Status and challenges of HIAF

High-Intensity heavy ion Accelerator Facility

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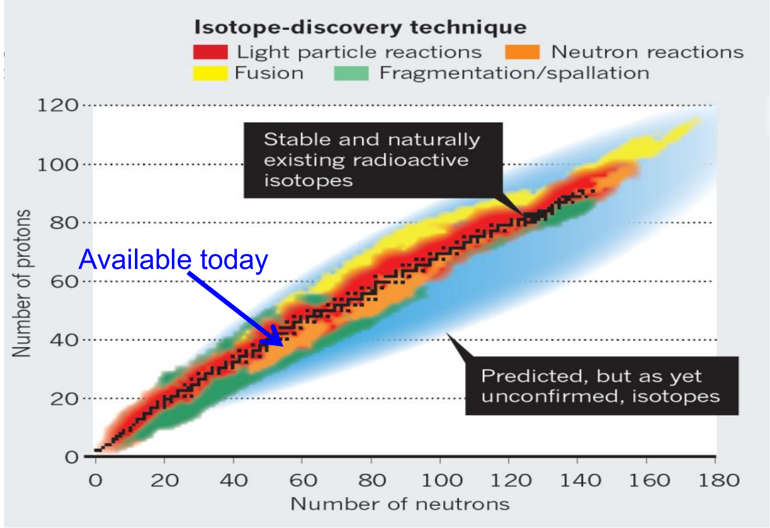
Outline

1. Brief introduction
2. The key components of accelerator complex
3. Experimental terminals and stations
4. Hardware fabrication and civil construction
5. Summary

Brief introduction



Fascinating and crucial questions

- **To explore the limit of nuclear existence**
- **To study exotic nuclear structure**
- **To understand the origin of the elements**
- **To study the properties of High Energy Density Matter(HEDM)**
- **……**

Next-generation facilities being constructed or proposed worldwide:

- SPIRAL2 at GANIL in Caen, France
- FRIB at MSU in the U.S.
- FAIR at GSI in Darmstadt, Germany
- EURISOL in Europe
- NICA at JINR, Dubna, Russia

High Intensity Heavy-ion Accelerator Facility

HIAF in China

Scientific motivations

Next-generation high intensity facility are needed for advances in nuclear physics and related research fields

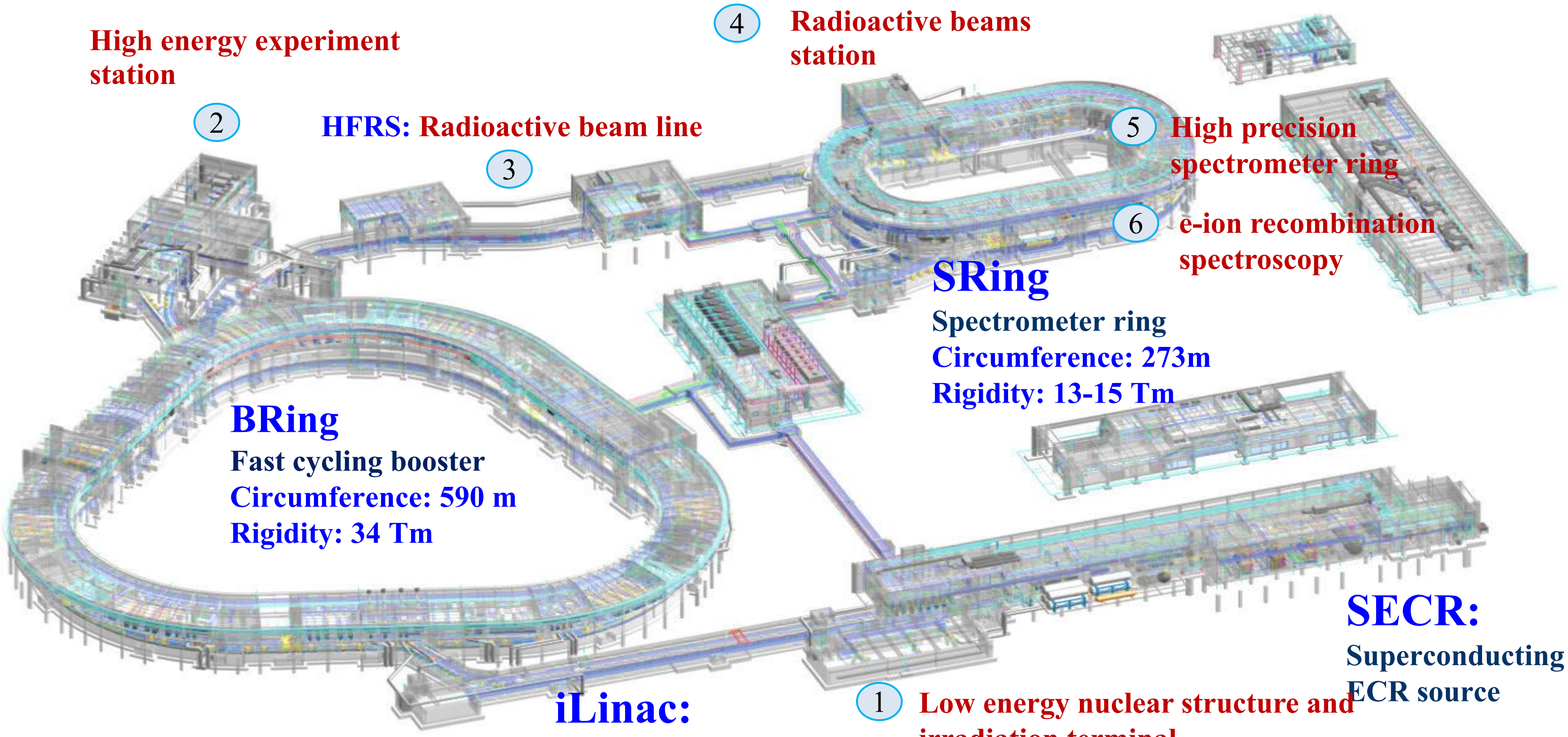
- Highly purified secondary beam for fascinating and crucial questions of nuclear physics:
  - **To explore the limit of nucleus existence**
  - **To study exotic nuclear structure**
  - **Understand the origin of the elements**
- Highly charged ions for a series of atomic physics programs.
- Slow extraction beam with wide energy range on thick targets.
- Ultra-short bunched ion beam for HEDM research.
- Precise mass and reaction spectrometry for high precision atom mass and energy level measurements
- Research issues with update programs:
  - **Hyper nuclear physics**
  - **Phase diagram of strongly interacting matter**
  - **Spontaneous electron–positron pair production of QED**

Brief introduction

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

Brief introduction of the HIAF

Accelerator components and experiment terminals



BIM (Building information model)

Brief introduction

- **HIAF main parameters**

Magnetic Rigidity:

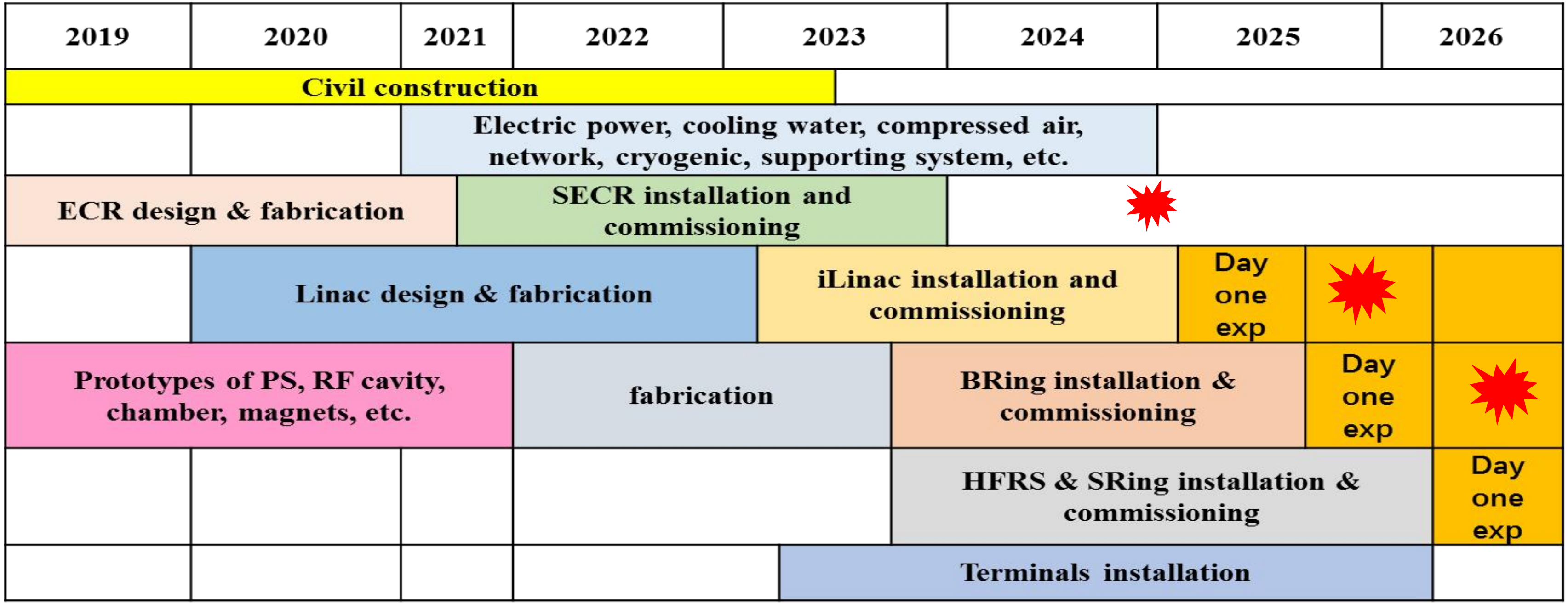
$$G = B\rho = \frac{P}{Qe}$$

To provide very high intensity heavy ion beam

	SECR	iLinac	BRing	HFRS	SRing
Length / circum. (m)	---	114	569	192	277
Energy of U (MeV/u)	0.014 (U^{35+})	17 (U^{35+})	835 (U^{35+})	800 (U^{92+})	800 (U^{92+})
Max. rigidity (Tm)	---	---	34	25	15
Max. intensity of U	50 pμA (U^{35+})	28 pμA (U^{35+})	2×10^{11}ppp 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 0.5%	200/100, 0.5%	±30mrad(H)/±15 mrad(V), ±2%	40/40, 1.5% (normal mode)

