26th International Symposium on Spin Physics
A Century of Spin

中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

From HIAF to EicC

a facility under construction and its future

Jiancheng Yang and Lijun Mao

on behalf of HIAF design group at IMP CAS

2025/09/26, Qingdao

Outline

I. Scientific motivation

II. Introduction of HIAF

III. Challenges and key technologies of HIAF accelerators

IV. From HIAF to EicC: collision, polarization and cooling

V. Conclusion

Outline

I. Scientific motivation

II. Introduction of HIAF

III. Challenges and key technologies of HIAF accelerators

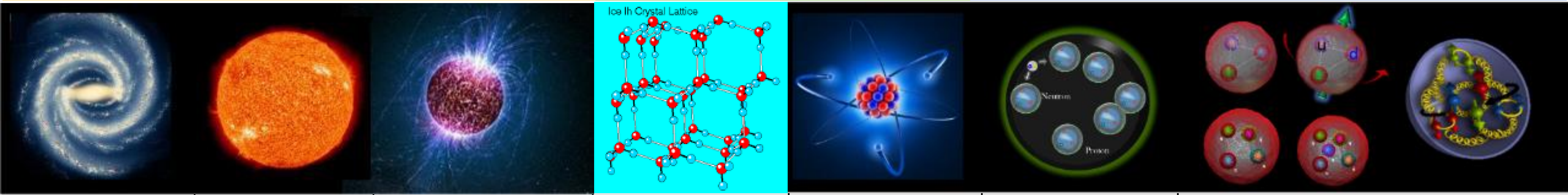
IV. From HIAF to EicC: collision, polarization and cooling

V. Conclusion

Scientific Motivation

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

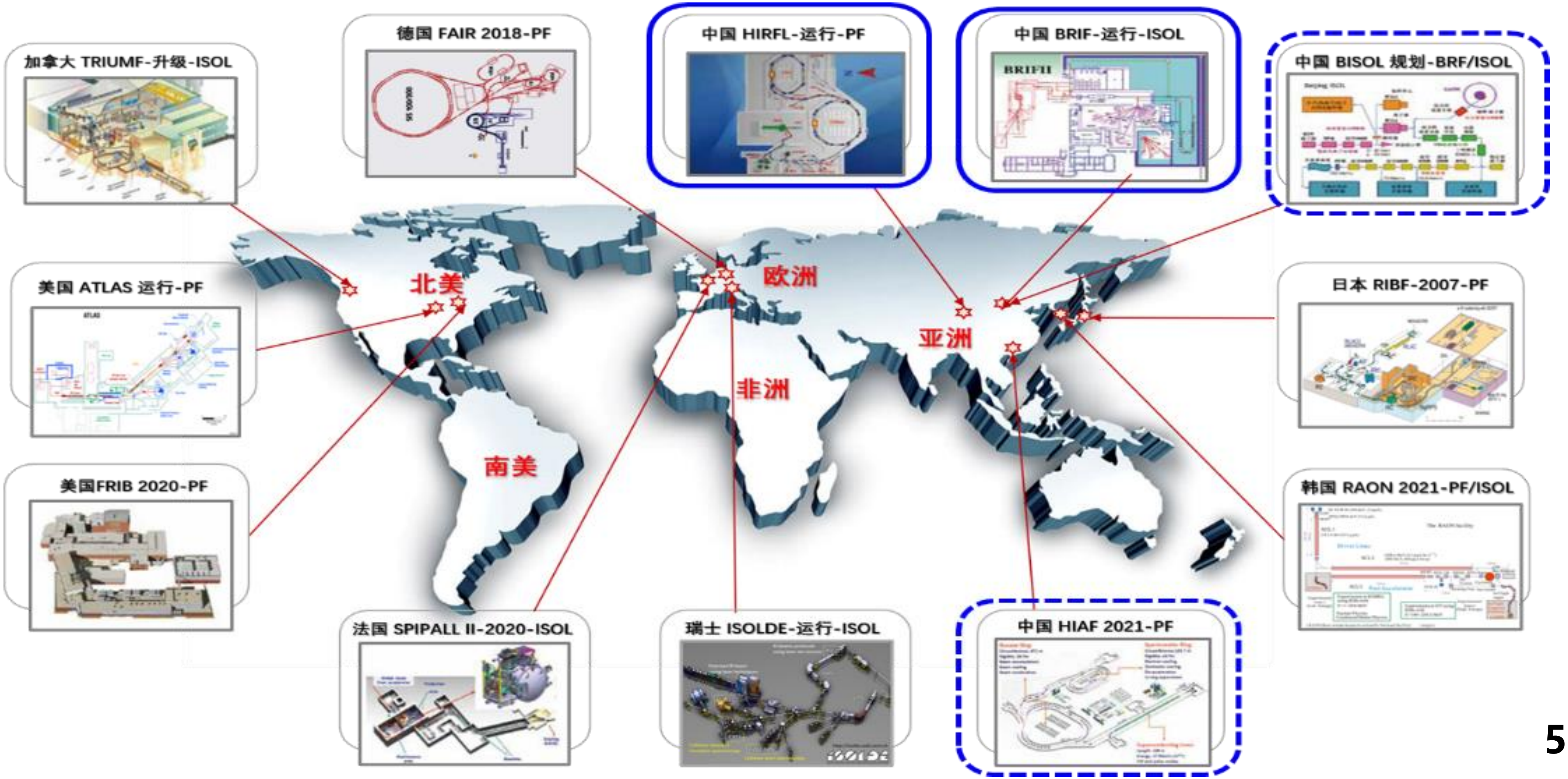


Gravitational force			Electromagnetic force		Strong force		
Galaxy ~10^{21}m	Solar ~10^{9}m	Neutron star ~10^{4}m	Crystal ~10^{-8}m	Atom 10^{-10}m	Atomic nucleus $10^{-15\,-\,14}$ m	nucleon（10^{-15}m）	
						Quark	Gluon
High intensity HI beams			**RIBs ~1.5-2 GeV/u**		**Relative. HI beams ~100 GeV/u**		

High Intensity ← → **High Energy**

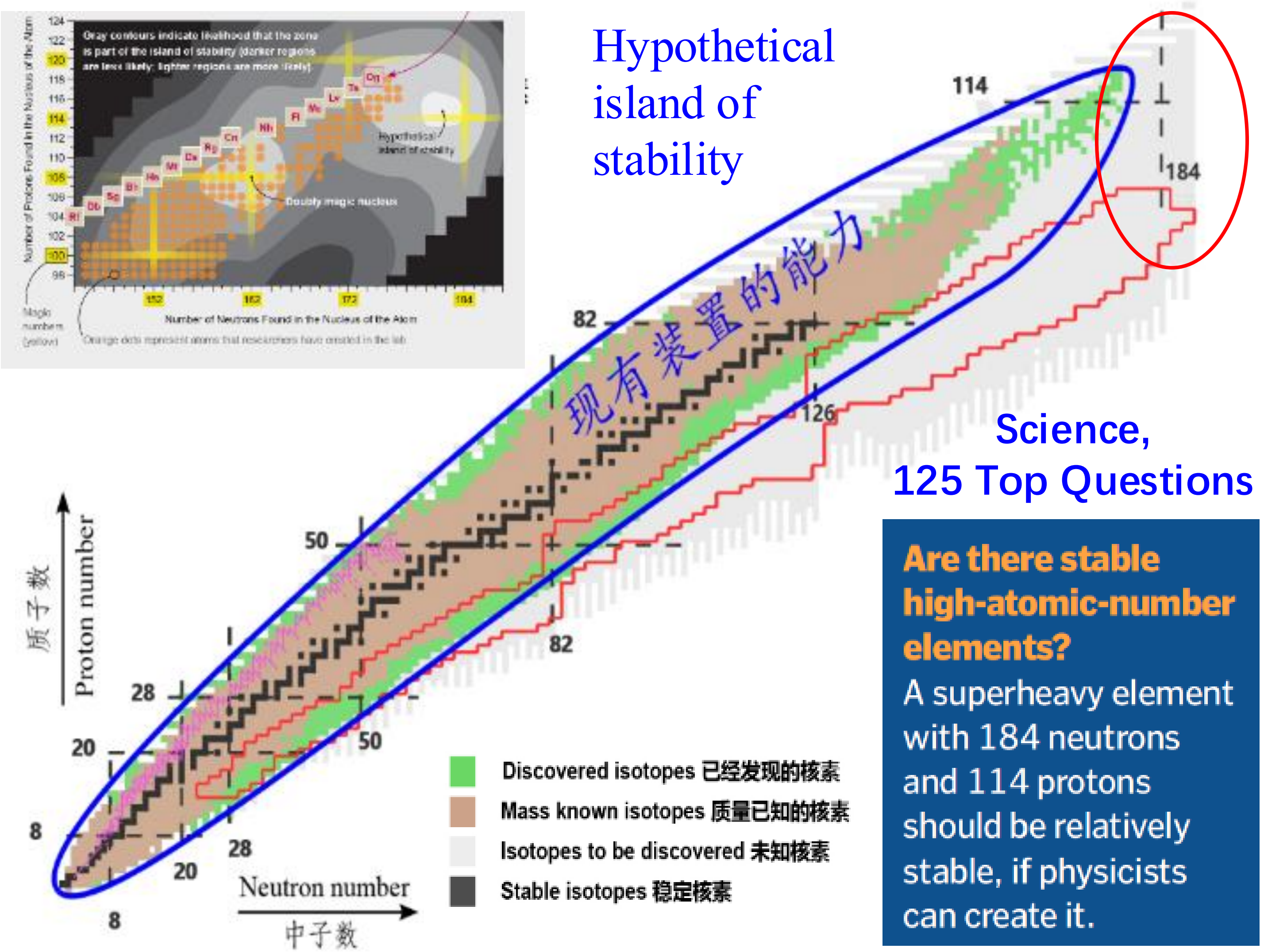
Scientific Motivation

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



Scientific Motivation

How to explore the limit of nuclear existence?



Hypothetical island of stability

Science, 125 Top Questions

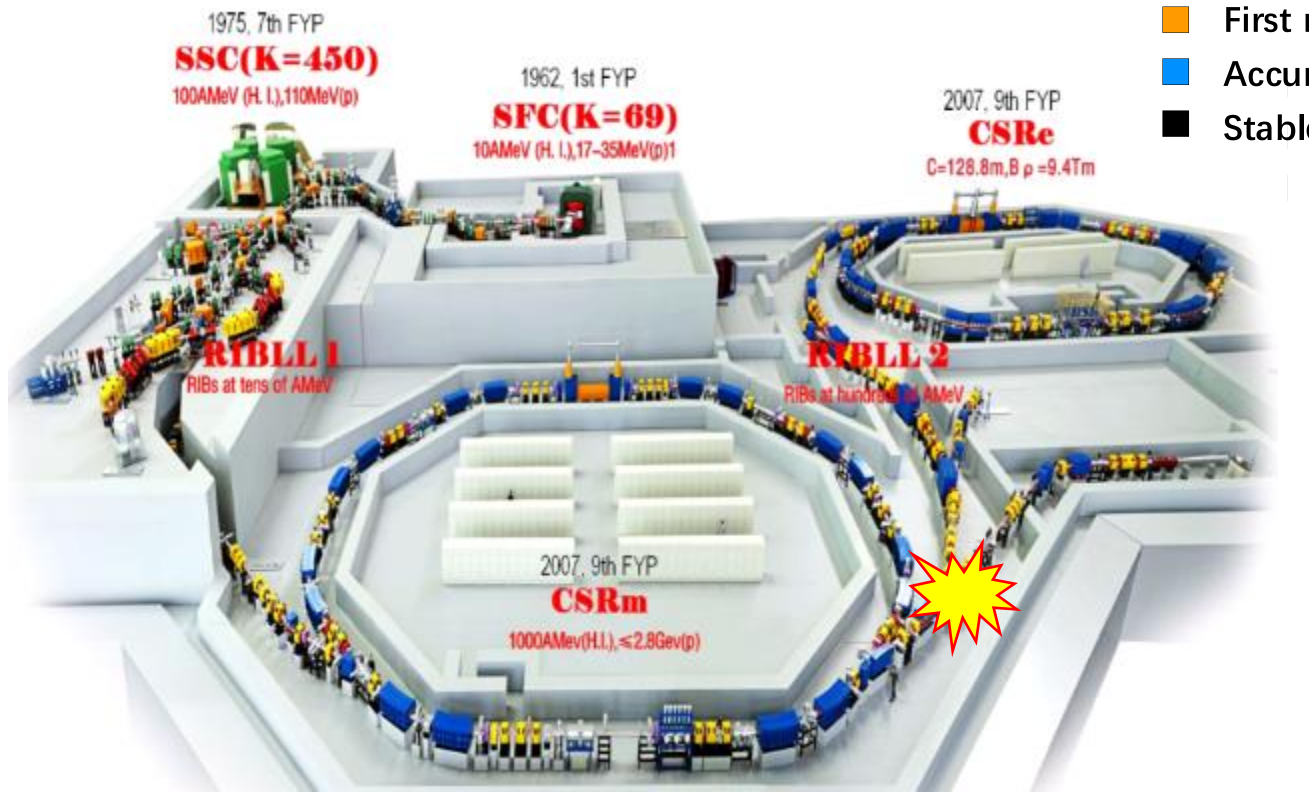
Are there stable high-atomic-number elements?

A superheavy element with 184 neutrons and 114 protons should be relatively stable, if physicists can create it.

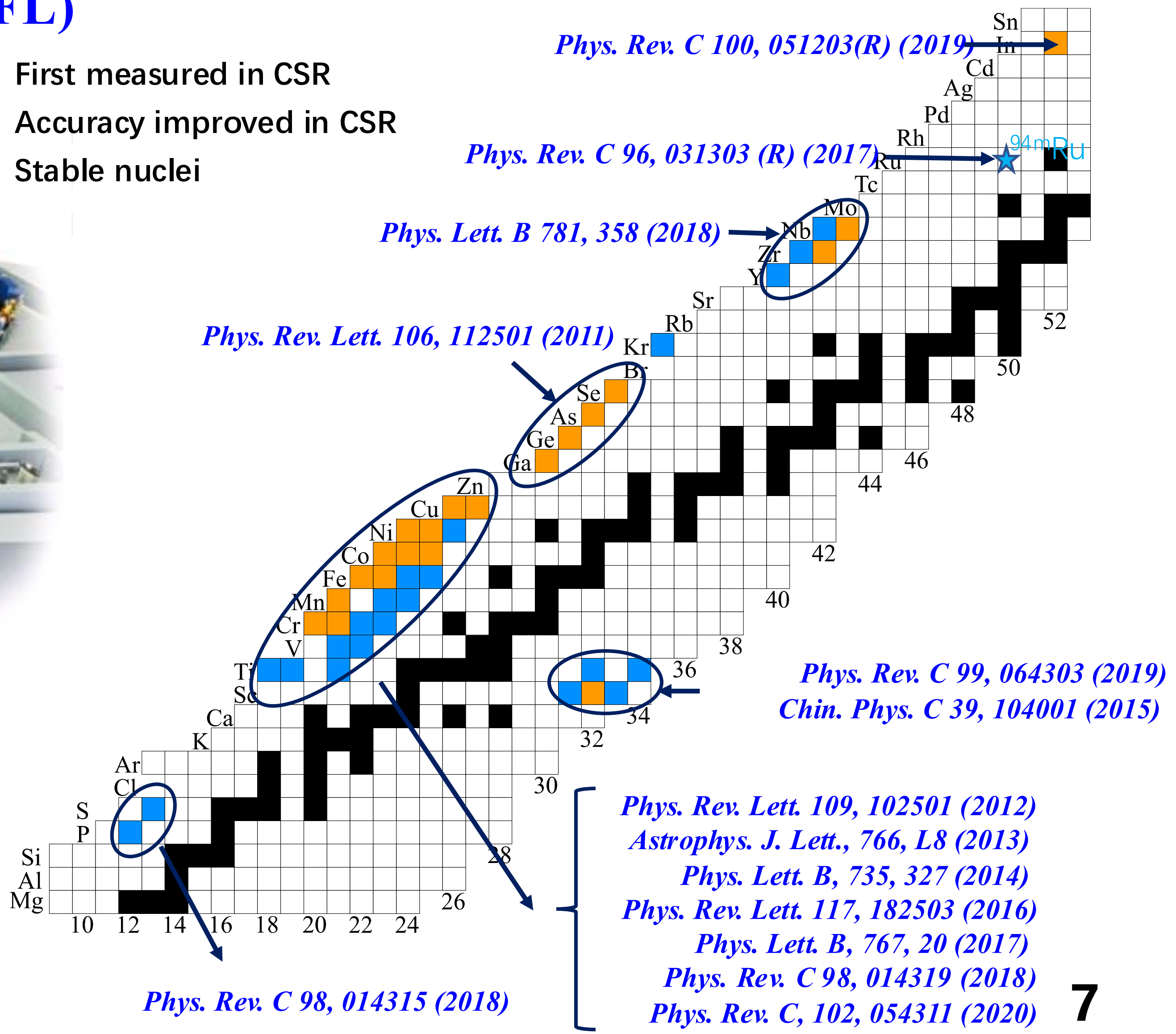
Energy frontier or Intensity frontier, that is the question

