeV/u	$1.0\text{-}2.0 \times 10^{11}$ ppp
			$^{238}\text{U}^{76+}$	2.45 GeV/u	$0.5\text{-}1.0 \times 10^{11}$ ppp
			p	9.3 GeV/u	5×10^{13}
	HIAF-U BRing-S	2027-2032	$^{238}\text{U}^{35+}$	2.95 GeV/u	2.0×10^{12} ppp
			$^{238}\text{U}^{76+}$	7.3 GeV/u	1.0×10^{12} ppp
			$^{238}\text{U}^{92+}$	9.1 GeV/u	1.0×10^{12} ppp
			p	25.0 GeV/u	4.0×10^{14}
	HIAF-U MRing	2027-2032	$^{238}\text{U}^{92+}$	4.4 GeV/u	2×10^{12} ppp
	HIAF-U iLinac	2027-2032	$^{238}\text{U}^{46+}$	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)

□ Future plan

High luminosity mode:

- Peak luminosity of e-p:
- $4.25 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
- Integral luminosity of e-p:
- $106 \text{ fb}^{-1} \text{ /year with 80\% duty factor}$
- Large emittance & intensity
- Large beam divergence at the IP
- High luminosity but **ultra-small angle productions not covered (only $\geq 16 \text{ mrad}$)**

Parameter	electron	proton
Circumference (m)	1151.20	1149.81
Kinetic energy (GeV)	3.5	19.08
CM energy (GeV)	16.76	
$f_{\text{collision}}$ (MHz)	100	
Polarization	80%	70%
Bp (T·m)	11.7	67.2
Bunch intensity ($\times 10^{11}$)	1.7	1.05
$\varepsilon_x, \varepsilon_y$ (nm·rad, rms)	50/15	100/50
β_x^*/β_y^* (cm)	10/4	5/1.2
RMS divergence (mrad)	-	1.4/2.0
Bunch length (cm, rms)	0.75	8
Beam-beam parameter ξ_x/ξ_y	0.102/0.118	0.0144/0.01
Laslett tune shift $\Delta\nu_x/\Delta\nu_y$	-	0.066/0.105
Energy loss per turn (MeV)	0.32	-
Total SR power (MW)	0.86	-
Average current (A)	2.7	1.68
Crossing angle (mrad)	50	
Hourglass	0.52	
Luminosity at nucleon level ($\text{cm}^{-2}\text{s}^{-1}$)	4.25×10^{33}	

□ Summary

- High intensity heavy ion accelerators are very important for nuclear physics, atomic physics and application researches
- Fast ramping synchrotron is a potential candidate to obtain high intensities heavy ion beams
- As a heavy ion machine, the store and acceleration of protons have to be calculated in detail.
- Challenges on magnets, power supplies, RF cavities and vacuum chambers have solution for normal conducting facilities, but still need new ideas for superconducting devices

Thanks for your attention!