Brief introduction

- HIAF construction time schedule

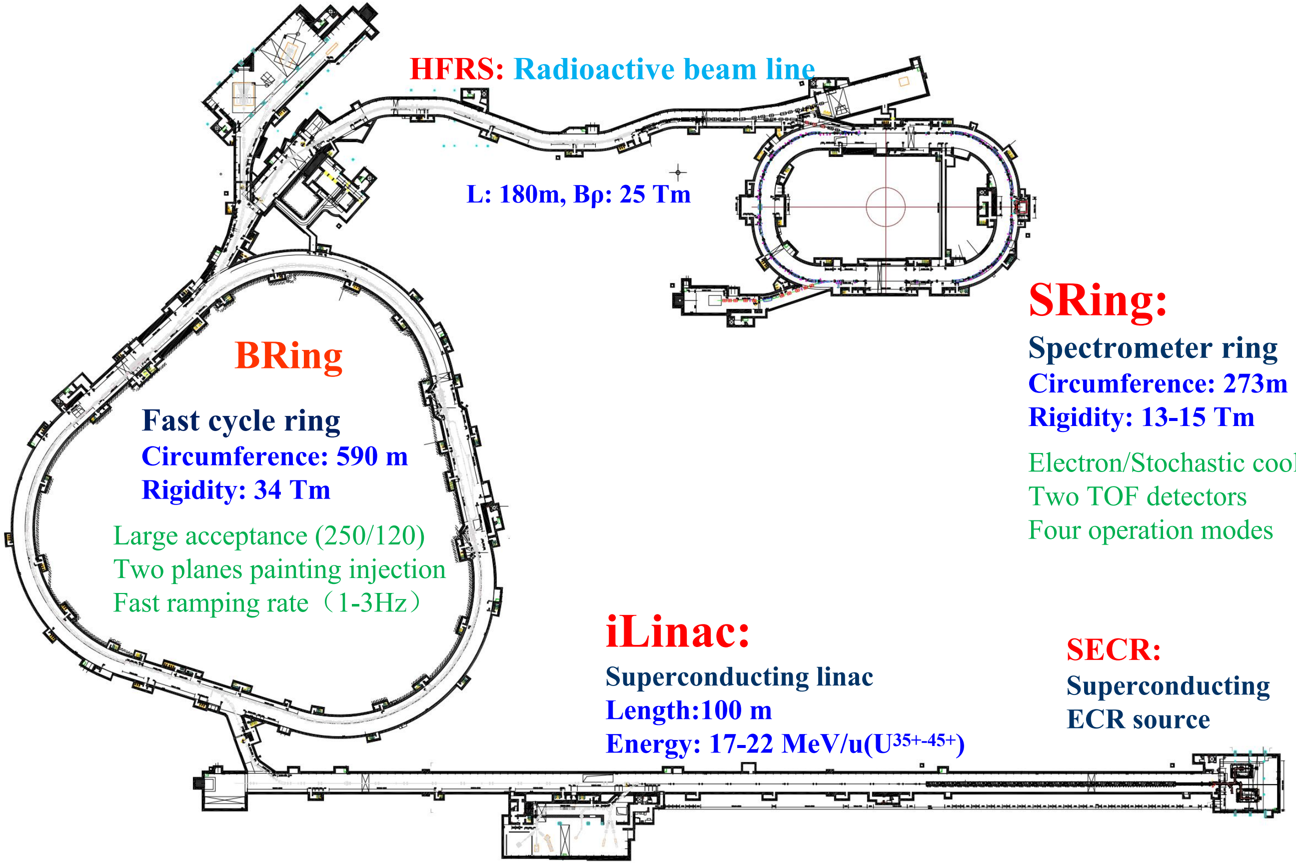


- The first ion beam provided by **FECR** is by the end of 2023;
- The low energy ion beam of **iLinac** is expected by the end of 2024;
- The high energy ion beam from **BRing** is in September of 2025
- The Day One Experiment in **SRing** will be in April of 2026

The key components of HIAF accelerator complex

Accelerator components

S-ECR + S-linac + fast BRing + HR-HFRS + HR-SRing



The front end

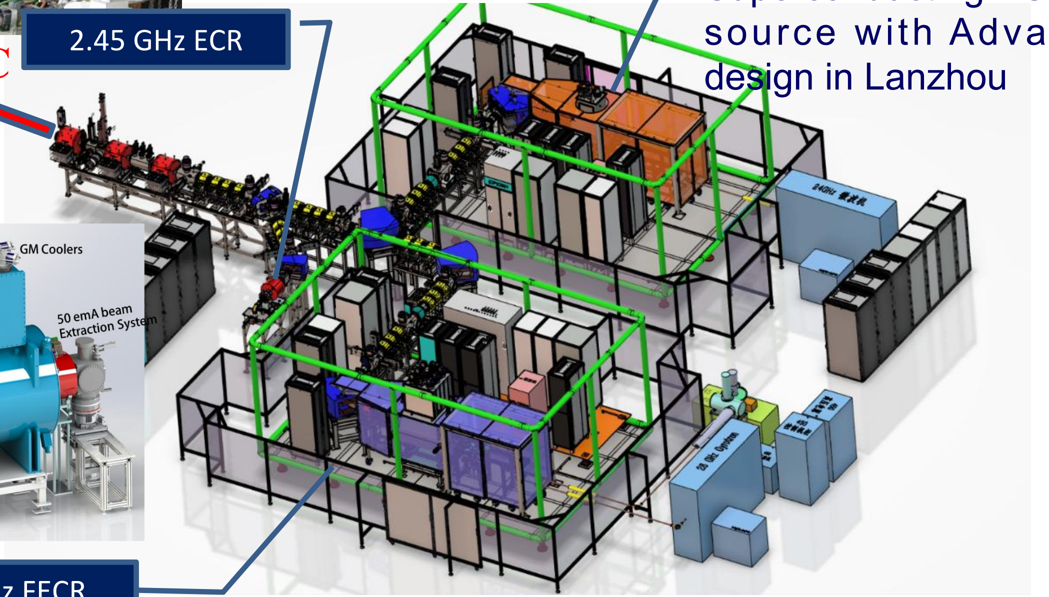
iLINAC

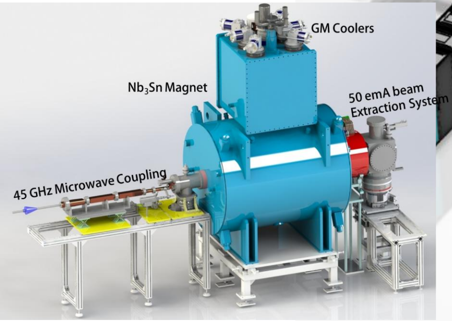
2.45 GHz ECR

Permanent magnet structure and reliable beam production

28 GHz SECRAL

3rd generation, Superconducting ECR ion source with Advanced design in Lanzhou





Ion	SECRAL II 28 +18 GHz (~2018, 10 kW)
O^{6+}	6700
O^{7+}	1750
Ar^{12+}	1190
Ar^{14+}	1040
Ar^{16+}	620
Kr^{18+}	1030
Kr^{23+}	436
Kr^{28+}	146
Xe^{27+}	870
Xe^{30+}	365
Xe^{34+}	135
Bi^{31+}	680
U^{33+}	450

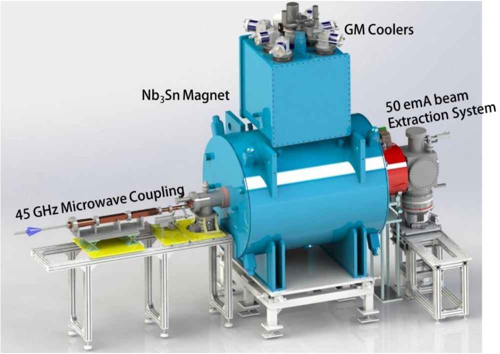
45 GHz FECR

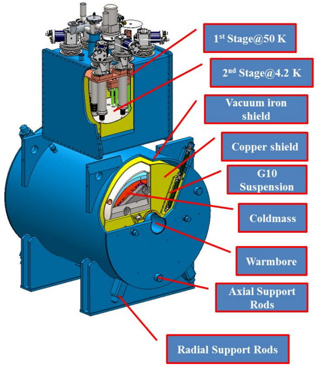
4th generation ECR ion source

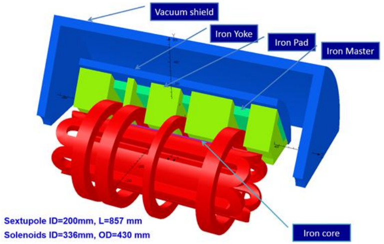
Solutions to the stringent needs of the superconducting linac capable of accelerating very intense beams with broad A/Q ratios.

The front end

The first 45GHz superconducting ECR in the world: 50 pμA (U^{35+})



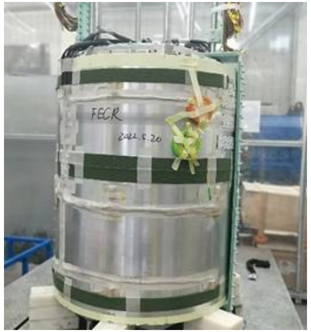




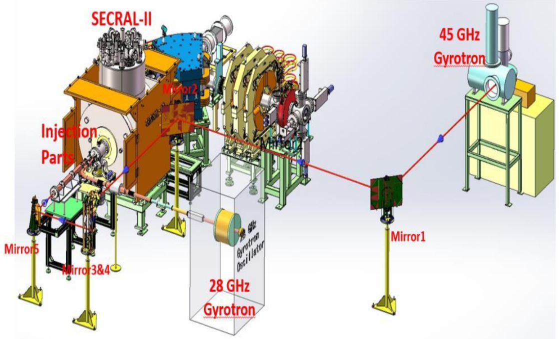
The first plasma heating with 45 GHz microwave is expected in 2023

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

Sextupole Coils



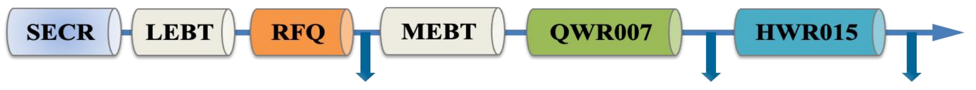
Full-sized cold mass

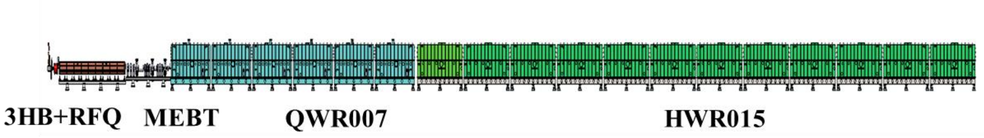


45 GHz microwave coupling

High current superconducting ion linac

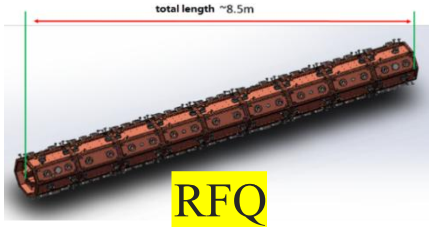
iLINAC

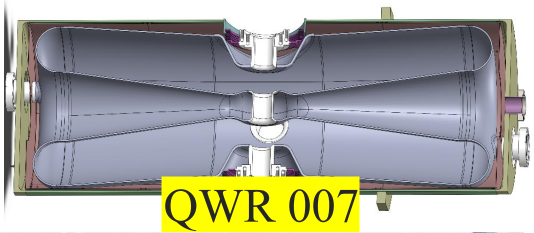


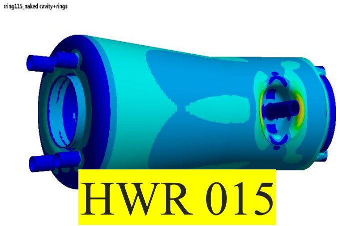


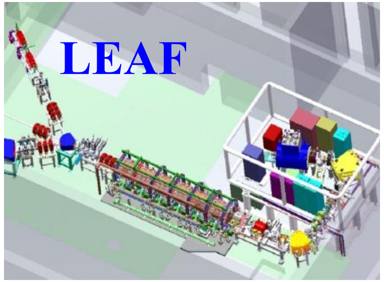
- **Pulsed**
  28 pμA U^{35+}
- **CW**
  15 pμA U^{35+}