Scientific Motivation

Heavy ion research facility at Lanzhou (HIRFL)



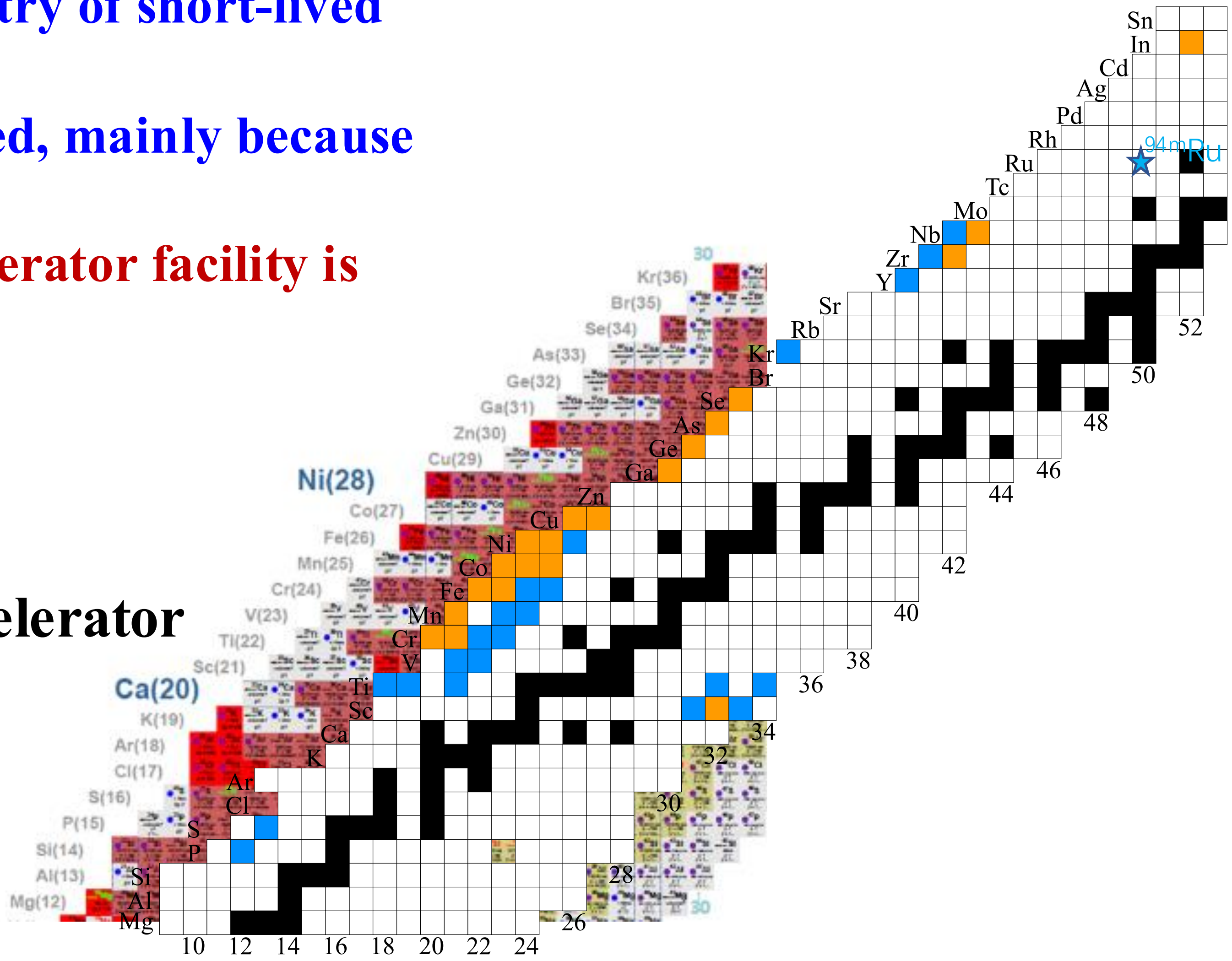
Ions	Energy (MeV/u)	Current (ppp)
$^{238}U^{74+}$	500	$\sim 10^8$
$^{78}Kr^{26+}$	500	$\sim 10^9$
$^{12}C^{6+}$	1000	$\sim 10^{10}$



Scientific Motivation

- Precise mass measurement spectrometry of short-lived nuclides
- 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 (**H**igh **I**ntensity heavy-ion **A**ccelerator **F**acility)
---proposed in 2011
---approved in 2015
---construction from 2018
---beam commissioning in 2025



Outline

I. Scientific motivation

II. Introduction of HIAF

III. Challenges and key technologies of HIAF accelerators

IV. From HIAF to EicC: collision, polarization and cooling

V. Conclusion

HIAF introduction

Budget ~3 billion CNY (including civil construction), start from Dec. 2018, installation finished in Sept. 2025, located in Huizhou.

HIAF introduction

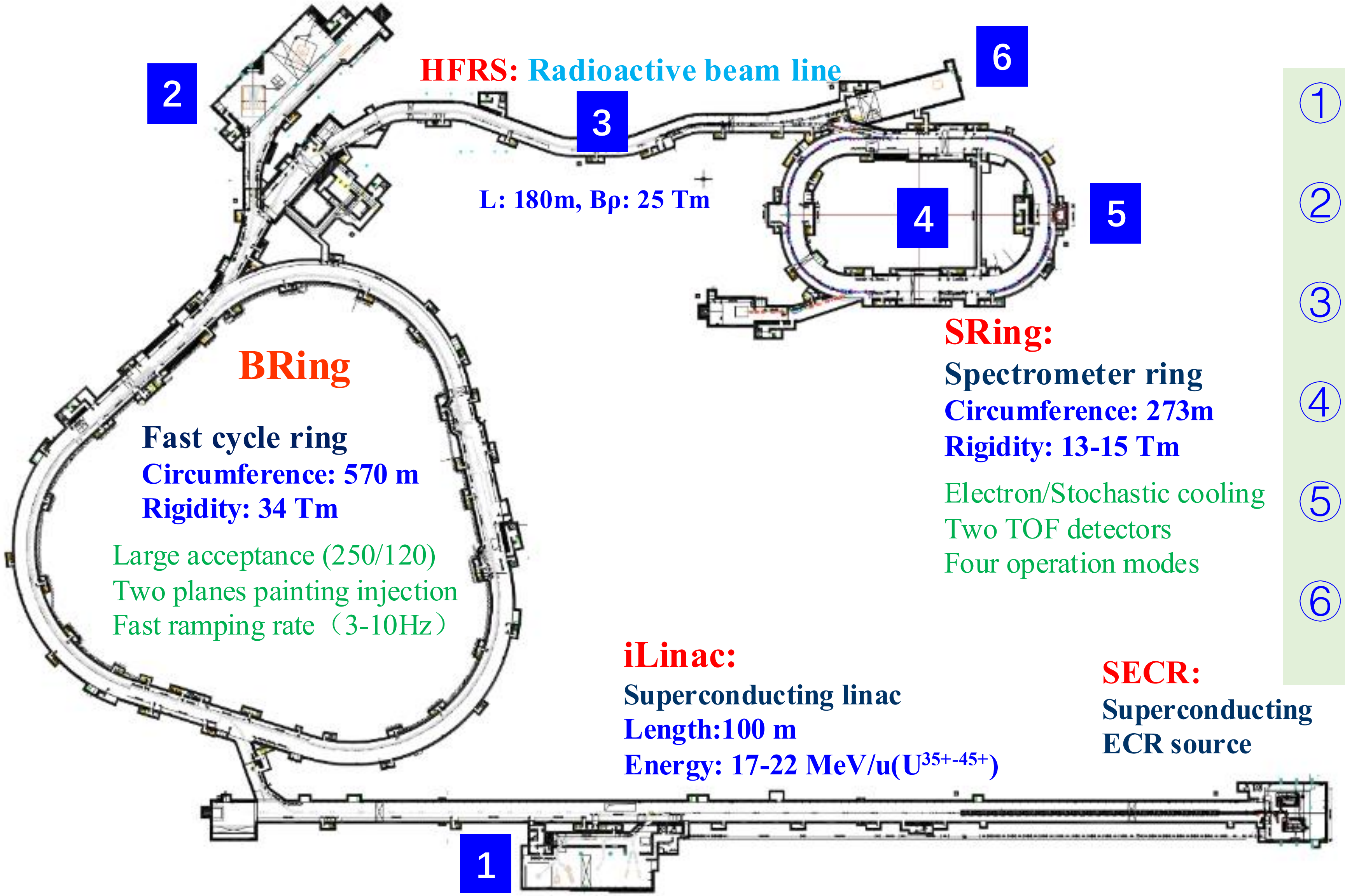
Budget ~3 billion CNY (including civil construction), start from Dec. 2018, installation finished in Sept. 2025, located in Huizhou.

December. 2018

September. 2025

HIAF introduction

HIAF = 4th SECR + superconducting Linac + Fast ramping rate 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

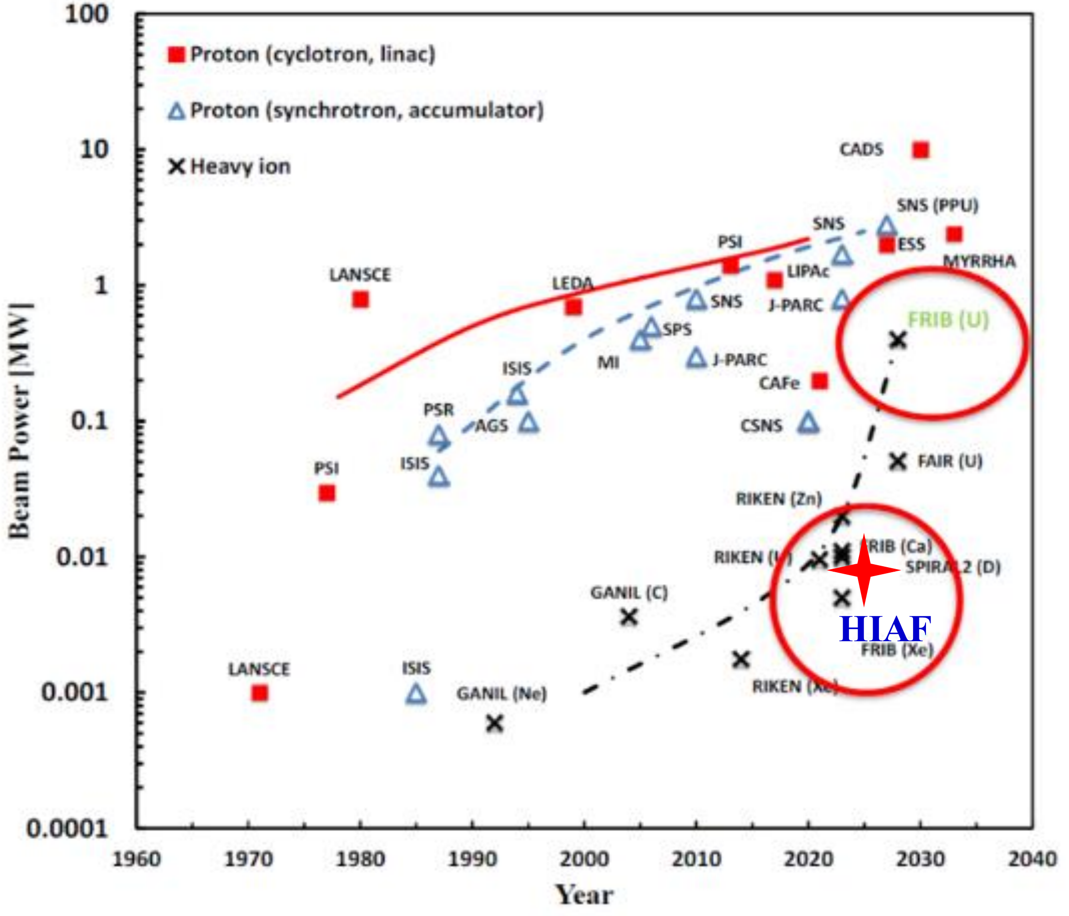
HIAF introduction

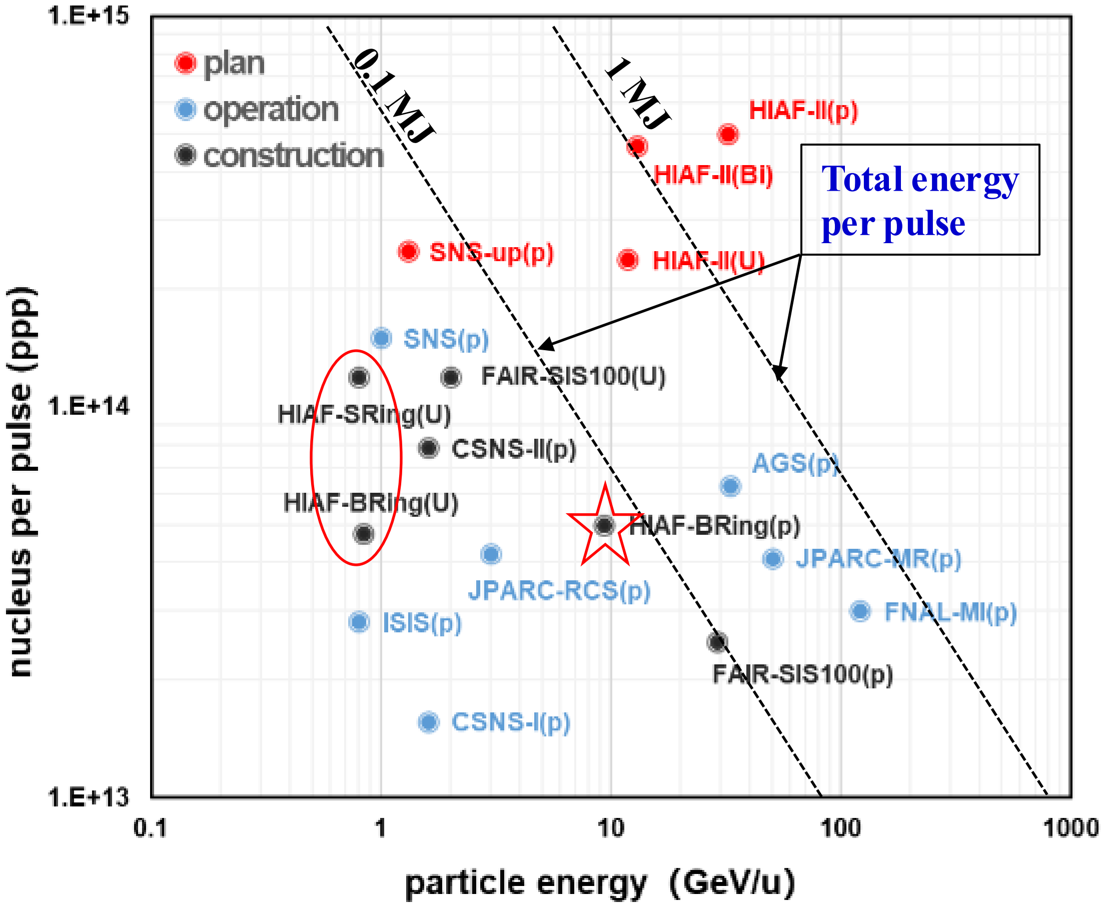
HIAF beam parameters: the highest heavy ion bunches in the world

	SECR	iLinac	BRing	HFRS	SRing	FAIR
Length / circumference (m)	---	114	569	192	277	**1080**
Final energy of U (MeV/u)	0.014 (U^{35+})	17 (U^{35+})	835 (U^{35+})	800 (U^{92+})	800 (U^{92+})	2700 (U^{28+})
Max. magnetic rigidity (Tm)	---	---	**34**	25	15	**100**
Max. beam intensity of U	50 pμA (U^{35+})	28 pμA (U^{35+})	**1×10^{11}ppp (U^{35+})**	-------	**$(2\text{~}4)\times10^{11}$ppp ($U^{92+}$)**	4×10^{11}ppp (U^{28+})
Operation mode	DC	CW or pulse	**fast ramping (12T/s, 3Hz)**	Momentum-resolution 1100	**DC,** deceleration	**0.5**

HIAF introduction

the average beam power is not competitive, the stopping power in materials is enough for high energy intensity physics.

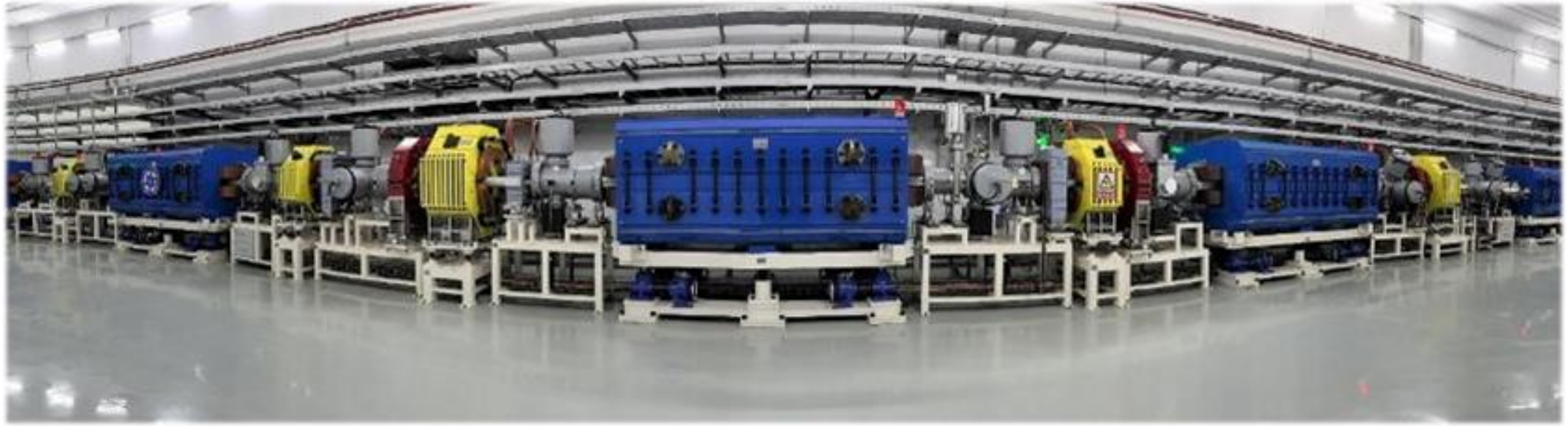




HIAF introduction



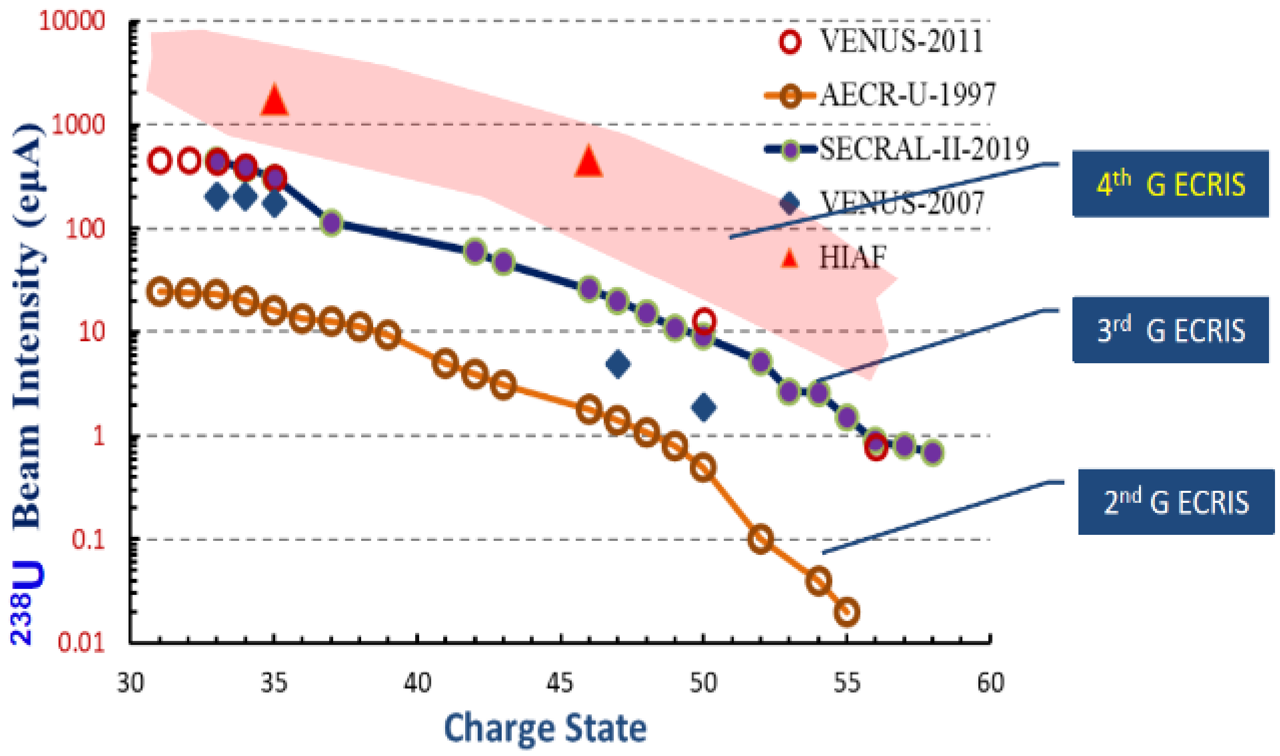


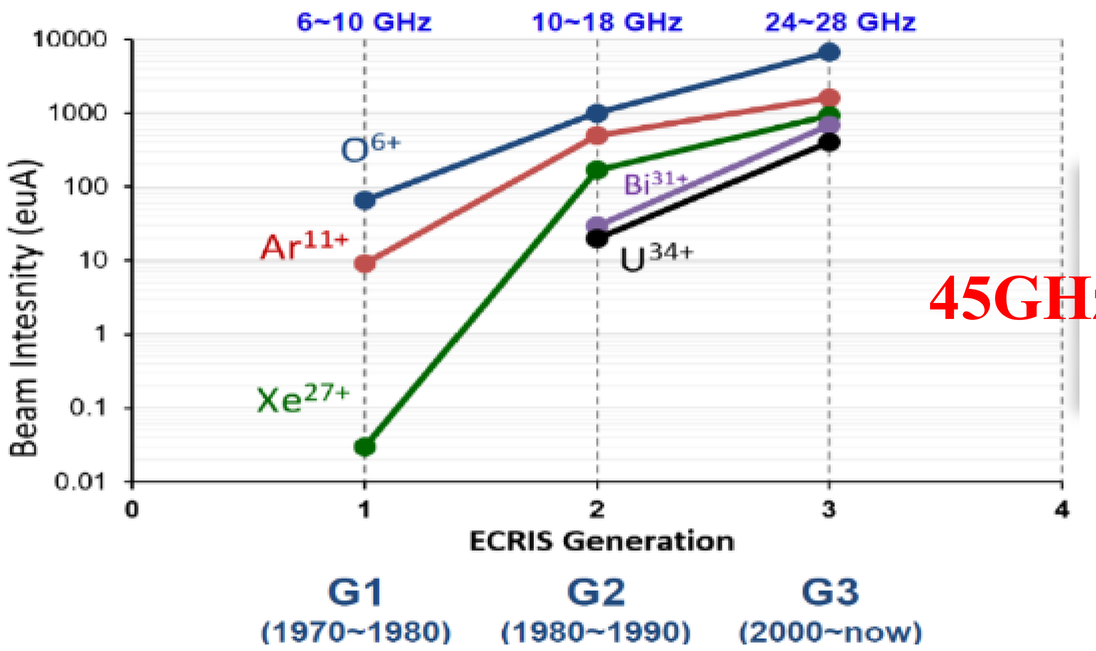



Outline

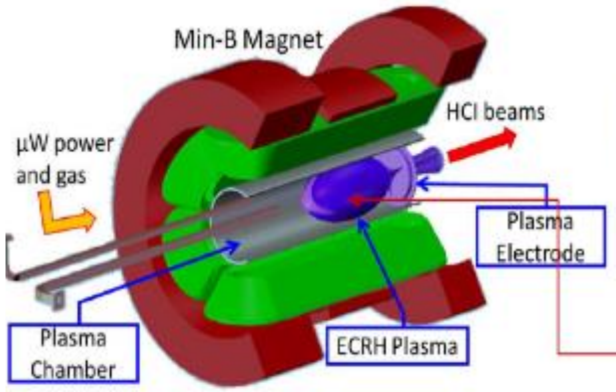
Challenges and key technologies

- **4^{th} SECR: state of the art ECRIS**
  - The goal of the stored particle number in HIAF needs a powerful ion source
  - 1 emA U^{35+} is required





45GHz



Plasma Magnet Microwave

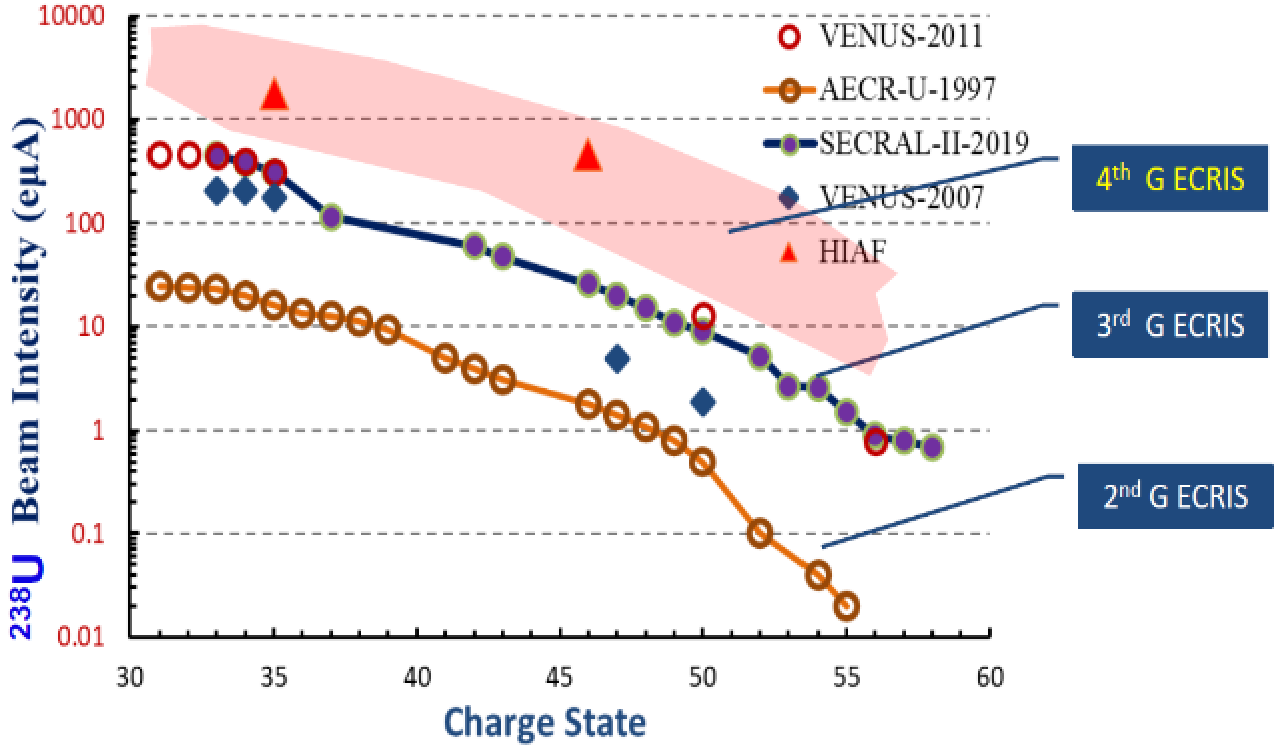
Electron Cyclotron Resonance Ion Source

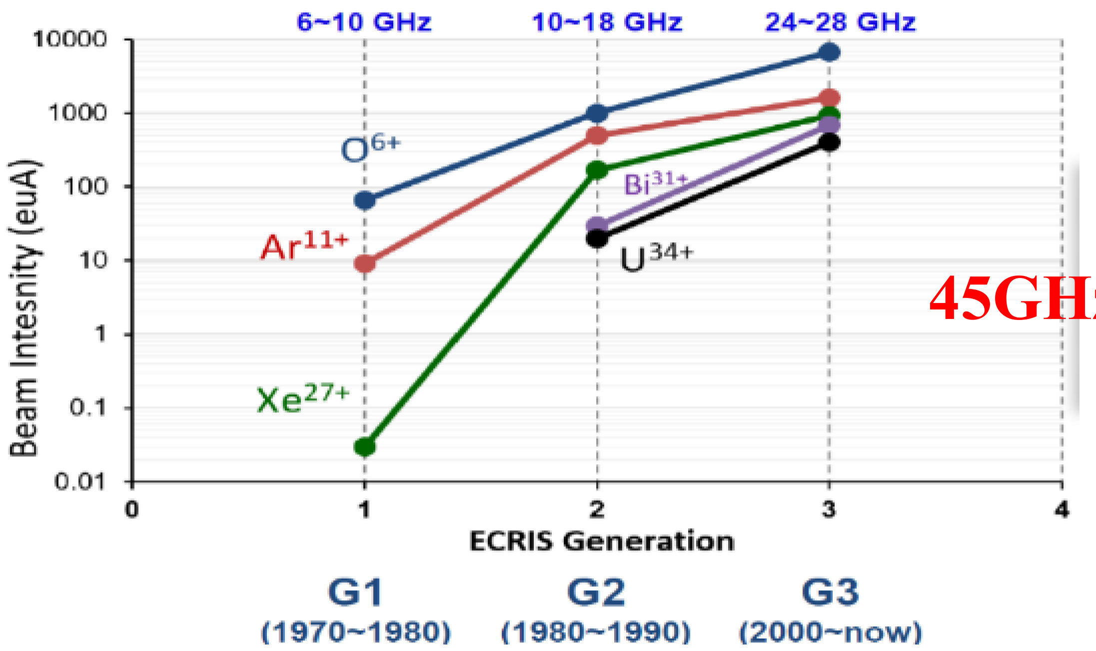
$$\omega_{ce} = \frac{e \cdot B_{ecr}}{m_e}$$