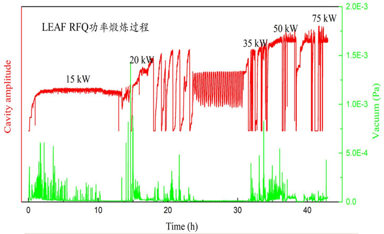
To BRing or Terminal 1











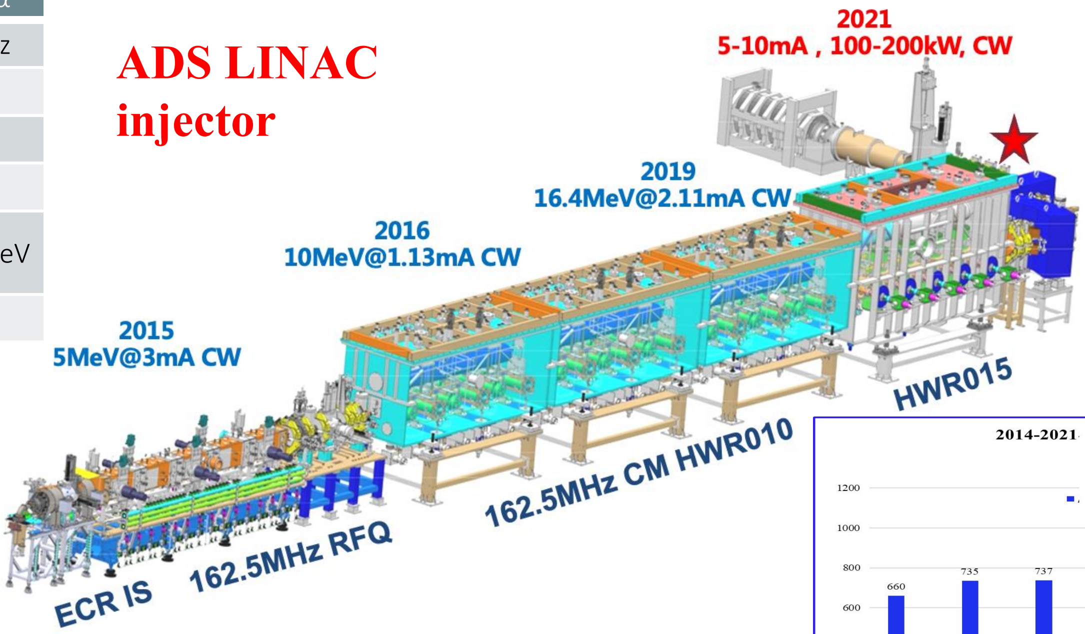
RF training of LEAF-RFQ

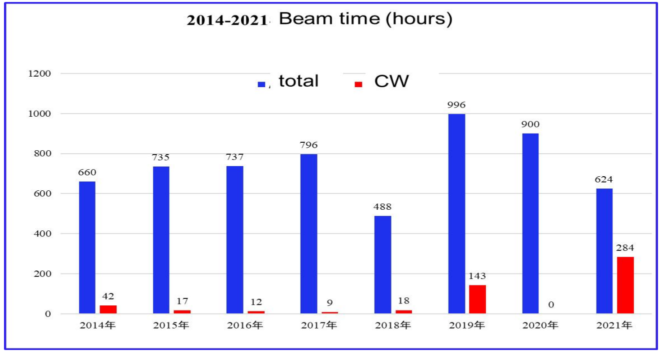
- ✓ A Platform is constructed to demonstrate the high current RFQ
- ✓ CW operation with heavy ion beam has been done
- ✓ Total operation time >1000 hours show the good performance

High current superconducting ion linac

ions	P, H_2^+, α
frequency	162.5 MHz
current	10 mA
E in RFQ	40 keV
E out RFQ	3.1 MeV
Energy	20/30/40MeV
Temp.	4.5 K

ADS LINAC injector





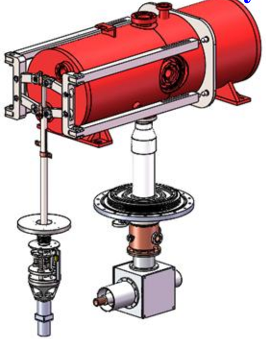
Supported by "Strategic Priority Research Program" of the Chinese Academy of Sciences

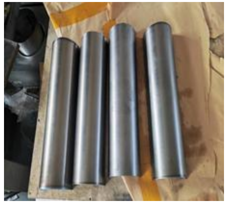
High current superconducting ion linac

SRF Main Hardware Progress

QWR007 Cavity

HWR015 Cavity

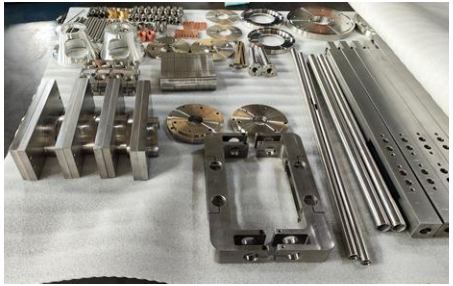




QWR007 Cavity Parts

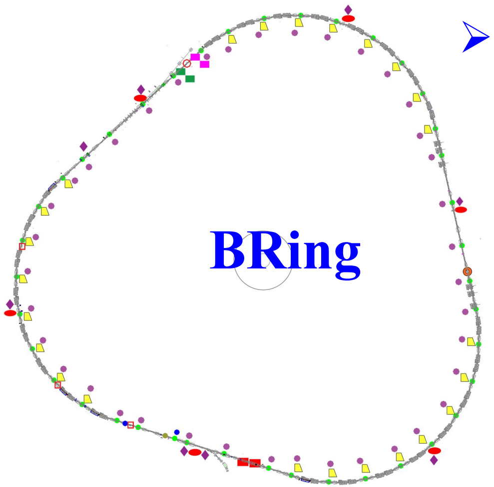
HWR015 Cavity Production

QWR Couplers

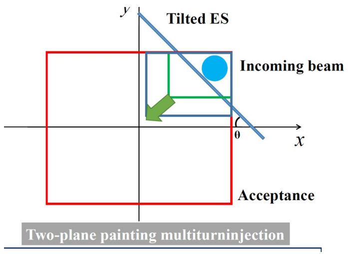


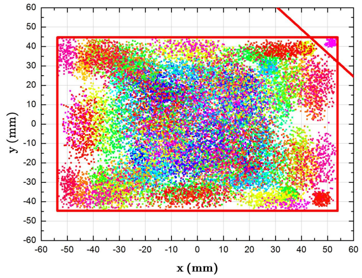
QWR/HWR Tuners

Fast ramping booster synchrotron BRing

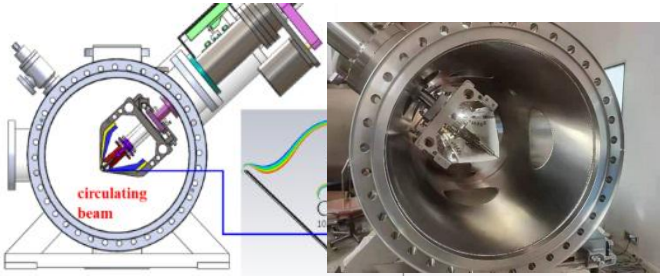


- **4-D painting injection**





Simultaneous injection in H and V planes



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

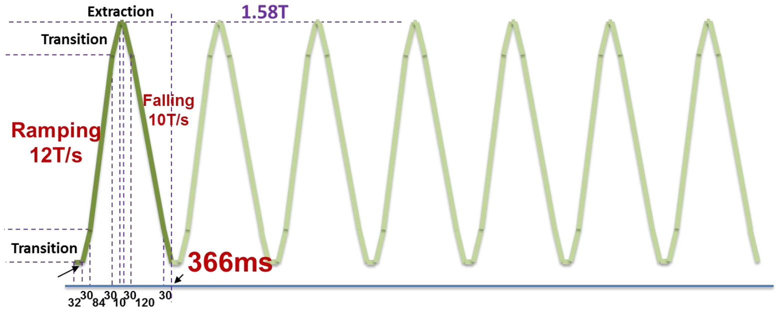
Novel electrostatic septum with low beam loss-**corner septum**

Nearly 10 times over the conventional single-plane injection.

Fast ramping booster synchrotron BRing

- **Fast ramping rate mode**

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



Repetition rate: 1-3 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

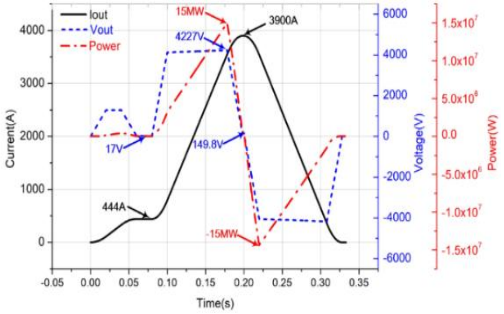
2. Magnetic alloy core loaded RF system

3. Ceramic / Ti-lined thin wall vacuum chamber

1. Fast ramping full energy storage power supply

- Load specification and performance requirement of dipole power converters featured by fast ramping rate： 12T/s, ±38000A/s

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

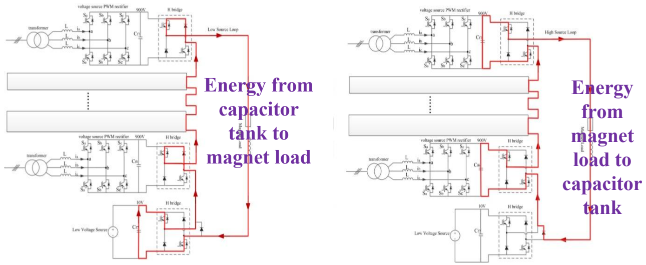


Peak power ±180MW at full load

Challenges:

- High tracking precision and low current ripple
- Strong line voltage fluctuation due to very large cyclic variation of active power

- An innovative power supply topology are proposed for HIAF BRing (variable forward excitation, full energy storage, PWM rectification technology)