---L. Sun, ICIS'23

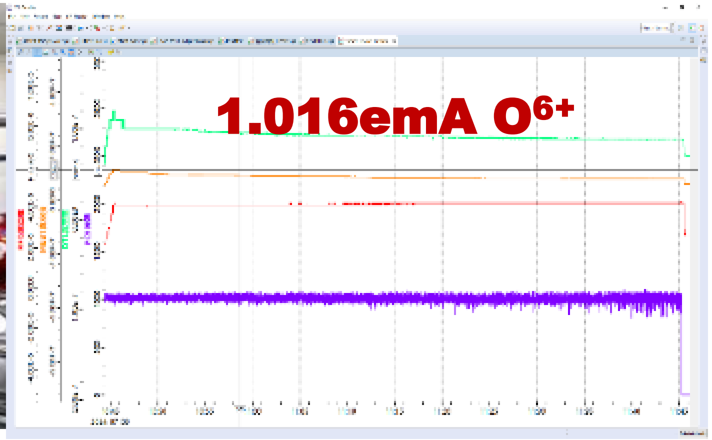
Challenges and key technologies

- **4th SECR:** state of the art ECRIS
  - The goal of the stored particle number in HIAF needs a powerful ion source
  - 1 emA U^{35+} is required





45GHz



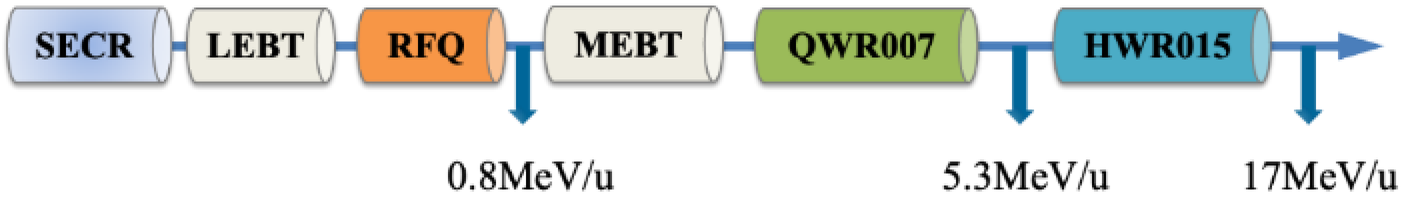
---L. Sun, ICIS'23

Challenges and key technologies

- **Superconducting linac:** CW and pulsed modes

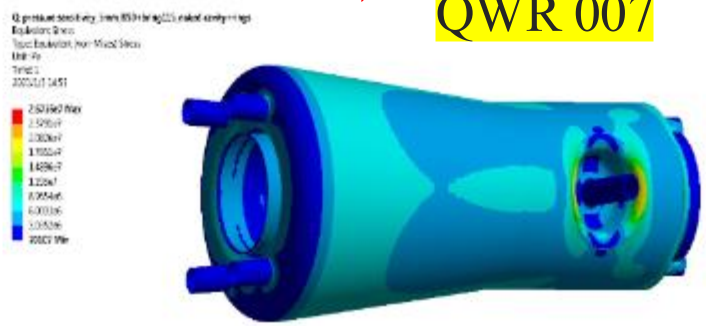
To BRing with 3 Hz pulsed beam

To low energy terminal with CW beam

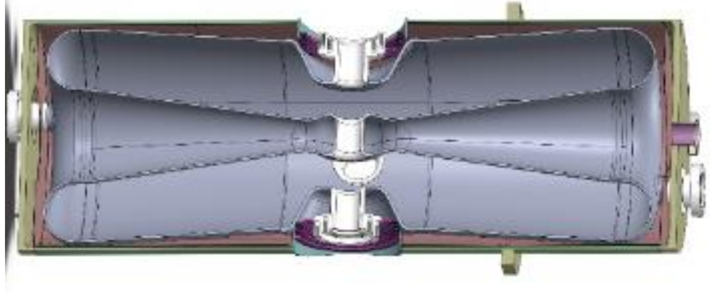


RFQ in tunnel

QWR 007



HWR 015



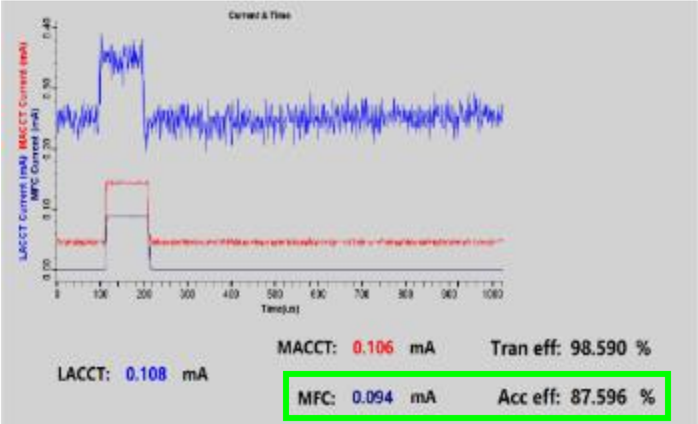
Cavities and Cryomodule

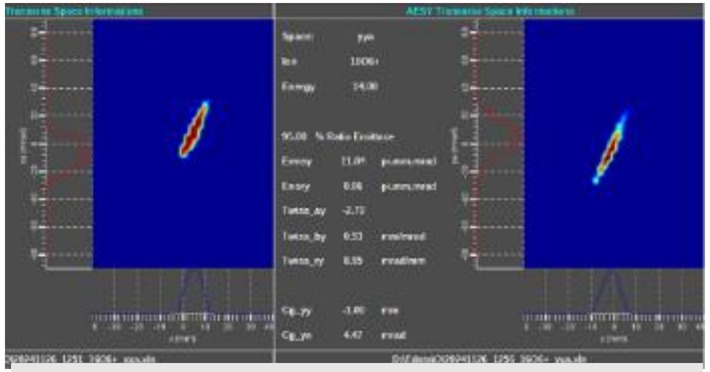
Challenges and key technologies

- **Primary commissioning of ESR and RFQ**
  - 1 emA $^{16}O^{6+}$ beam has been obtained from RFQ, Kr and Bi have been accelerated successfully
  - Efficiency as well as stabilities have to study in detail

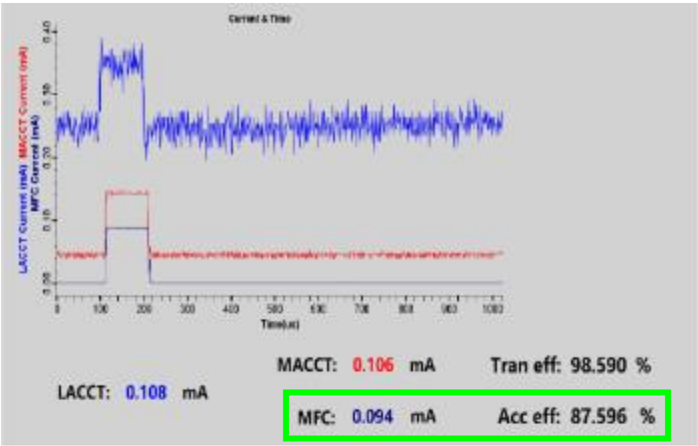
Commissioning results

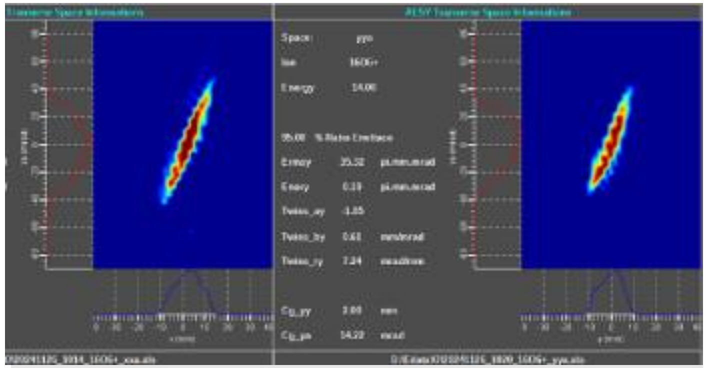
Ion	Current	Pulse width	Energy	Trans. effy	Accel. effy
$^{16}O^{6+}$	**1 emA**	1ms@1Hz	12.86 MeV	70.9%	60.6%
$^{84}Kr^{19+}$	**115 eμA**	1ms@1Hz	-	94.6%	86.4%
$^{209}Bi^{31+}$	**52 eμA**	1ms@1Hz	169.4 MeV	93.0%	-





RFQ entrance: 0.07 π.mm.mrad





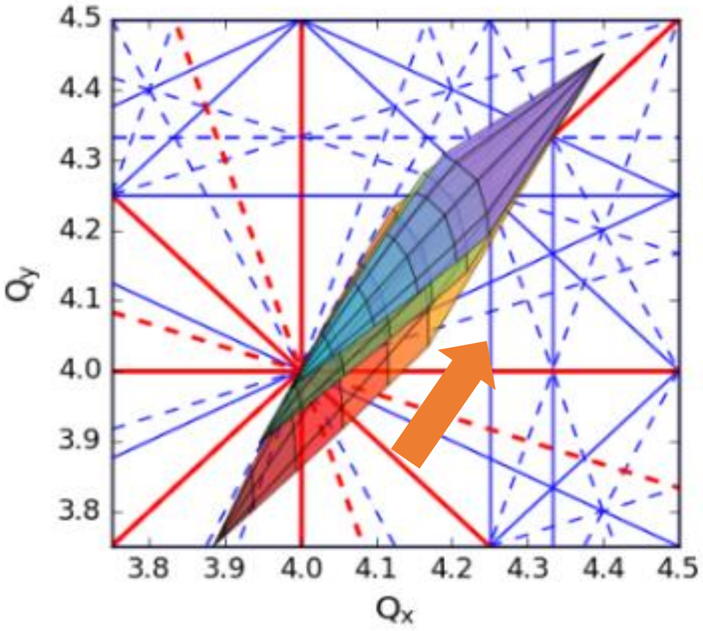
RFQ entrance: 0.23 π.mm.mrad

Challenges and key technologies

- **Booster Ring (BRing):** Fast ramping rate synchrotron

- 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**

1. Very high current ramping rate up to 38 kA/s for dipole PS
2. High acceleration voltage up to 240kV/turn
3. Thin wall vacuum chamber to avoid distortion with eddy current



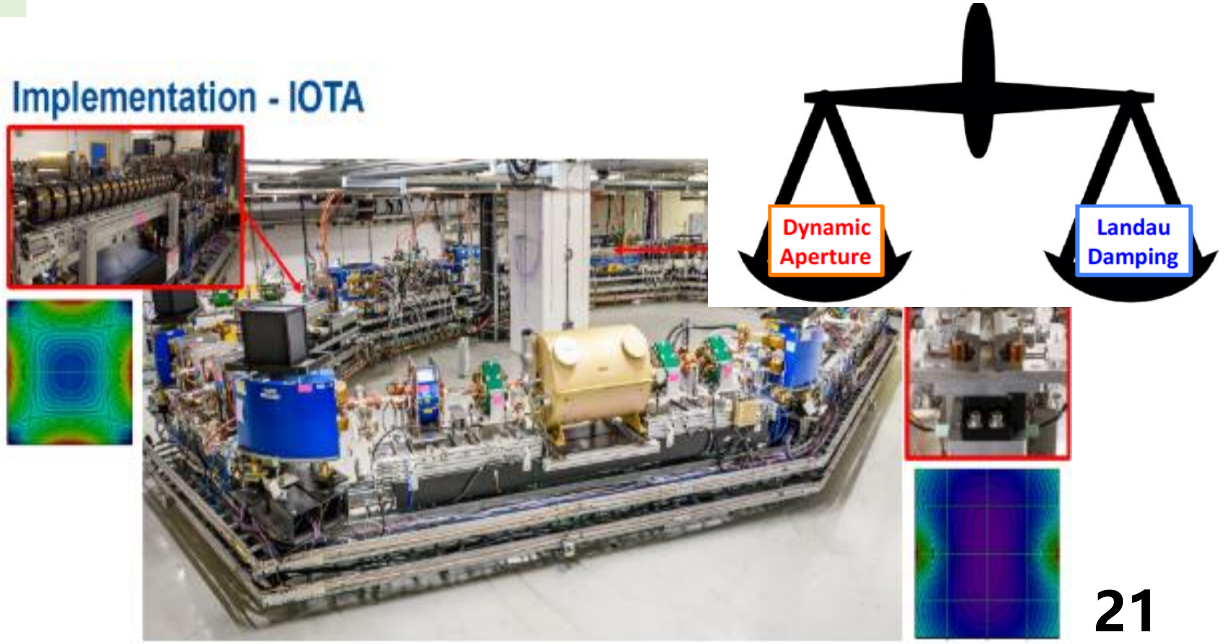
0.6T/s @ HIRFL

↓

10T/s @ SIS 18

↓

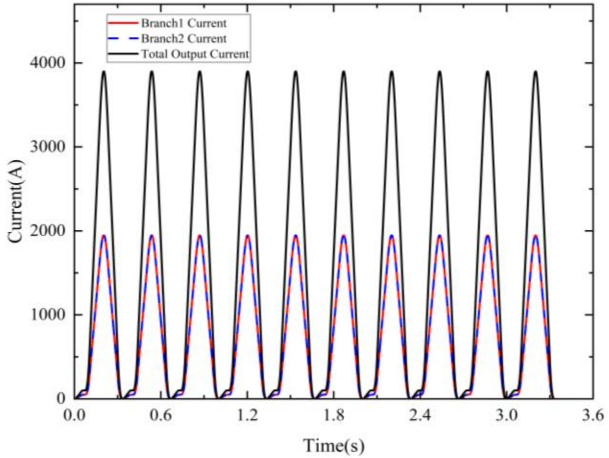
12T/s @ BRing

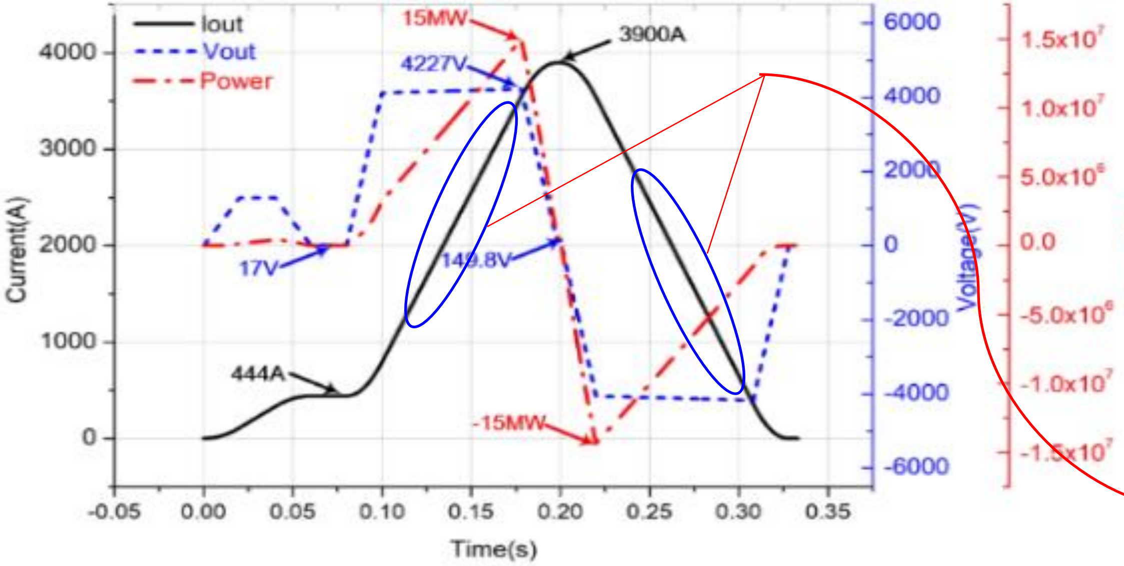


Challenges and key technologies

1. 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





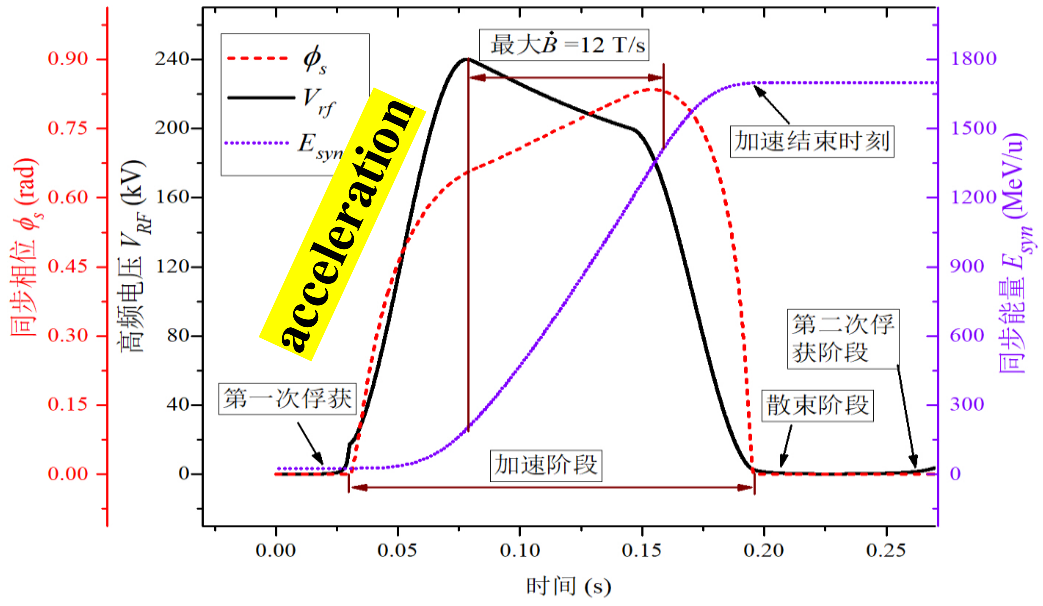
Power (MVA)	Conventional	Energy storage
BRing bendng magnet	**180**	**15**
BRing quadruple magnet	**50**	**6**
Total of BRing	250	41
Total of HIAF	297	88