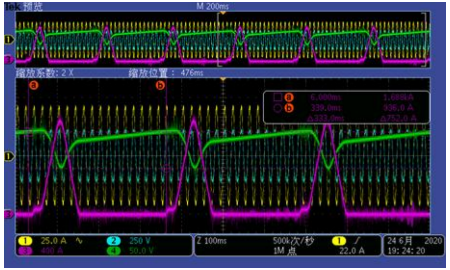
Block diagram of dipole power supply

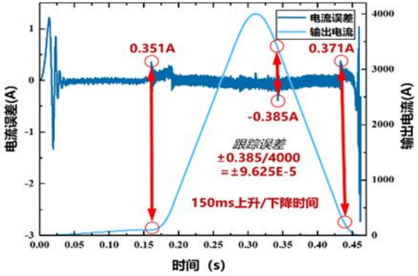
- Energy capacitor will be used to store energy during the falling, and provide the energy for next fast ramping

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

1. Fast ramping full energy storage power supply

➢ **A full size prototype has been developed successful， the key technology and design of the power supply have been verified**



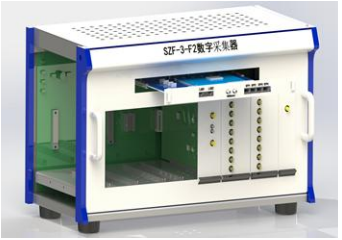


Cutting edge performance has been achieved, output results on the real magnet loads:

Current 3900A, ramping rate > 38000A/s, tracking error < ±9.625e-5

Power from net reduced from 180MVA to 15MVA

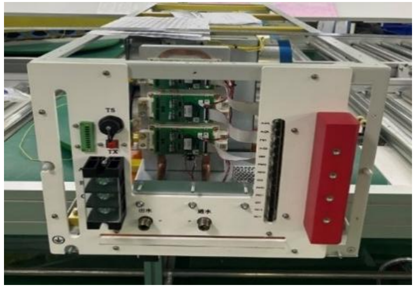
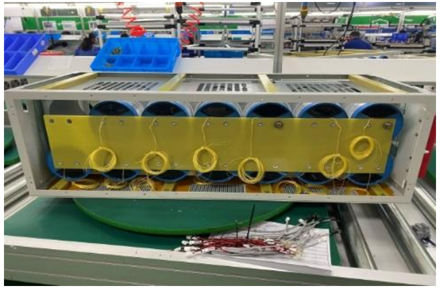
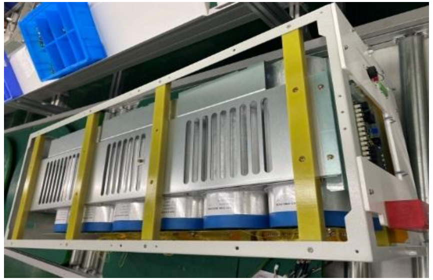
➢ **New generation of FPGA-based full digital controllers:** High-speed serial communication, distributed real-time high computing performance control system



The series of full digital controller SZF-3 for HIAF

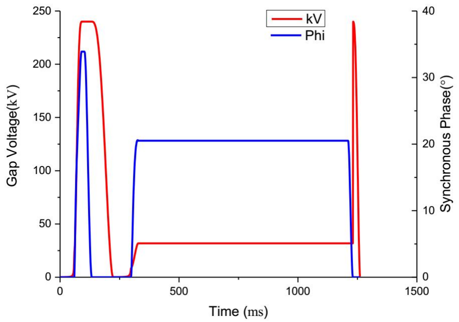
1. Fast ramping full energy storage power supply

- Power units have been processed and are being assembled


2. 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:

Wideband and high-field gradient features

50kV@0.3~2.1MHz

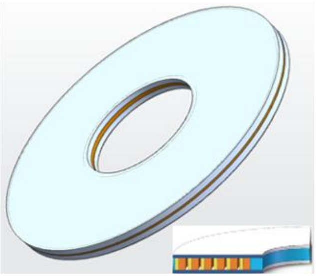
Challenge:

Fabrication of MA core module

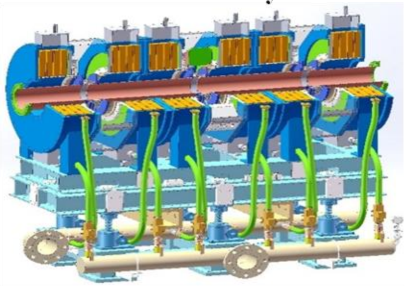
Cooling of MA-loaded cavities operating at intense power dissipation

MA loaded RF system:

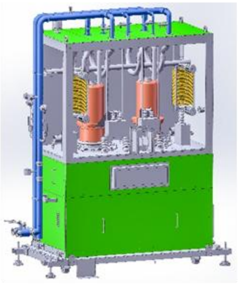
Large size oil cooled MA core



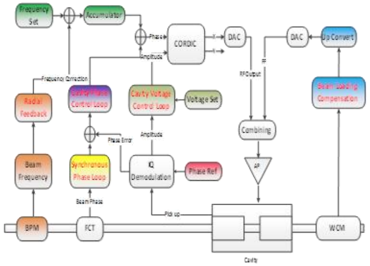
High gradient direct cooling MA- loaded cavity



Broadband push-pull tetrode amplifier



Multi harmonic digital LLRF



2. Magnetic alloy core loaded RF system

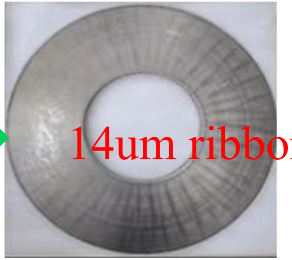
➢ Domestic development of large size high μQf MA core

- Over ten years exploration from small(φ90), medium (φ460), to large (φ780) MA core.

95×65×25mm

460×230×25mm

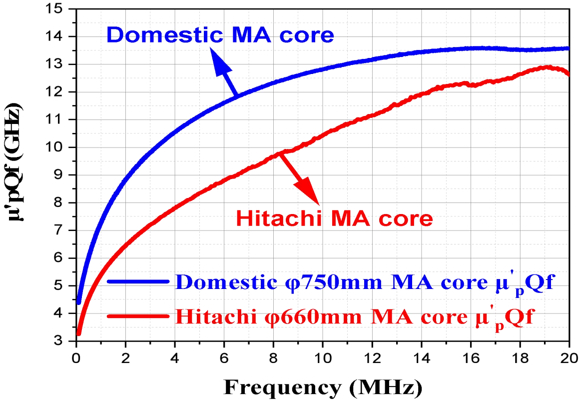
750×345×35mm



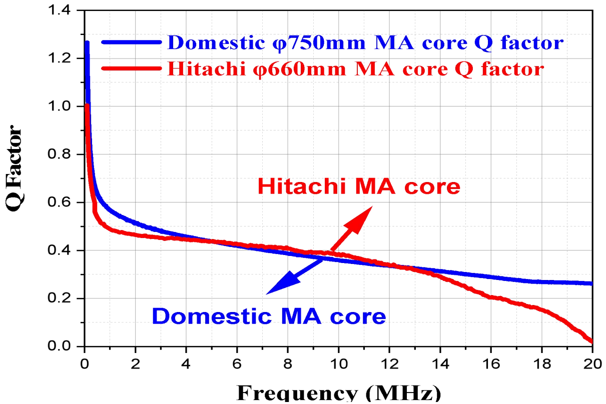
780×360×35mm

➢ Breakthrough in MA fabrication, international leading level:

$\mu'_p Q_f$: 5.3GHz @ 0.3MHz



Q value: (0.65~0.3) @ (0.1~20MHz)



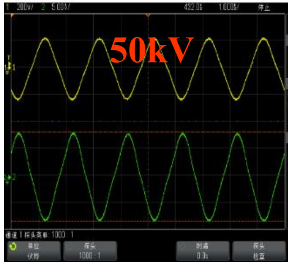
2. Magnetic alloy core loaded RF system

➢ **The first direct oil-cooled MA core loaded cavity in China**

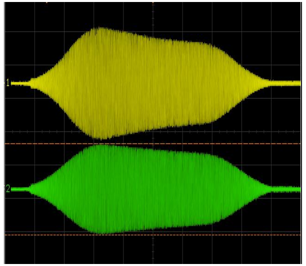
MA RF system

TH558 final stage

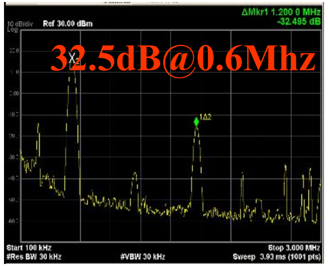
- ☐ The power test is carried out, voltage can reach 50kV@0.3~2.1MHz, and the third harmonic suppression is better than 25dB



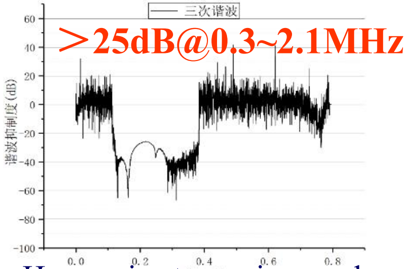
Cavity pick-up voltage



Voltage of ramping mode



Harmonic suppression



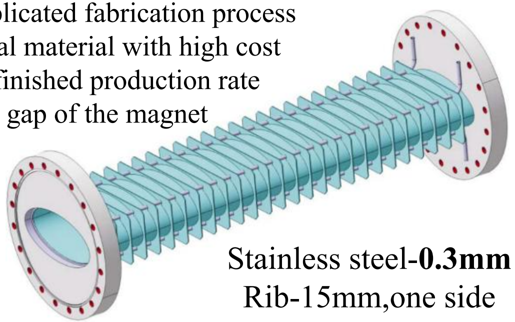
Harmonic at ramping mode

3. The ceramic-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

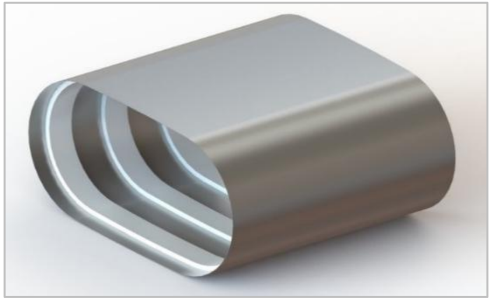
Complicated fabrication process
Special material with high cost
Low finished production rate
Large gap of the magnet



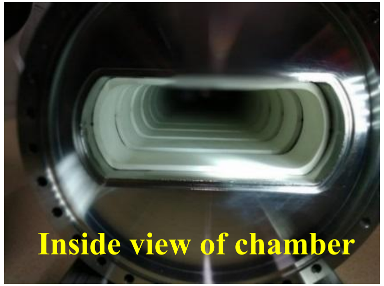
Stainless steel-**0.3mm**
Rib-15mm,one side

■ New scheme:

Supported by ceramic/Ti rings



Stainless steel wall: **0.3mm**
Ceramic supporting ring: 3mm



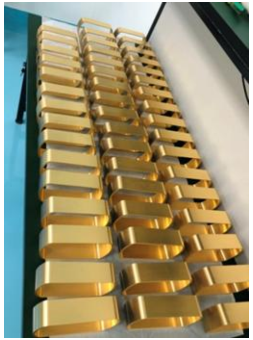
Inside view of chamber

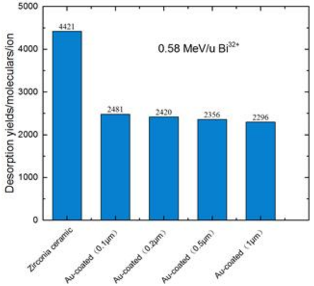
Vacuum pressure is 4.3×10^{-12} mbar after baking (250 ºC, 72 h)

L=1.2m, straight thin wall chamber prototype have been developed

3. The ceramic-lined thin-wall vacuum chamber

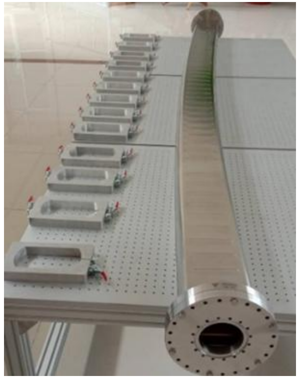
- Ti/Cu/Ti/Au coating process was proposed to reduce the desorption yield and the impedance, magnetron sputtering coating machine has been built to mass-production

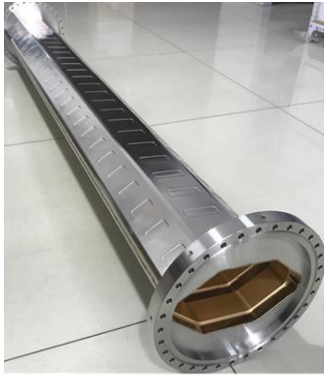


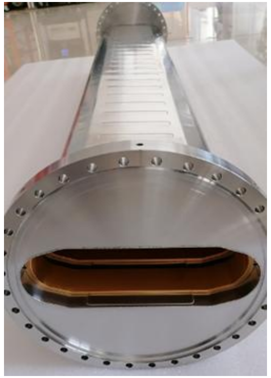


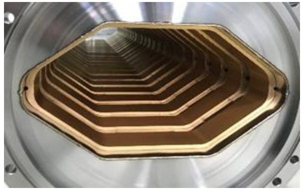
Desorption yield decreased significantly after Au-coated

- A serial of full size chambers have been fabricated and key technology has been verified after several rounds of baking , the mechanical and vacuum performance test



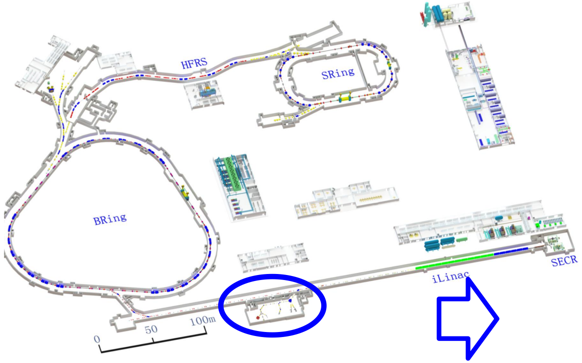






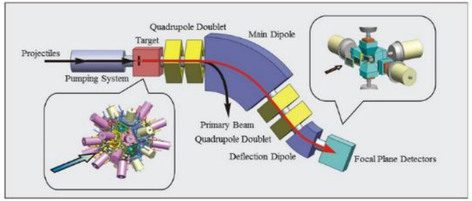
Experimental terminals & stations

1. Low energy nuclear structure terminal

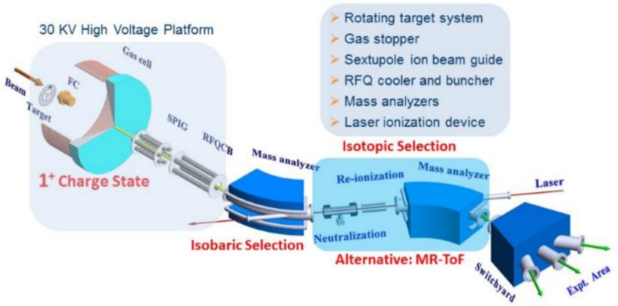


Very high intense beam from iLinac

- **CW 15 pμA U^{35+}, 5-10 MeV/u**
- **Energies can be adjusted finely**



The gas-filled recoil separator



Multi-nucleon transfer reaction separator

- **Synthesize new elements and isotopes**
- **Study nuclear decay properties**

New gas-filled recoil separator, SHANS2

- **Measure nuclear masses and lifetimes**
- **Determine nuclear charge radii and moments**

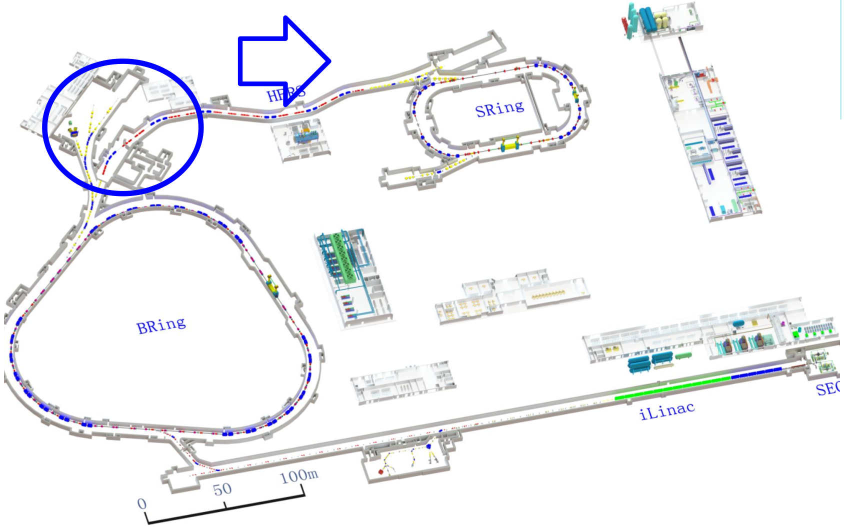
Explore the super-heavy region in the nuclear chart, new element ?

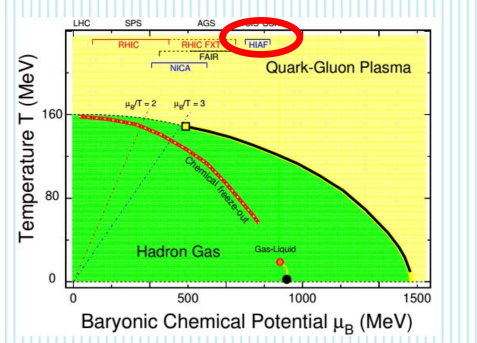
2. High-energy experimental station

Ion species	Energy (GeV/u)	Intensity (ppp)
p	9.3	2.0×10^{12}
$^{12}C^{6+}$	4.2	6.0×10^{11}
$^{78}Kr^{19+}$	1.7	3.0×10^{11}
$^{209}Bi^{31+}$	0.85	1.2×10^{11}
$^{238}U^{35+}$	0.835	1.0×10^{11}

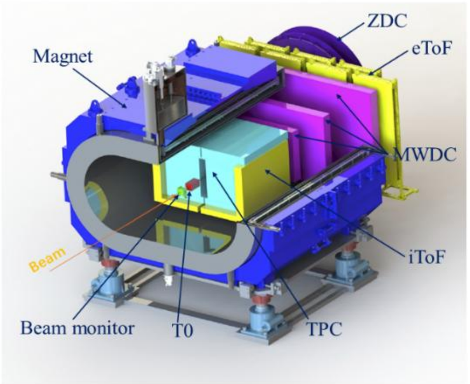
- Hyper nuclear physics
- Phase diagram of strong interacting matter

- Several GeV/u, high quality slow extraction

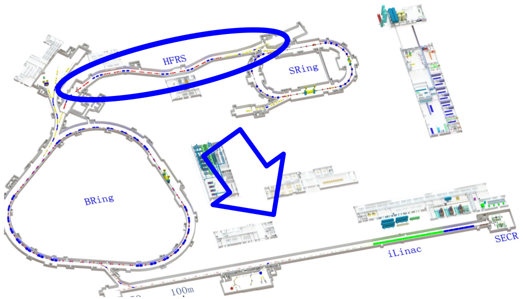




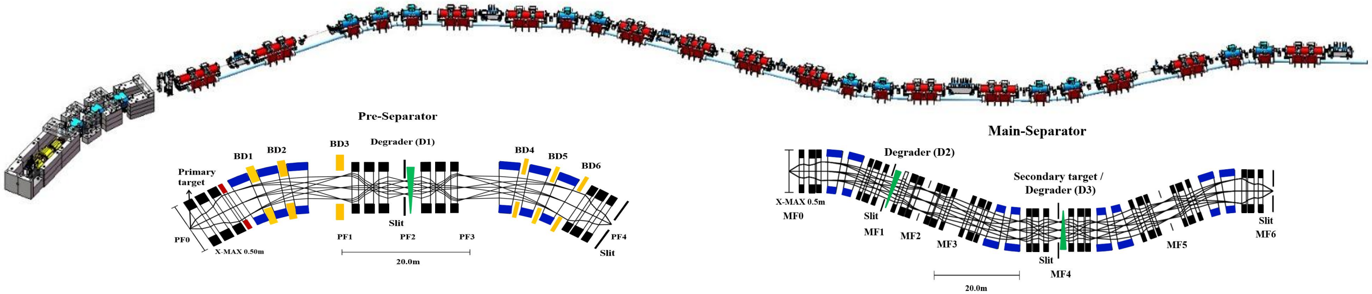
Structure of QCD Matter



3. High energy fragment separator (HFRS)



Rigidity /Tm	Spot size target/mm	Angular accept./mrad	Δp/p accept.	First order Momentum resolution
25	x=±1; y=±2	x'=±30; y'=±15	±2.0%	1100 (30 π μm)
15	x=±1; y=±1.5	x'=±10; y'=±25	±0.03%	10000 (10/35 π μm)



A world-unique facility, and its peculiarities are:

- **Maximum magnetic rigidity of 25 Tm,** high-energy RIBs with energy up to 2.9 GeV/u for A/Z=2 nuclides and 1.7 GeV/u for A/Z=3 nuclides,
- **High primary beam power and excellent separation power or R**
- **Versatile spectrometer, dispersive or achromatic mode**