Energy **capacitor** is used to **store energy** during the falling, and provide the energy for next fast ramping

Challenges and key technologies

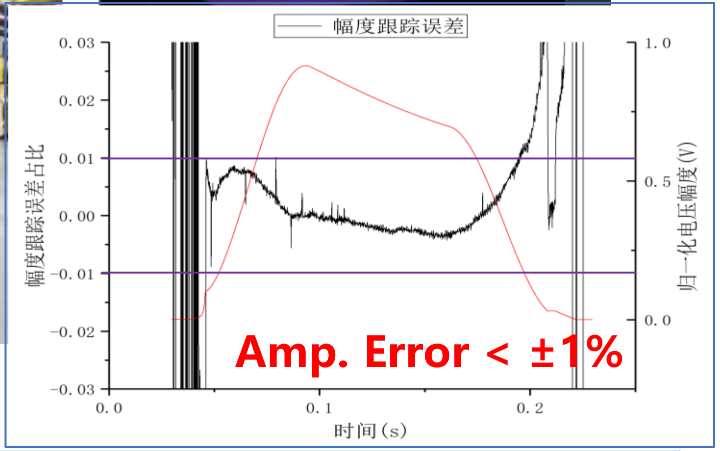
2. Magnetic ally core loaded RF system

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 key technologies

3. 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

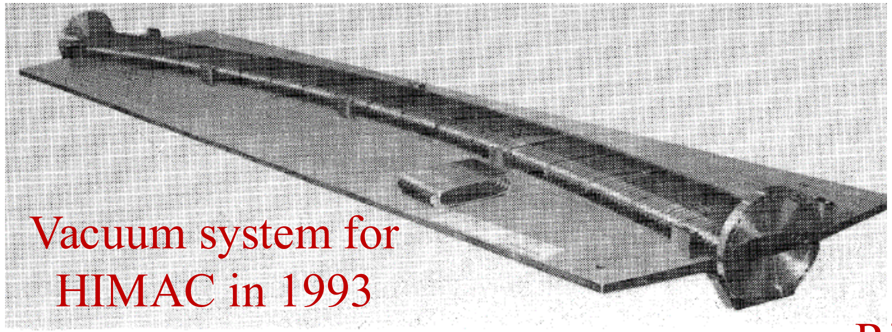
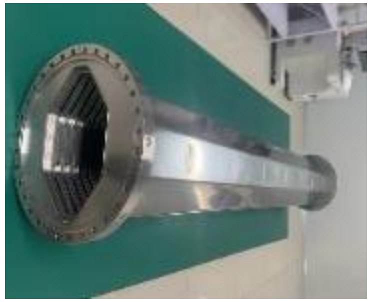


Figure 1a. One section of vacuum chamber set on a steel plate with the same curvature as the bending magnet.

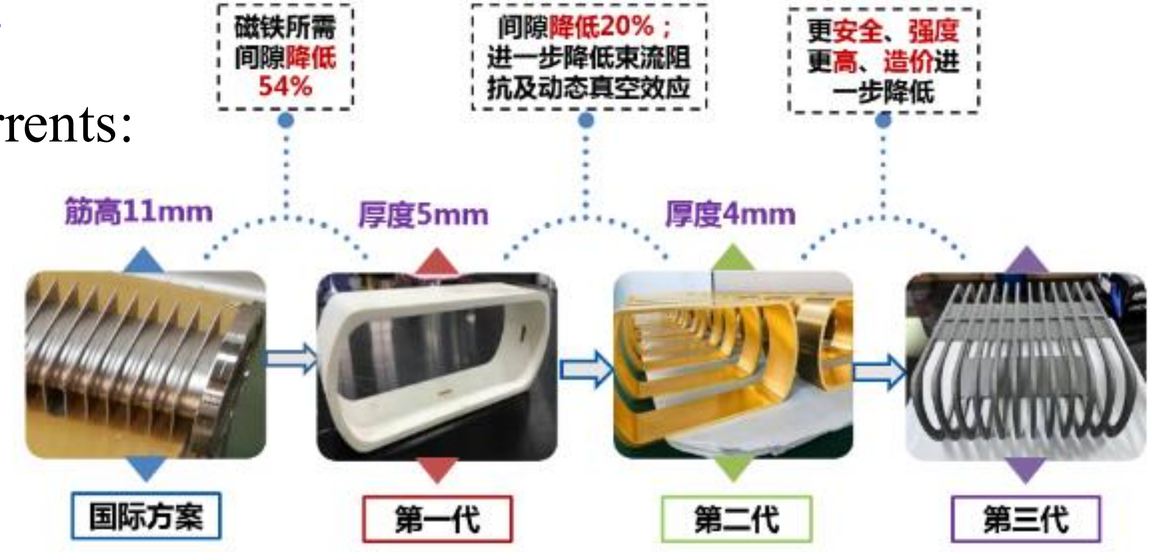


Rings inside @ IMP

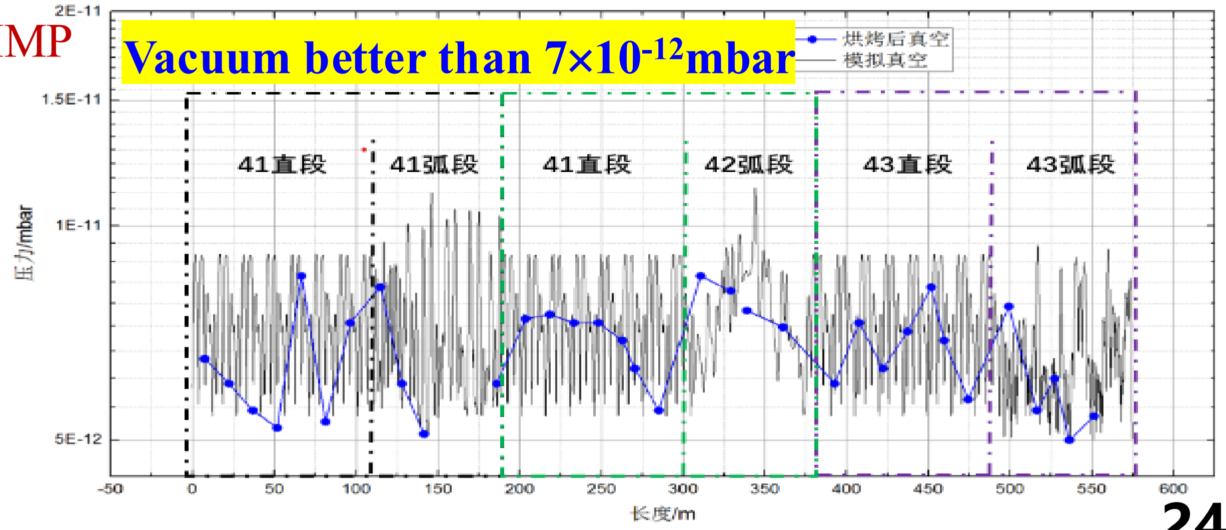
Solution from GSI

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

Quadrupole Chamber



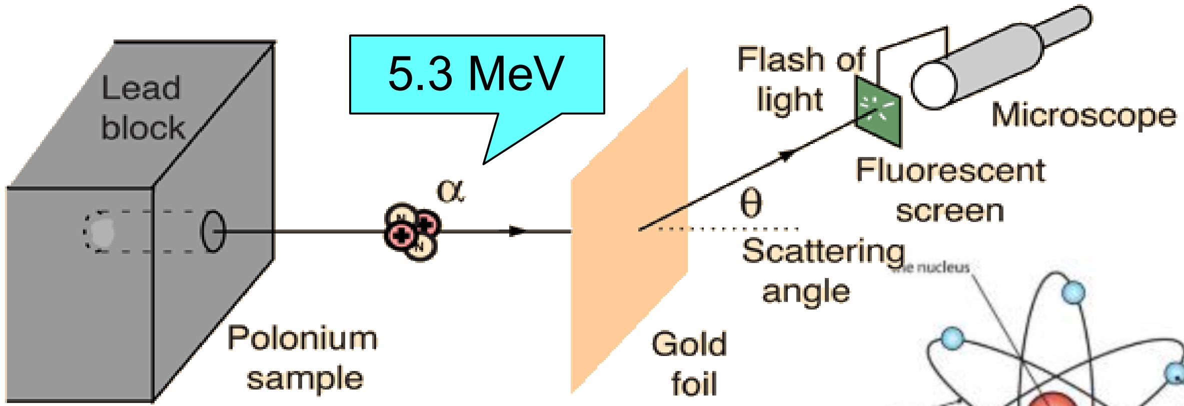
Vacuum better than 7×10^{-12}mbar

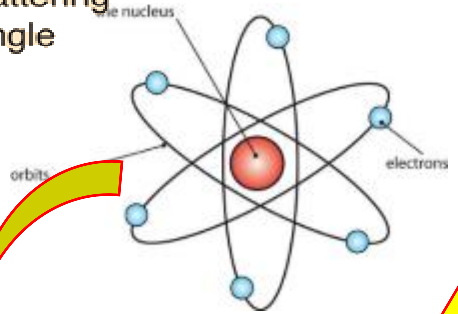


Outline

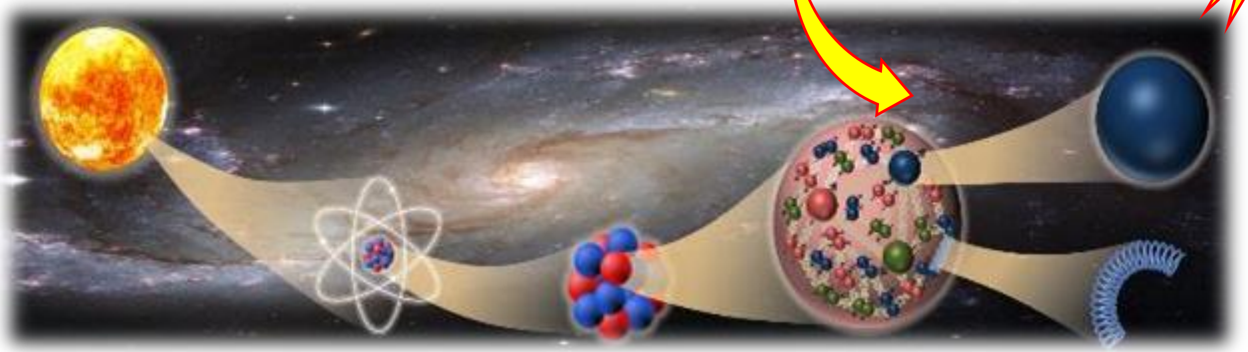
EicC motivation

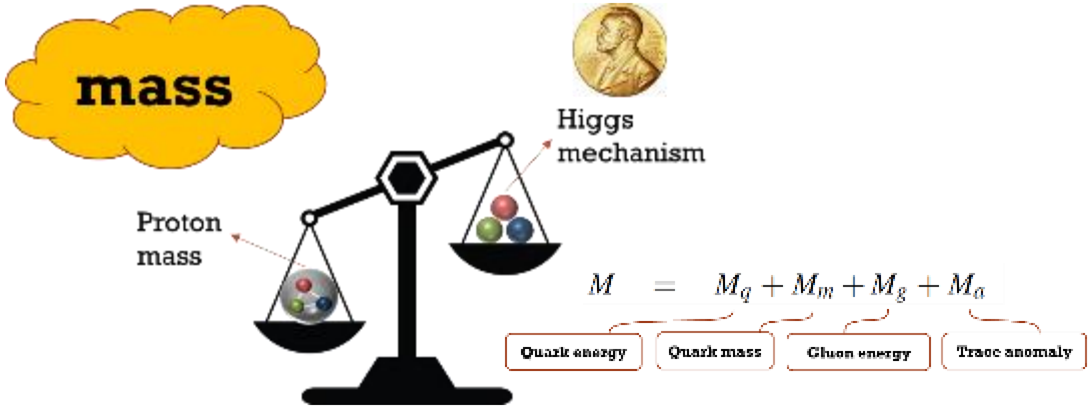
- **Rutherford experiment**

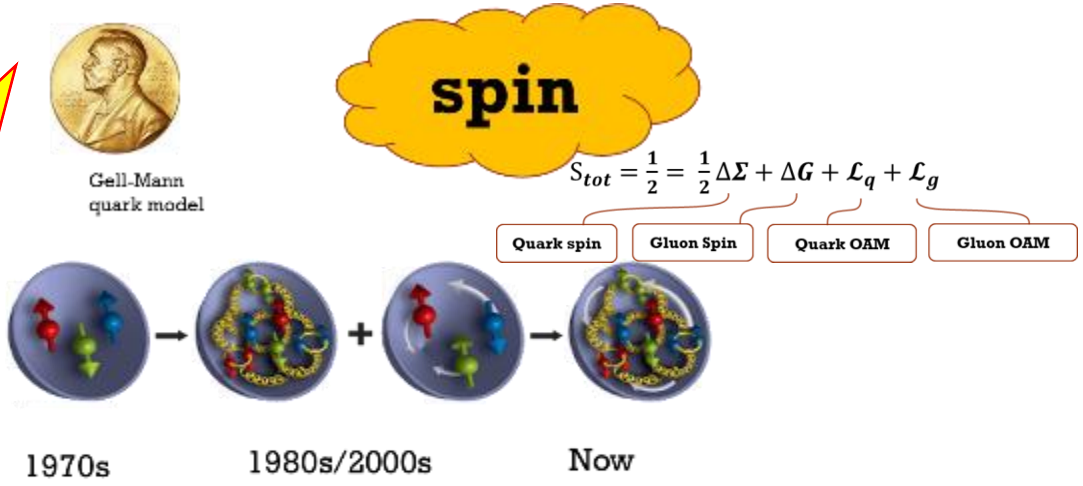




Proton, neutron not discovered yet





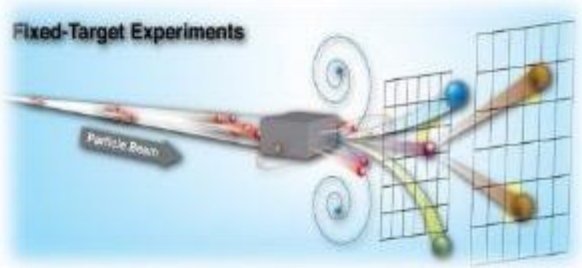


Experimentally… we need to determine each of the above contributions

EicC motivation

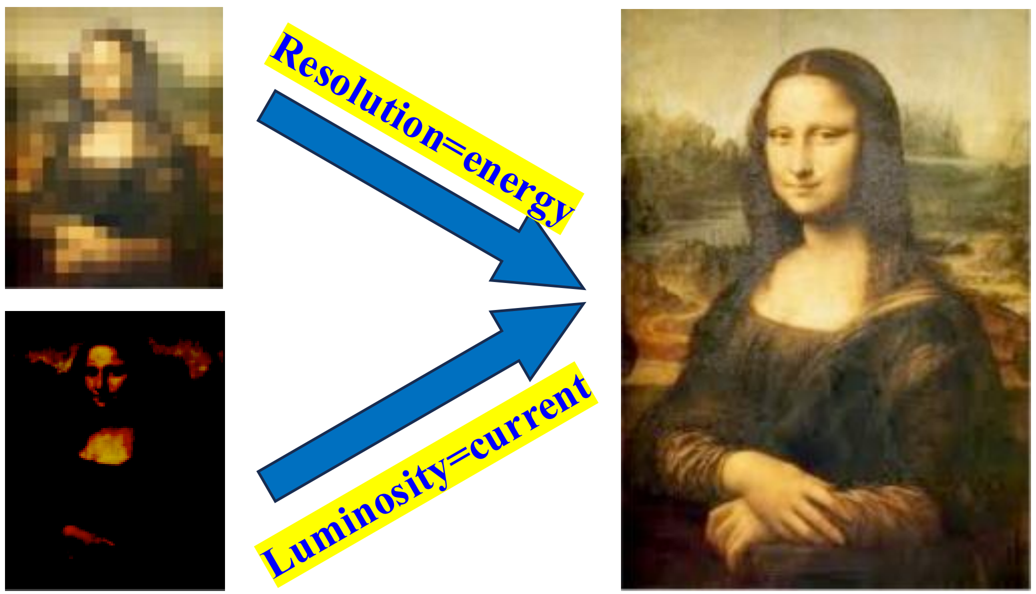
- **From fixed target to collider**

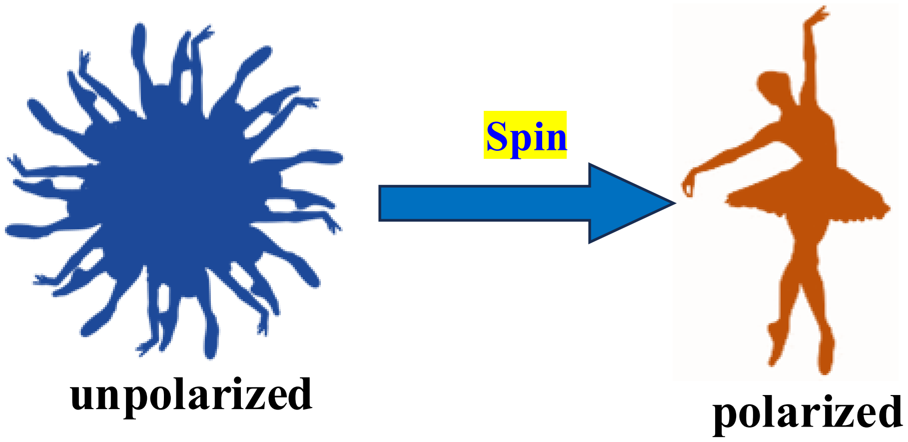
Improve the energy, luminosity and polarization



$$E^* = 1.37\sqrt{E_{inc}}\sqrt{GeV}$$

$$E^* = 2\sqrt{E_1}\sqrt{E_2}$$

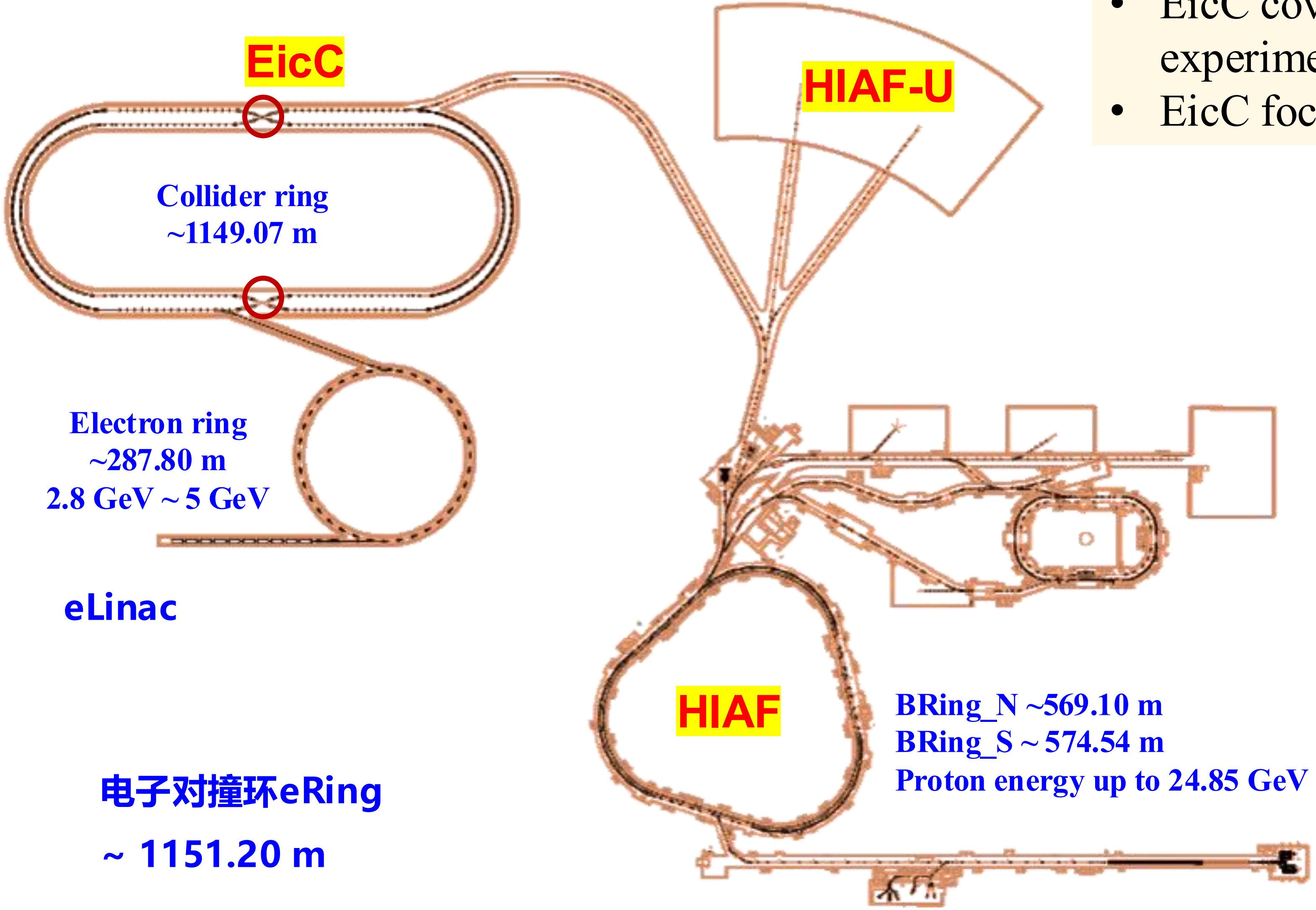




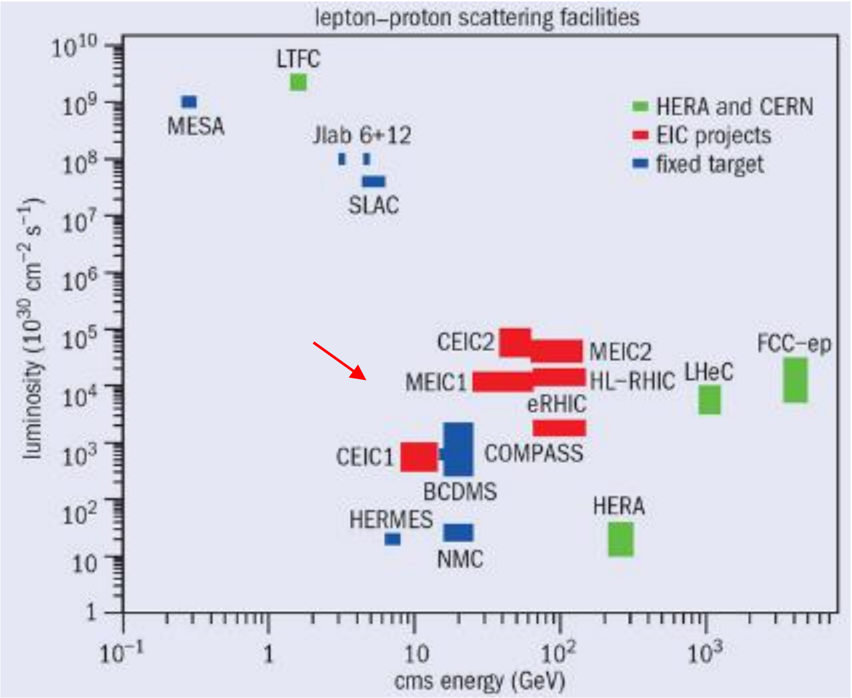
---Y.Zhang, Jlab, EIC leture

EicC motivation

- **Electron cooler and electron target**



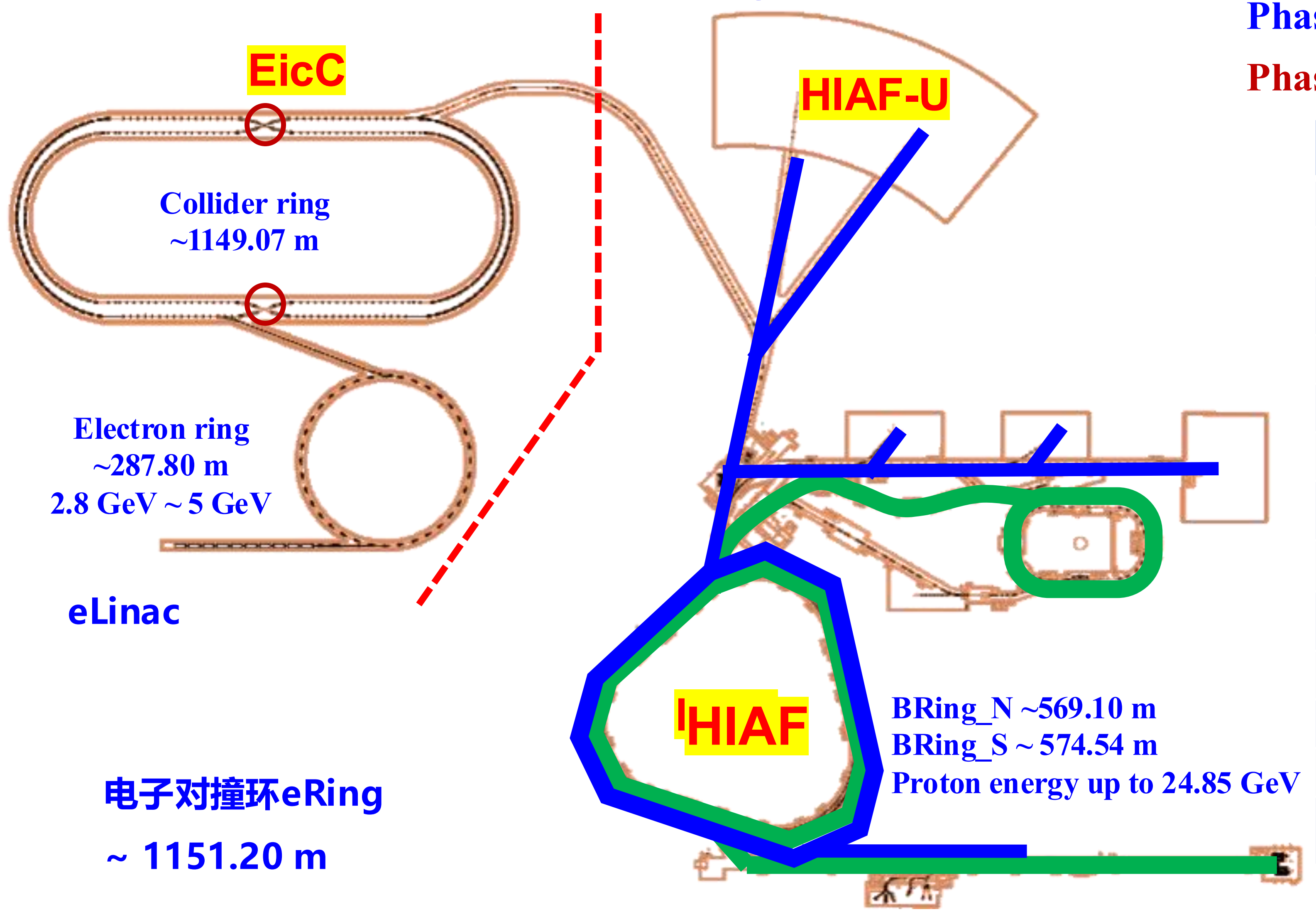
- EicC covers the kinematic region between JLab experiments and EIC@BNL
- EicC focuses on moderate x and sea-quark region



---Max Klein, University of Liverpool，2014

EicC motivation

- Electron cooler and electron target



Phase 1: HIAF for nuclear physics

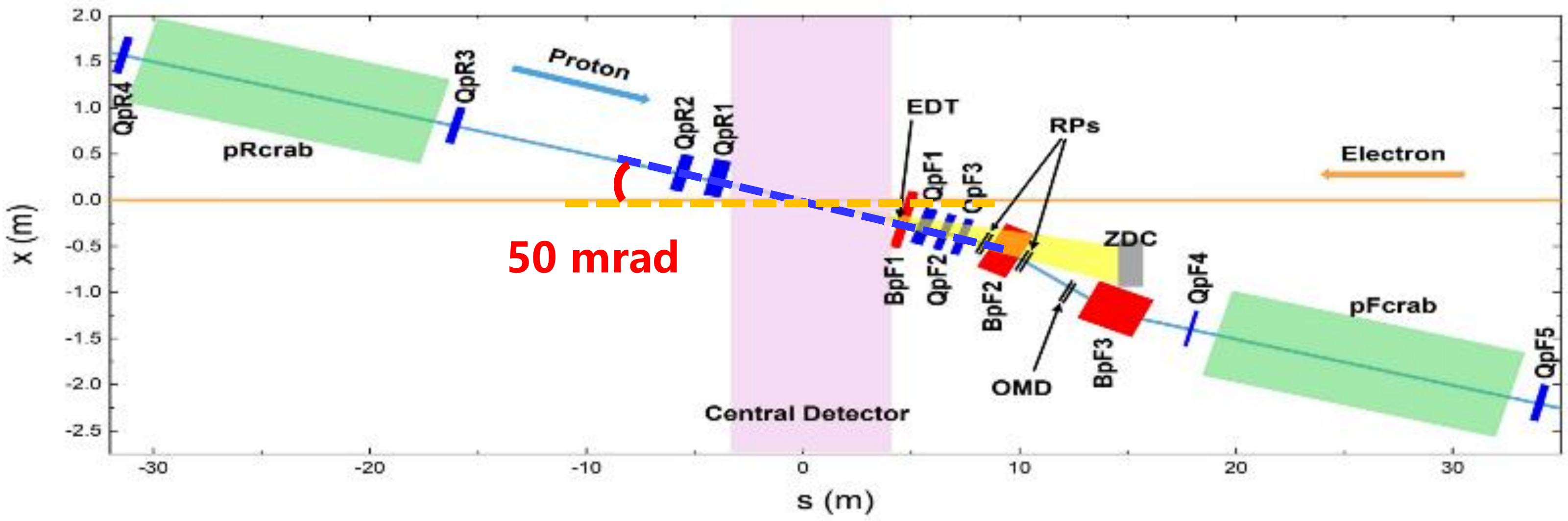
Phase 2: HIAF upgrade for applied science