3. High energy fragment separator (HFRS)

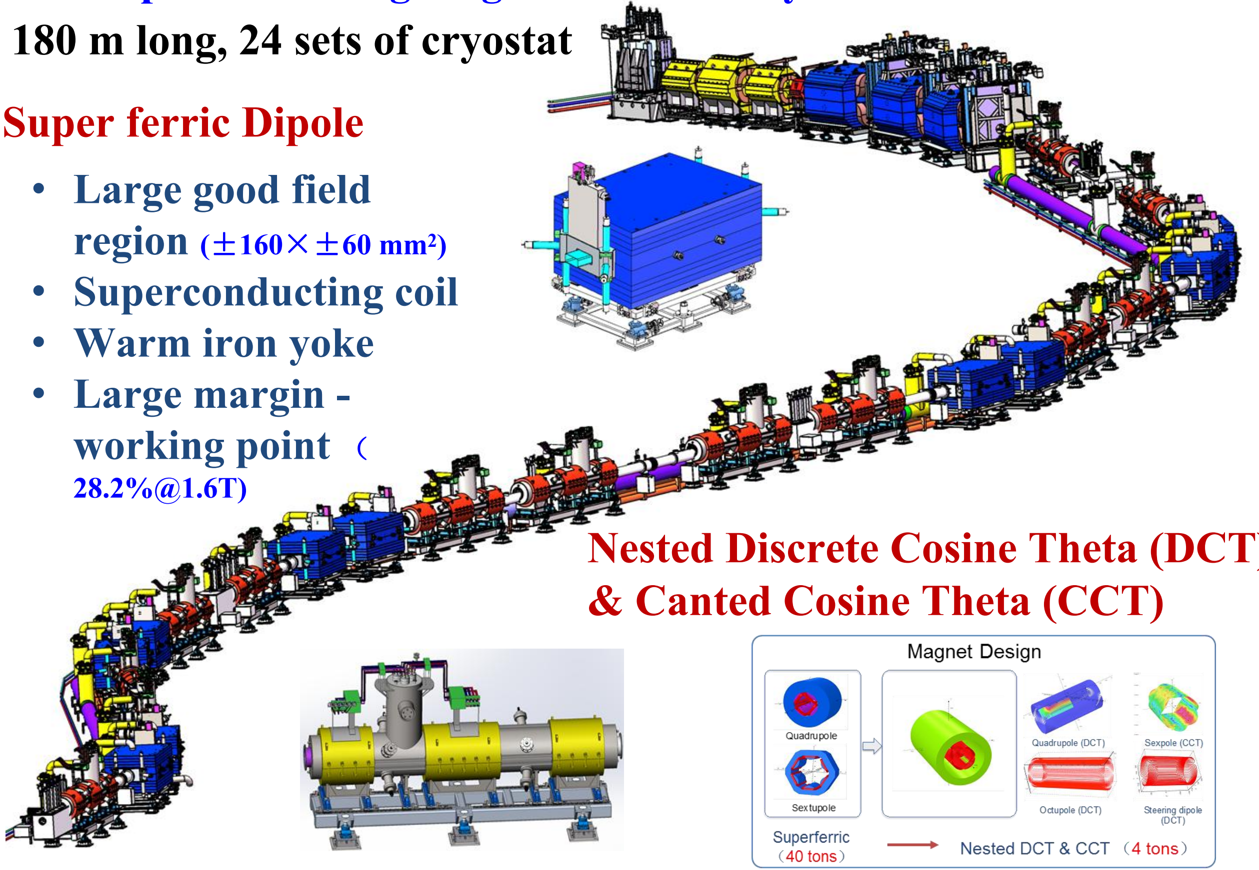
- **Full superconducting magnet beam line system**

180 m long, 24 sets of cryostat

Super ferric Dipole

- Large good field region (±160×±60 mm²)
- Superconducting coil
- Warm iron yoke
- Large margin - working point （28.2%@1.6T)

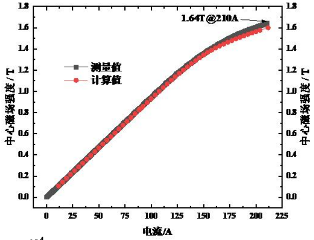
Nested Discrete Cosine Theta (DCT) & Canted Cosine Theta (CCT)

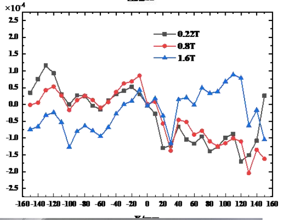


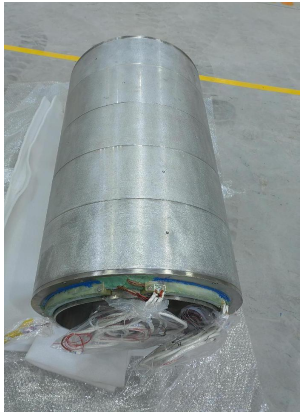
3. High energy fragment separator (HFRS)

Design parameters of HFRS dipole

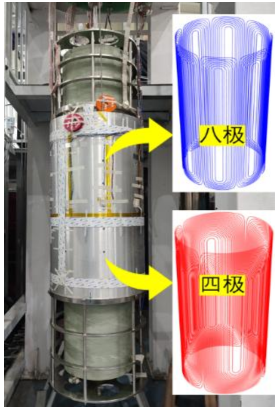
Effective length	2.74 m
Gap	160 mm
Central field	1.6 T
Operation current	210 A
Inductance	20 H
Weight of Iron	40 t
Cooling method	LHe bath cooling
Operation temperature	4.2 K







L800-1



L800-2

L1200

4. Multi-function storage ring

Key devices

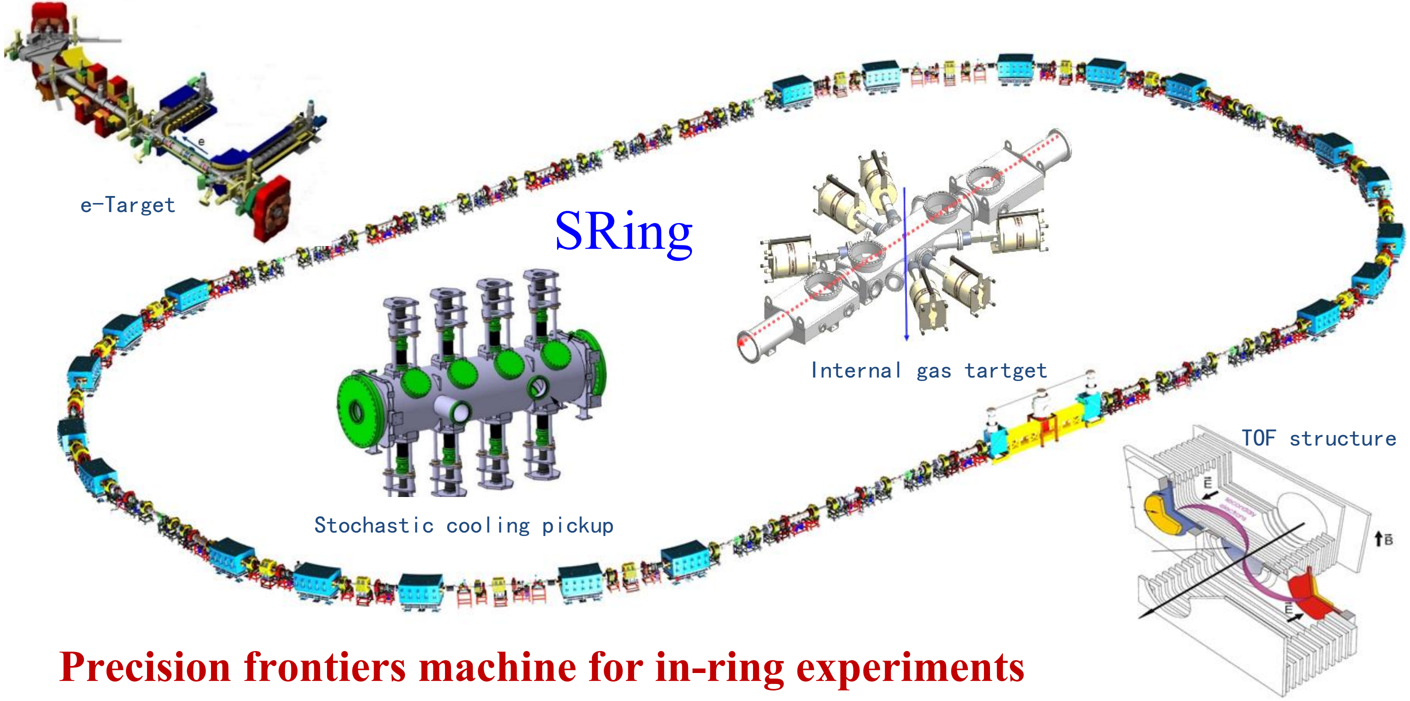
- Electron cooling
- Stochastic cooling
- Two TOF detectors
- Electron target

Operation modes

- Isochronous mode
- Normal Mode
- Internal-target Mode
- Ion-ion merging Mode

Experiment programs

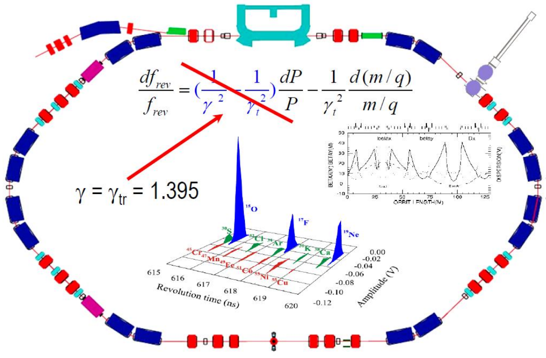
- Gas-jet target experiments
- DR experiments
- IMS & SMS
- Laser cooling
- Ion-ion merging experiments



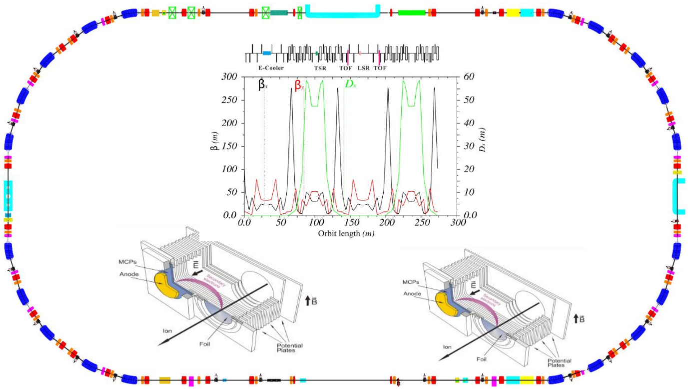
Precision frontiers machine for in-ring experiments