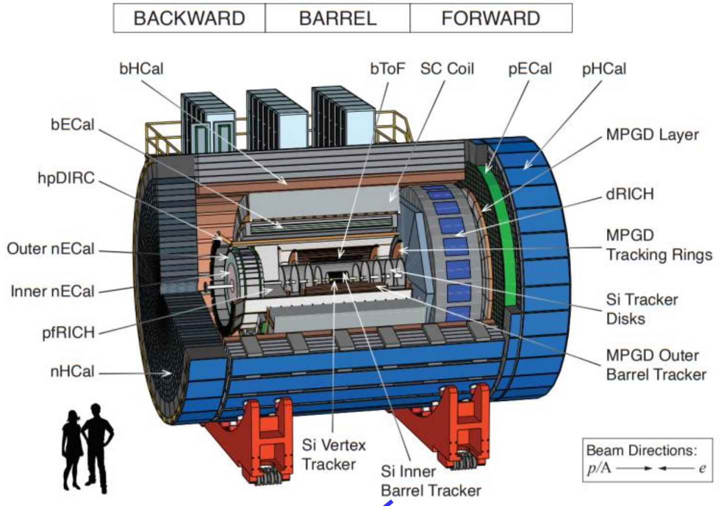
Phase 3: EiccC

Parameter	electron	proton
Circumference (m)	1151.20	1149.81
Kinetic energy (GeV)	3.5	19.08
CM energy (GeV)	16.76	
$f_{collision}$ (MHz)	100	
Polarization	80%	70%
Bunch intensity ($x10^{11}$)	0.44	0.27
$\varepsilon_x, \varepsilon_y$ (nm·rad, rms)	12.5/3.75	25/12.5
β_x^*/β_y^* (cm)	10/4	5/1.2
RMS divergence (mrad)	-	0.7/1.0
Bunch length (cm, rms)	0.75	8
Crossing angle (mrad)	50	
Hourglass	0.52	
Luminosity ($cm^{-2}s^{-1}$)	1.13×10^{33}	

Collision

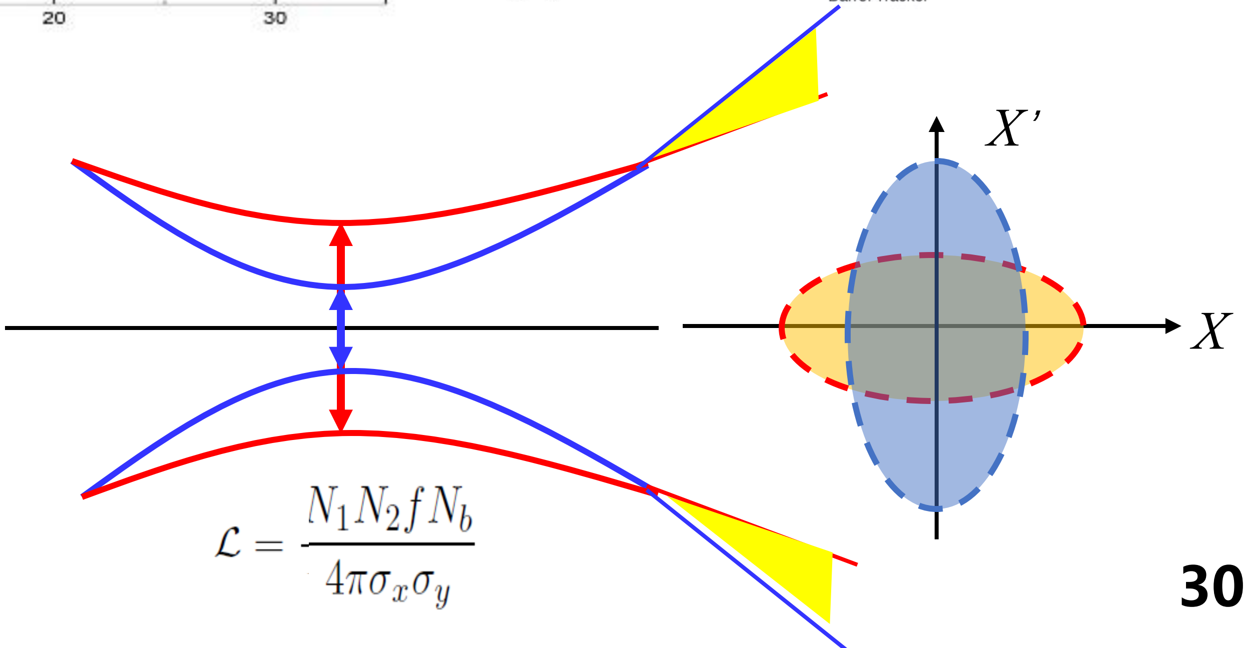
- **High luminosity and quasi-full-acceptance**





High luminosity mode: large particle number, small betatron function, peak luminosity up to $4.25 \times 10^{33}\ cm^{-2}s^{-1}$

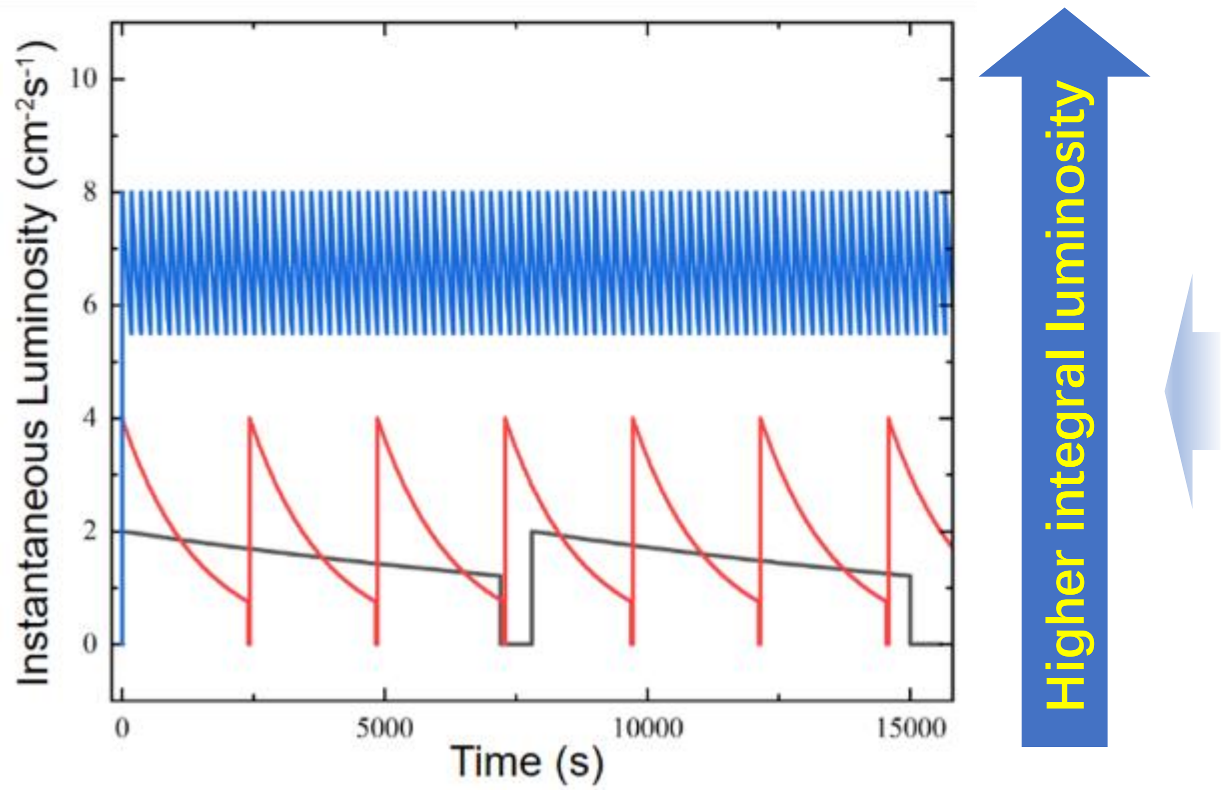
Quasi-full-acceptance mode: large particle number, small betatron function, peak luminosity up to$1.13 \times 10^{33}\ cm^{-2}s^{-1}$



$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y}$$

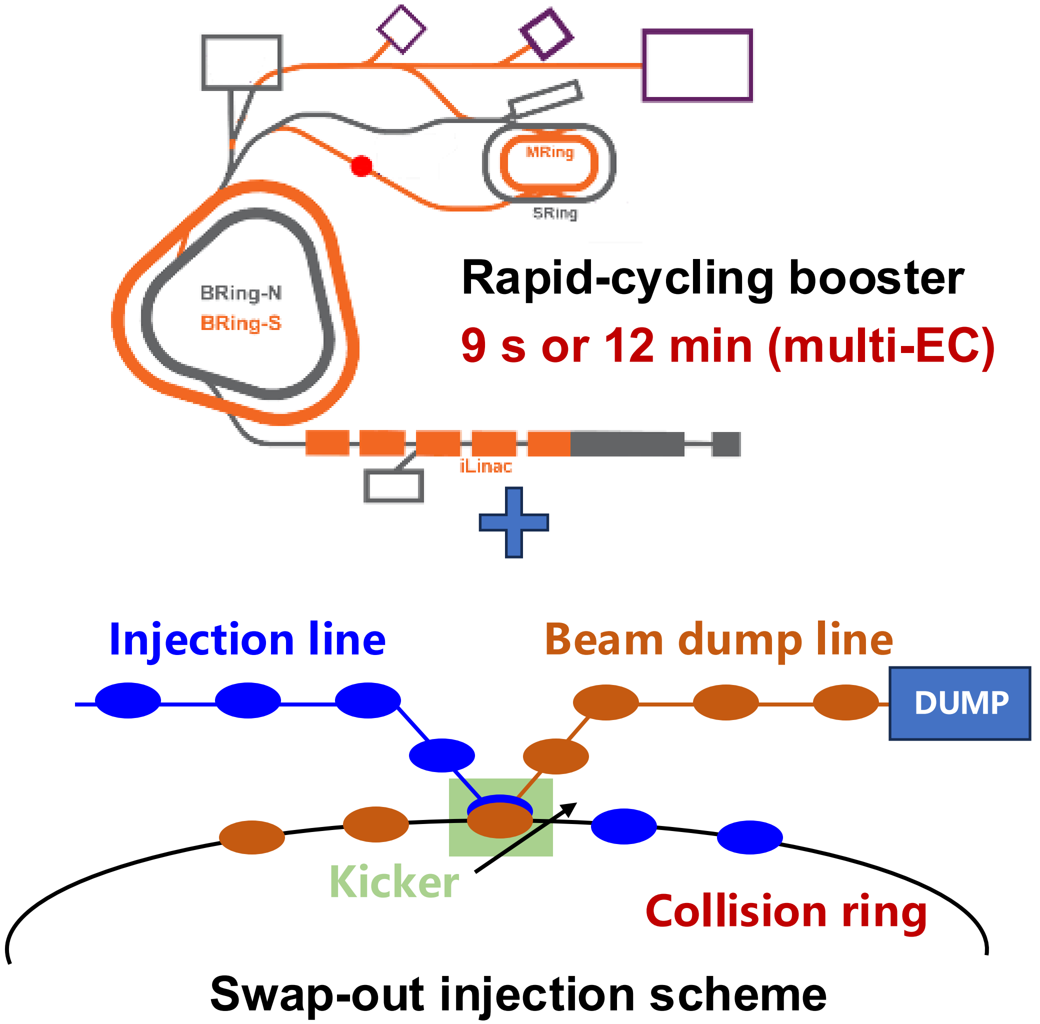
Collision

- **Rapid cycling operation mode**



the collision bunches are replaced online and quickly enough, much higher peak and integral luminosity is feasible

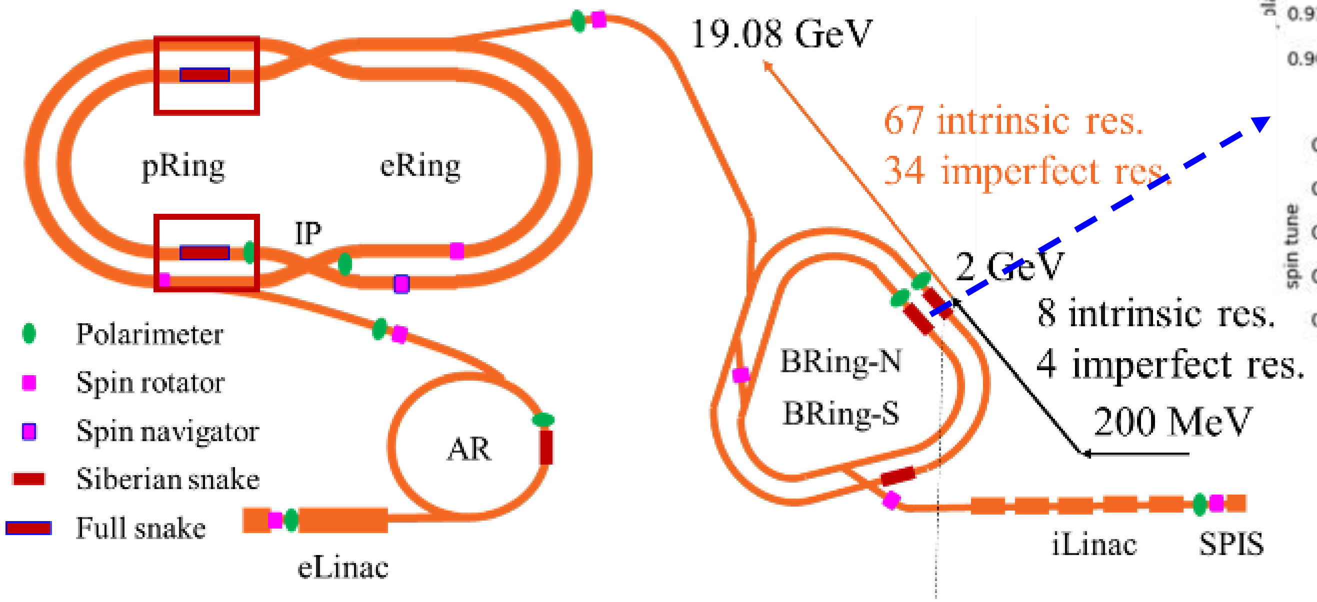
- **Replace all in minutes or seconds**

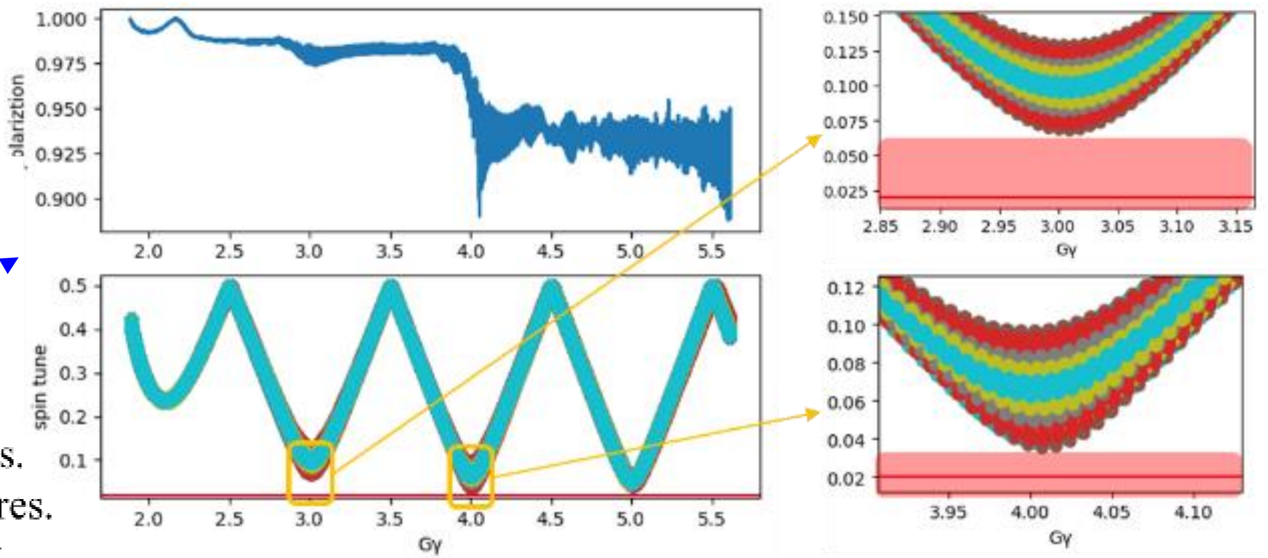


Polarization

- **Constant-field solenoid Siberian snake**

A **constant field solenoid Siberian snake** has been designed in the BRing-N





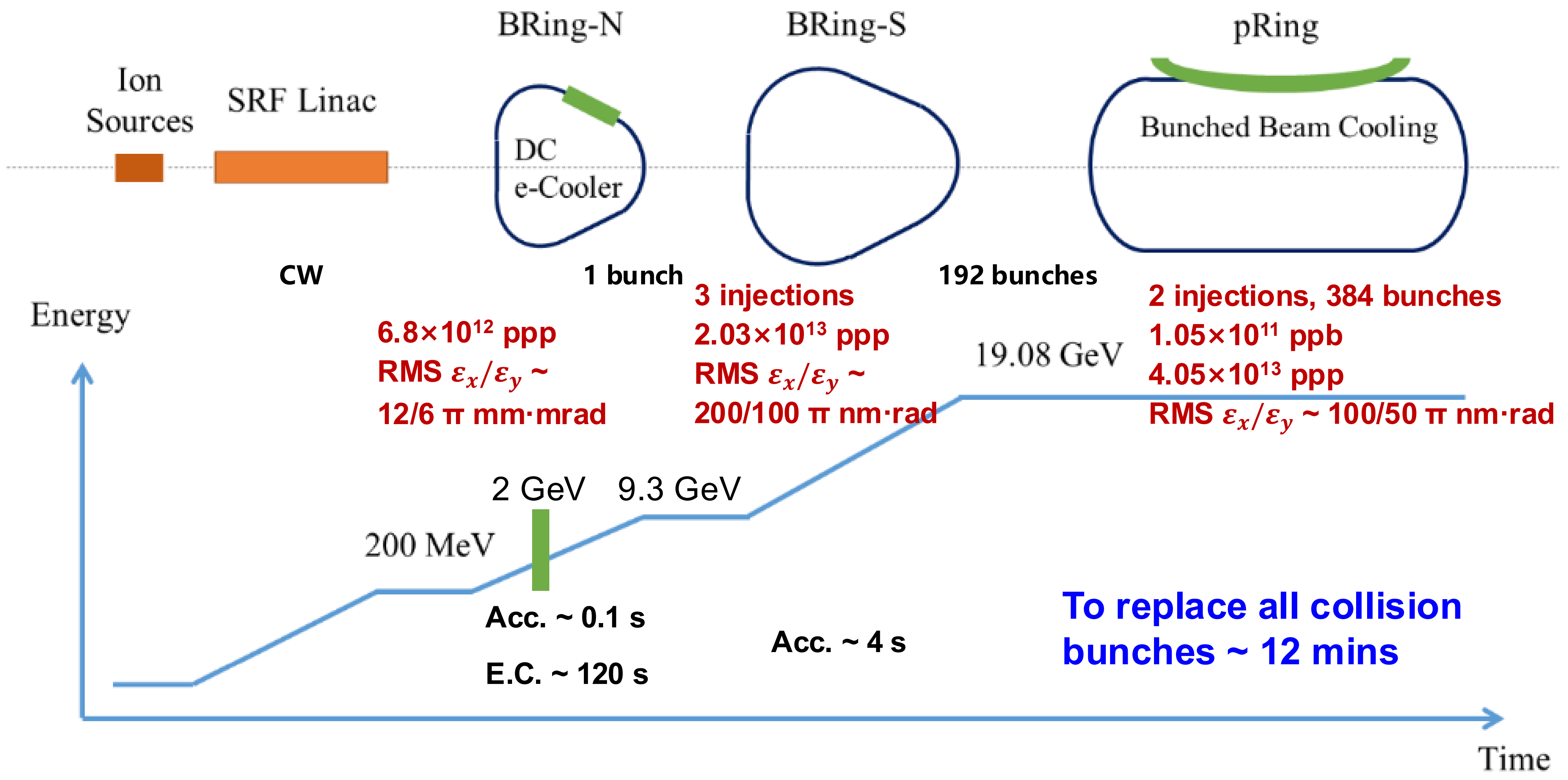
Mingxiang Li, et al., PRAB, 28, 094002 (2025)

- The required magnetic field ramp rate for a conventional constant-strength solenoid Siberian snake is 29 T/s, to control the depolarization loss below 10%;
- The spin tune gap generated by a constant-field solenoid Siberian snake is sufficient to avoid the vertical tune (red line), which will significantly reduce hardware challenges;

Beam cooling

Beam cooling can be used for accumulation, improving beam quality and compensating the emittance growth.

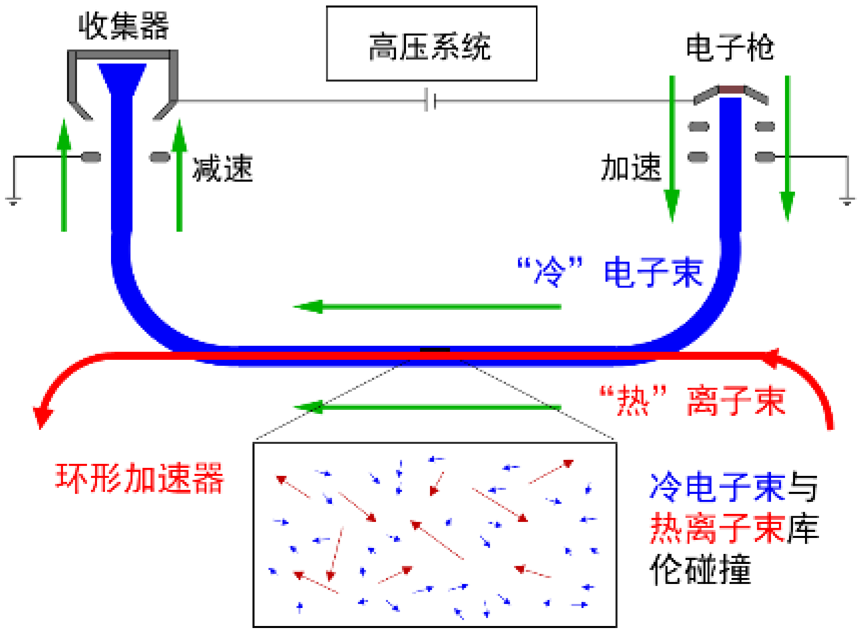
Proton beams as an example!

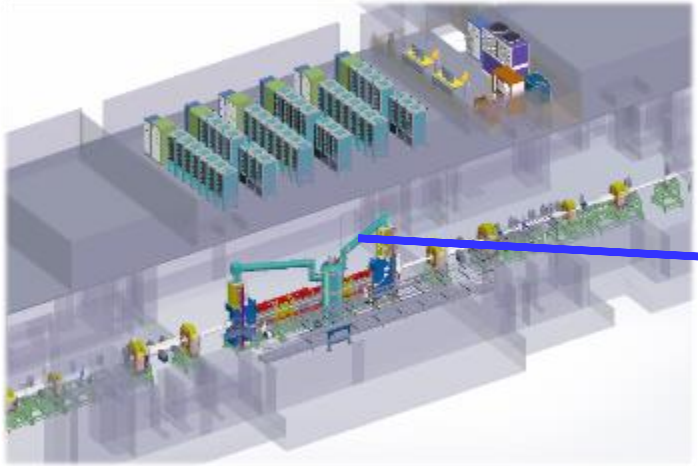


To replace all collision bunches ~ 12 mins

Beam cooling

Magnetized DC electron cooling can be used in BRing-N for beam accumulation.

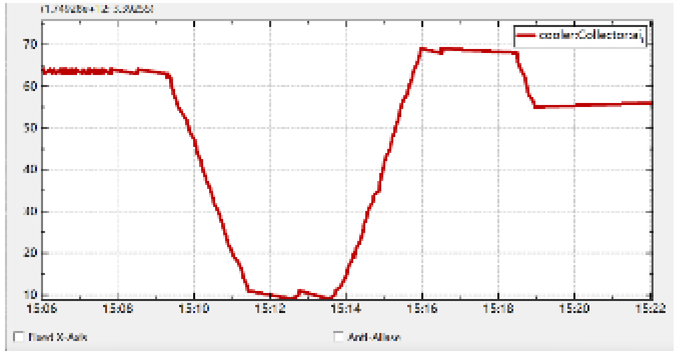




$$\tau \propto \frac{A}{Z^2}\frac{1}{n_e}\beta\gamma^2\varepsilon^{1.5}$$

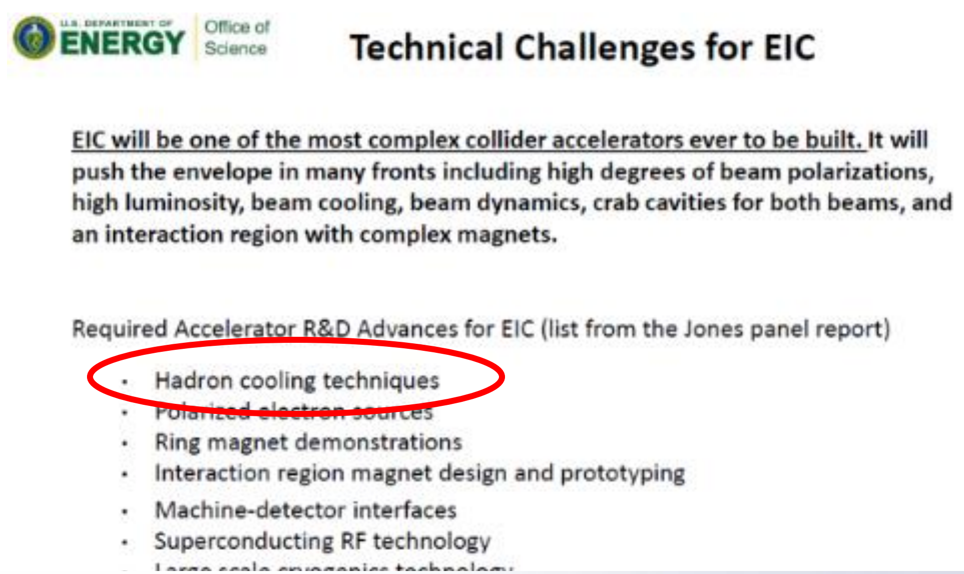
lower energies, better cooling

	E-cooling
energy (keV)	450
current (A)	2.0



Beam cooling

Relativistic electron cooling will be used in collider ring for compensation



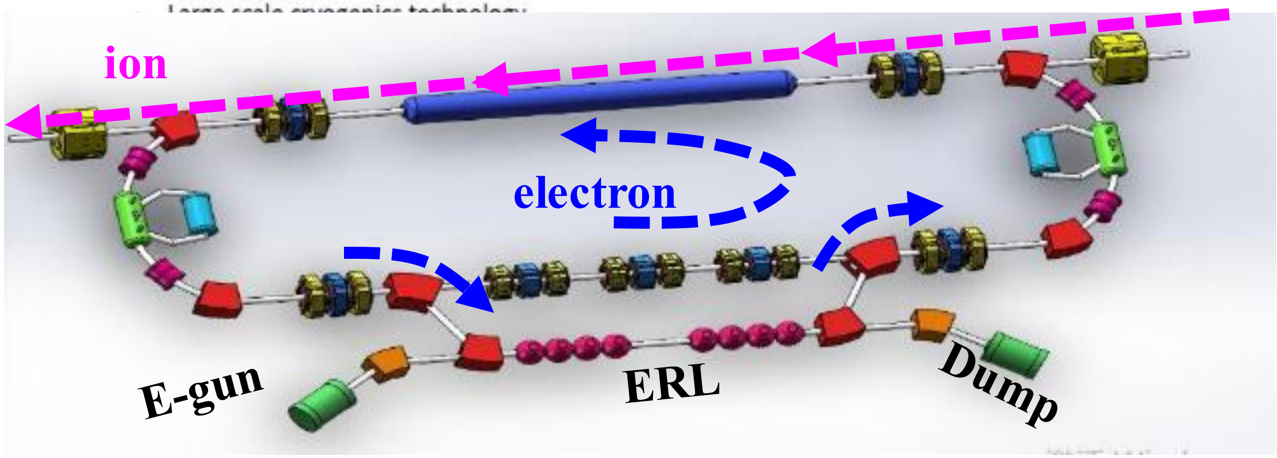
Technical Challenges for EIC

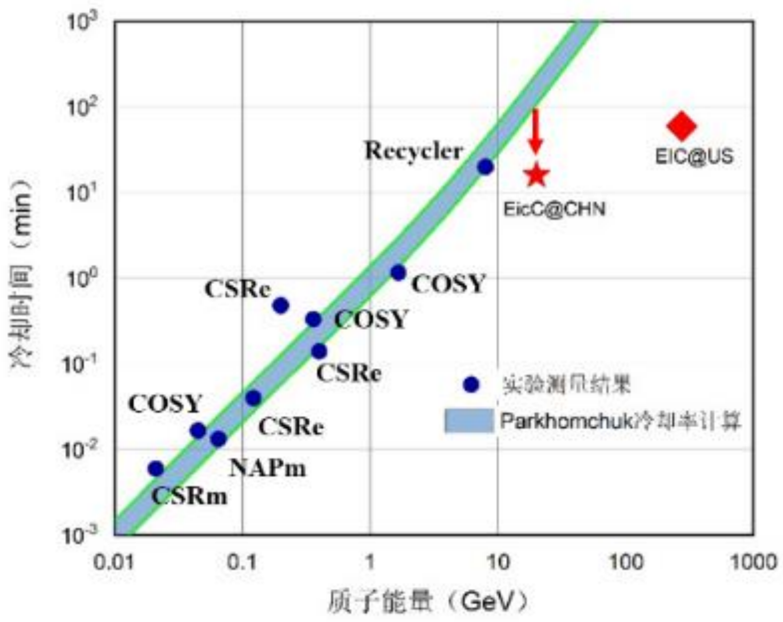
EIC will be one of the most complex collider accelerators ever to be built. It will push the envelope in many fronts including high degrees of beam polarizations, high luminosity, beam cooling, beam dynamics, crab cavities for both beams, and an interaction region with complex magnets.

Required Accelerator R&D Advances for EIC (list from the Jones panel report)

- Hadron cooling techniques
- Polarized electron sources
- Ring magnet demonstrations
- Interaction region magnet design and prototyping
- Machine-detector interfaces
- Superconducting RF technology

Items	Value
energy	>11 MeV/u
charge/bunch	>1 nC
bunch length	~ 4 cm
average current	>100 mA





Outline

Conclusion

- As an injector of EicC, the HIAF accelerator complex (phase 1) has been installed completely
- The upgrade project of HIAF will focus on the improvement of energies and intensities, in order to satisfy the requirement of EicC
- The beam dynamics and technical challenges related to collision, polarization and beam cooling should be studied and solved in coming years

Thanks for your attention!