4. Multi-function storage ring

Isochronous mode with two TOF



HIRFL-CSRe



HIAF-SRing

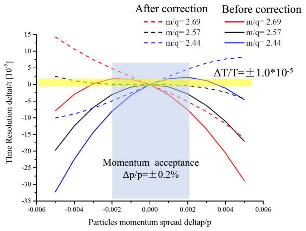
43 masses are measured

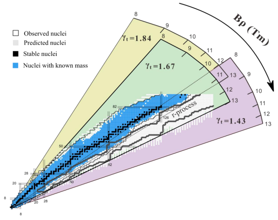
Measured for the first time: 16

Precision improved: 27

Precision achieved: $\Delta M/M \sim 10^{-7}$

Demonstrated the two TOF mode first time in the world



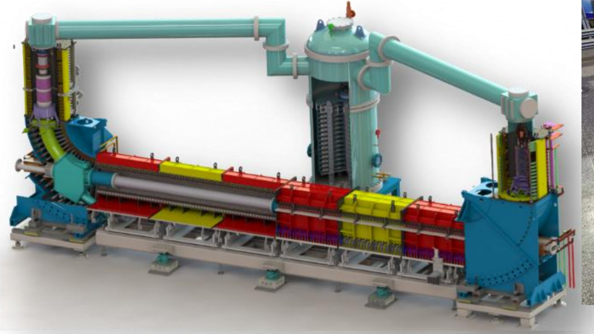


$\Delta M/M \sim 10^{-7}\text{-}10^{-8}$

The highest precision of isochronous mass measurement

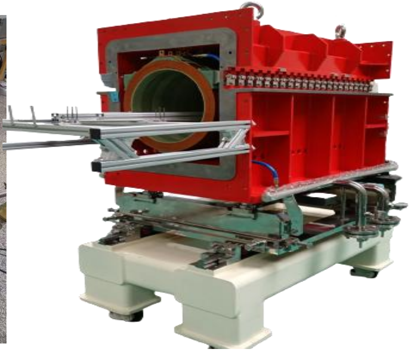
4. Multi-function storage ring

■ Electron cooler in SRing



450 keV DC magnetized electron cooler

Collector



Cooling section unit

Energy	450 keV
Maximum current	2.0 A
Magnetic field	1500 Gs
Cooling length	7.4 m

coils

gun

Hardware fabrication and civil construction

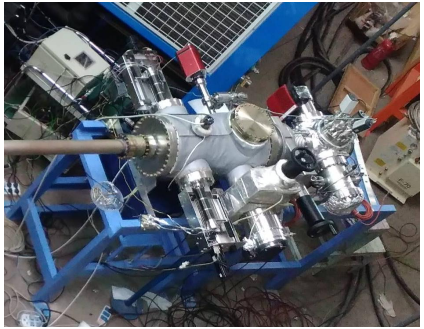
Hardware fabrication

- Most of the hardware are in mass production

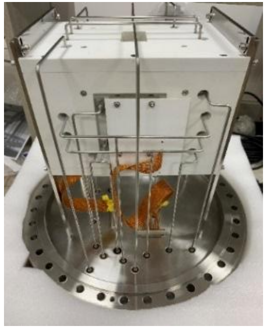
Dipole magnet

Quadrupole magnet

Primary target



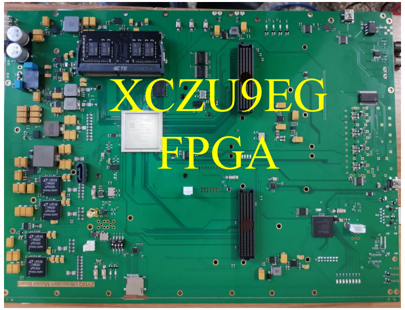
Collimator

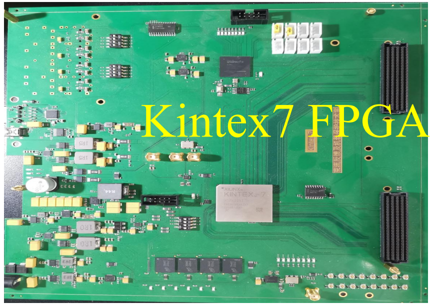


Beam instruments

Hardware fabrication

- Most of the hardware are in mass production





Civil construction

Civil construction

Civil construction

Summary

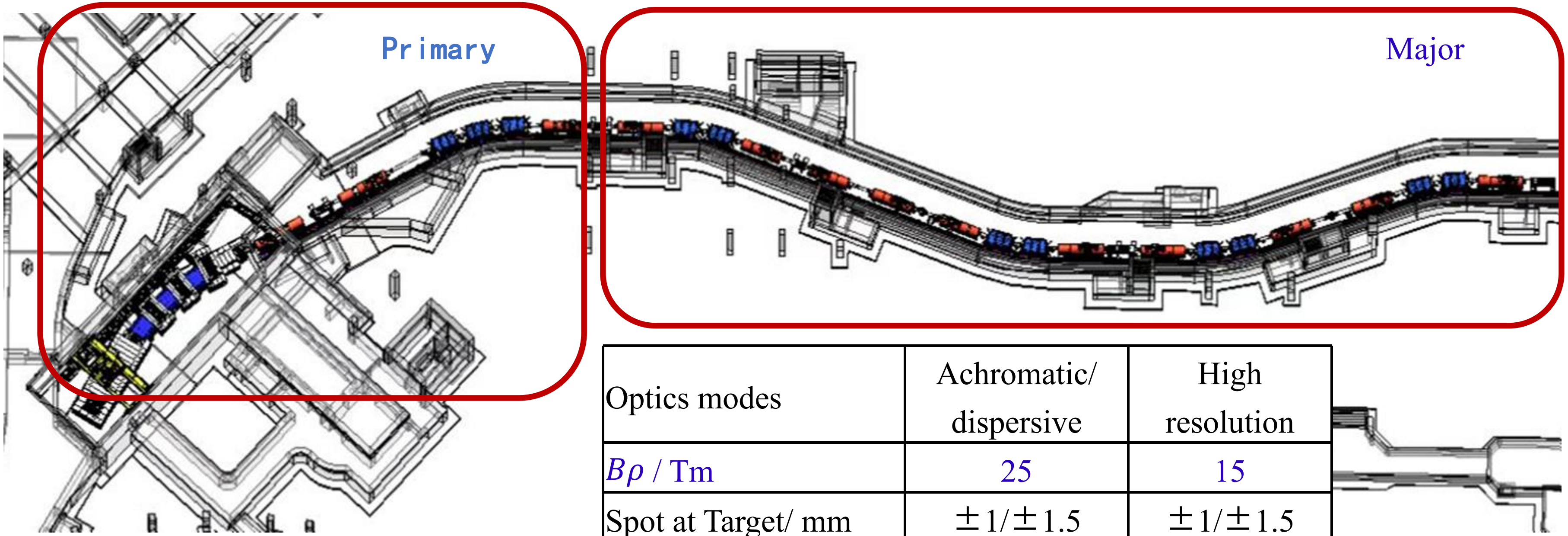
- HIAF will be a world leading facility with very intense heavy ion beam and technical challenges
- The most of challenges, such as next generation FECR, SRF technology and very fast cycle acceleration, have been verified successfully through extensive R&D work in past ten years.
- Hardware mass fabrication and volume production of various apparatuses are under progress, some of them come to the system integration and test stage.
- Phased installation of accelerator components and common system will begin in 2023.
- The early completion of project is expected at end 2025


HIAF
HIAF will be world-class scientific facility for scientists and researchers!
Welcome to join us to exploring the universe!


@新华网

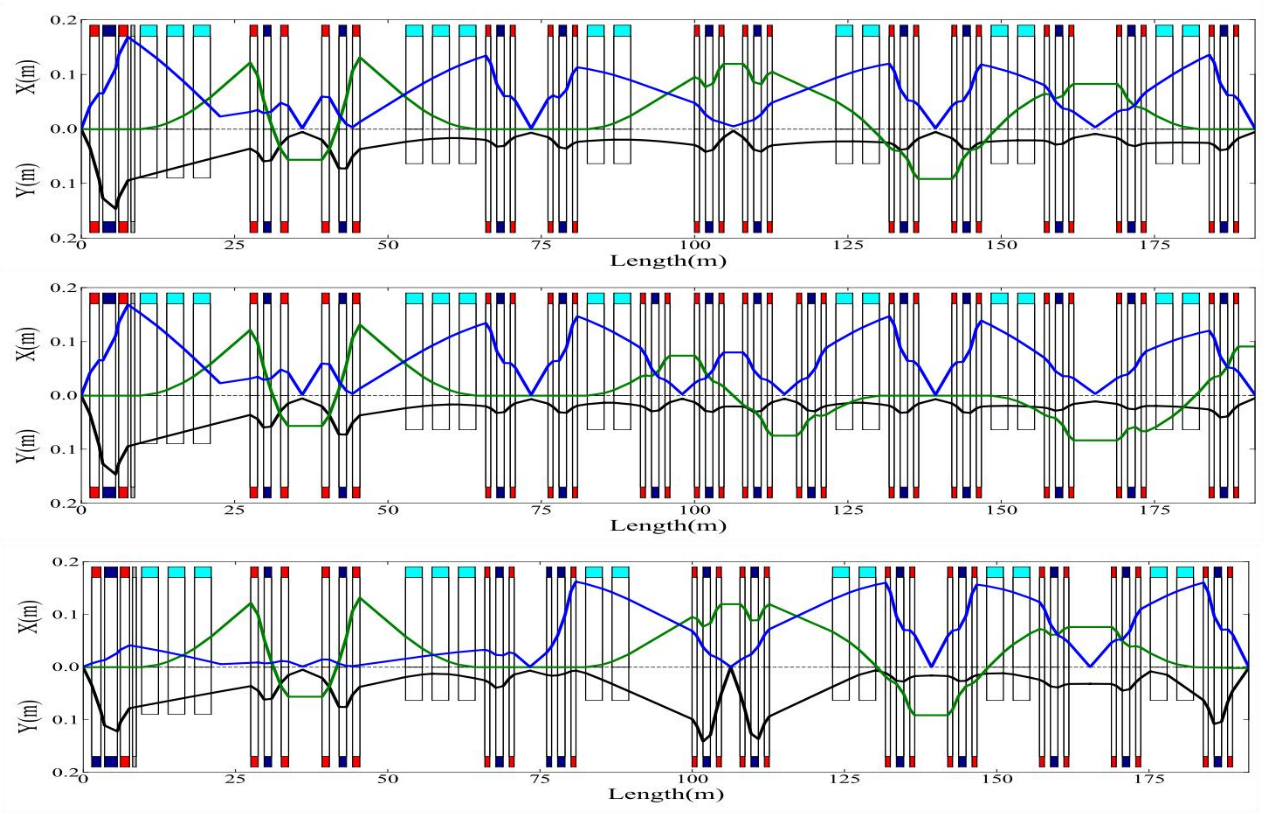
HIAF FRagment Separator - HFRS

Highest G separator worldwide. Primary + Major structure, High acceptance and Resolution.



Optics modes	Achromatic/ dispersive	High resolution
$B\rho$ / Tm	25	15
Spot at Target/ mm	±1/±1.5	±1/±1.5
Angle acc./ mrad	±30/±25	±10/±25
Momentum acc.	±2.0%	±0.03%
Resolution(P/M)	850 /1100	970 /10000

HIAF FRagment Separator - HFRS



Envelope 1st order: Achromatic (up), dispersive(middle), High resolution(down)

Matrix for Major separator:
dispersive (up)/high resolution

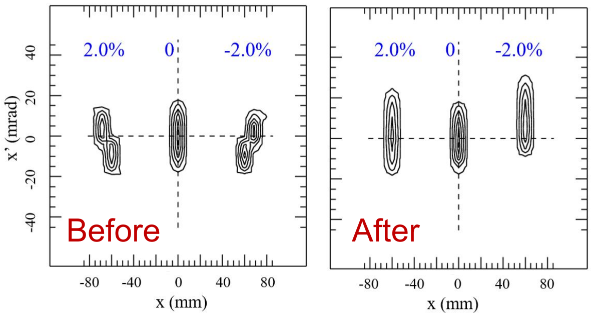
R	MF1	MF4	MF6
(x,x)	-2.638	-1.5	-1.856
(x,x')	0	0	0
(x',x')	-0.378	-0.662	-0.537
(x, δ)	3.7	0	4.55
(x', δ)	0	0	0
(y,y)	5.0	5.0	3.759
(y,y')	0	0	0
(y',y')	0.2	0.2	0.266

R	MF4	MF6
(x,x)	0.225	0.213
(x,x')	0	0
(x',x')	4.404	4.649
(x, δ)	-4.55	0
(x', δ)	0	0
(y,y)	11.18	1.443
(y,y')	0	0
(y',y')	0.089	0.693

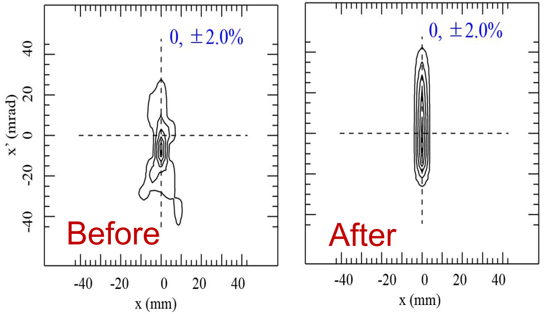
HIAF FRagment Separator - HFRS

◆ High order corrections of aberration

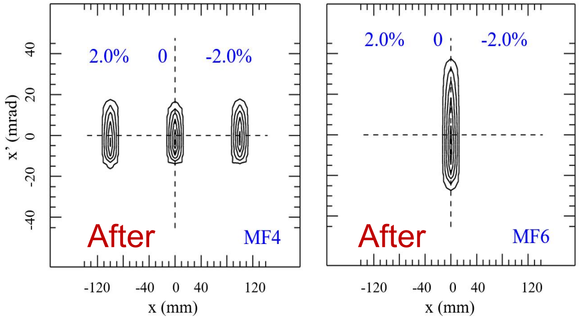
① PF2



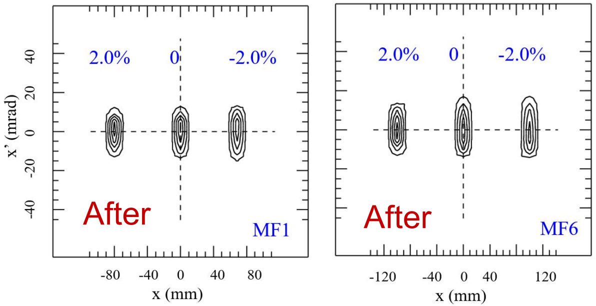
② PF4



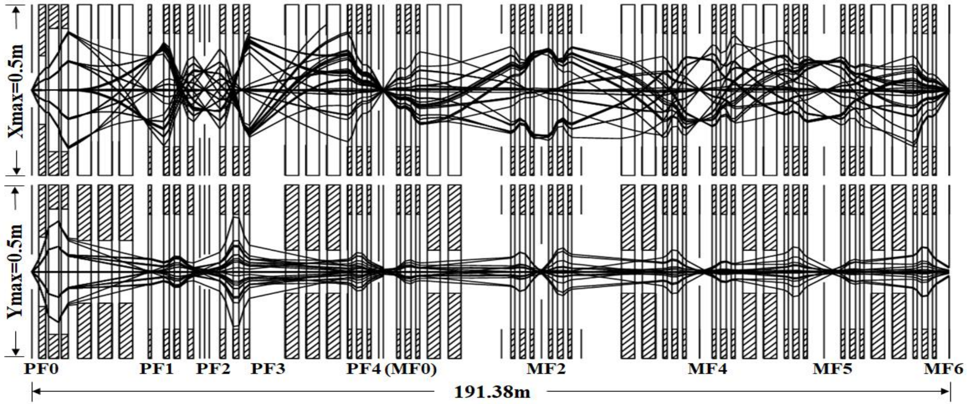
③ MF4/MF6 (Achromatic)



④ MF4/MF6 (Dispersive)



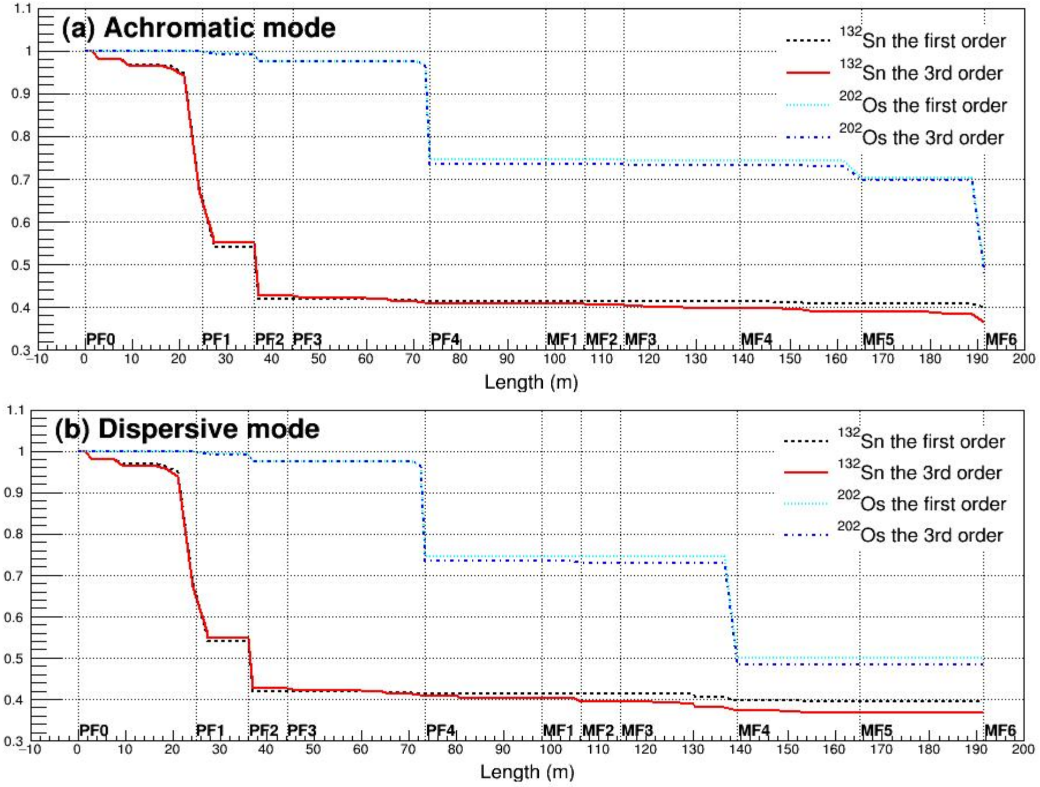
⑤ Envelop 3rd order (Achromatic mode, transmission efficiency >85%)



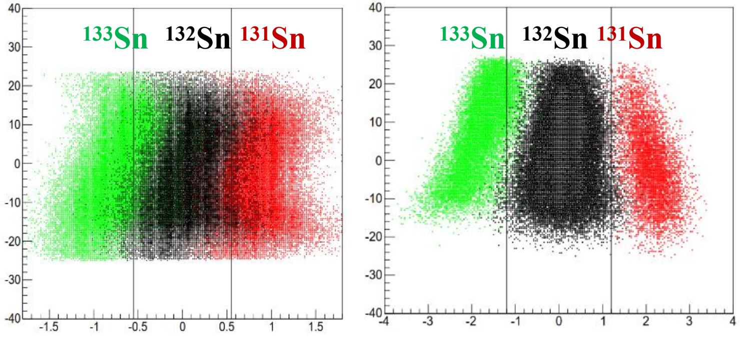
Python+GICOSY

HIAF FRagment Separator - HFRS

◆ Transmission efficiency of target species



Transmission of target species ^{132}Sn/^{202}Os



PF4 MF6

Transmission efficiency and purity of ^{132}Sn

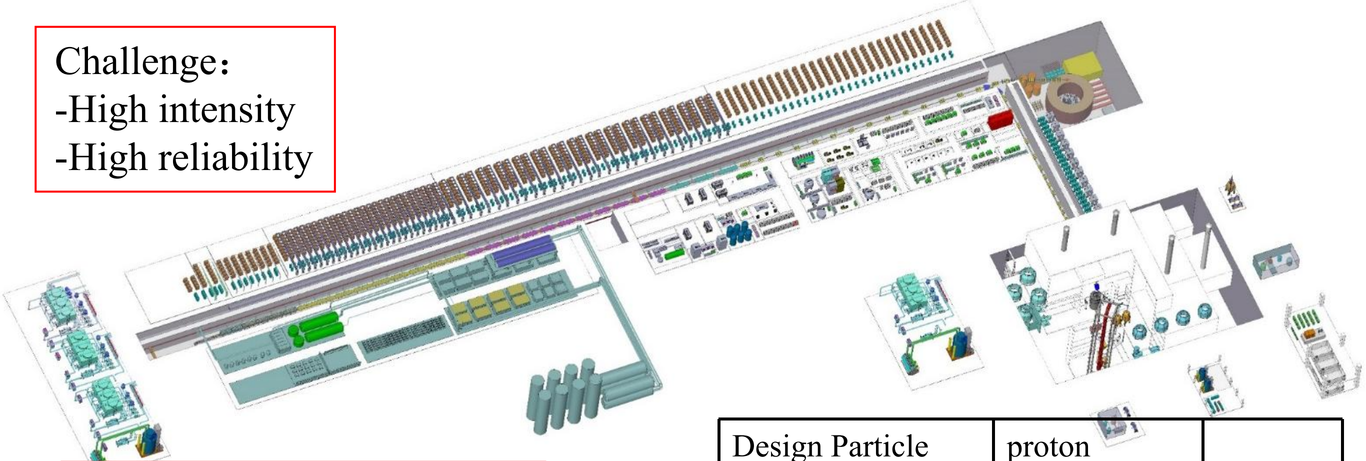
Foci	PF4	MF6
^{132}Sn efficiency	44.08%	36.54%
^{132}Sn purity	62.31%	95.64%

Based on the field distributions of model simulation, and prototype measurements.

CiADS Project

The first demonstration of ADS at MWs level

Challenge：
-High intensity
-High reliability



Only one injector
Non-local compensation

Beam trips goal:
<10s, -
10s～5min, 2500/y
>5min, 300/y

Design Particle	proton	
Energy	500 (250)	MeV
Beam current	5 (10)	mA
Beam power	2.5	MW
Operation mode	CW&Pulse	
Beam loss	＜0.1	W/m
Reactor power	7.5	MWt