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HIAF

Status and challenges of HIAF

High-Intensity heavy ion Accelerator Facility

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Outline

1. Brief introduction of the HIAF

2. The key components of accelerator complex

3. Experimental terminal and station

4. Hardware fabrication and civil construction

5. Summary

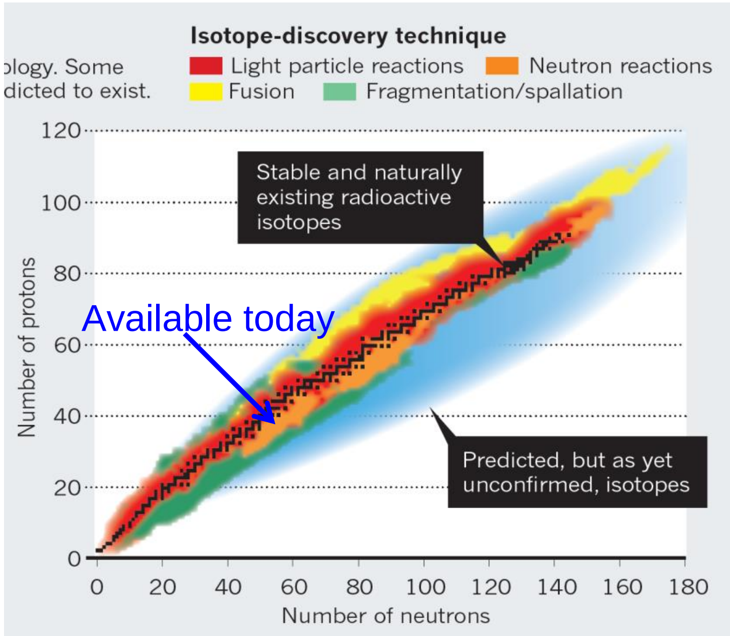
Brief introduction of the HIAF

High-Intensity Heavy Ion Accelerator Facility-HIAF

HIAF is one of the mega scientific facilities approved by the central government in Twelfth Five-Year Plan

The project is proposeded by IMP, CAS
The campus locates in Huizhou City of Guangdong Province
The total budget is 2.8 billion CNY
The construction of project started at the end 2018, and the period is 7 years

Brief introduction of the HIAF



Fascinating and crucial questions

- **To explore the limit of nuclear existence**
- **To study exotic nuclear structure**
- **Understand the origin of the elements**
- **To study the properties of High Energy and Density Matter**

……

Next-generation facilities being constructed or proposed worldwide:

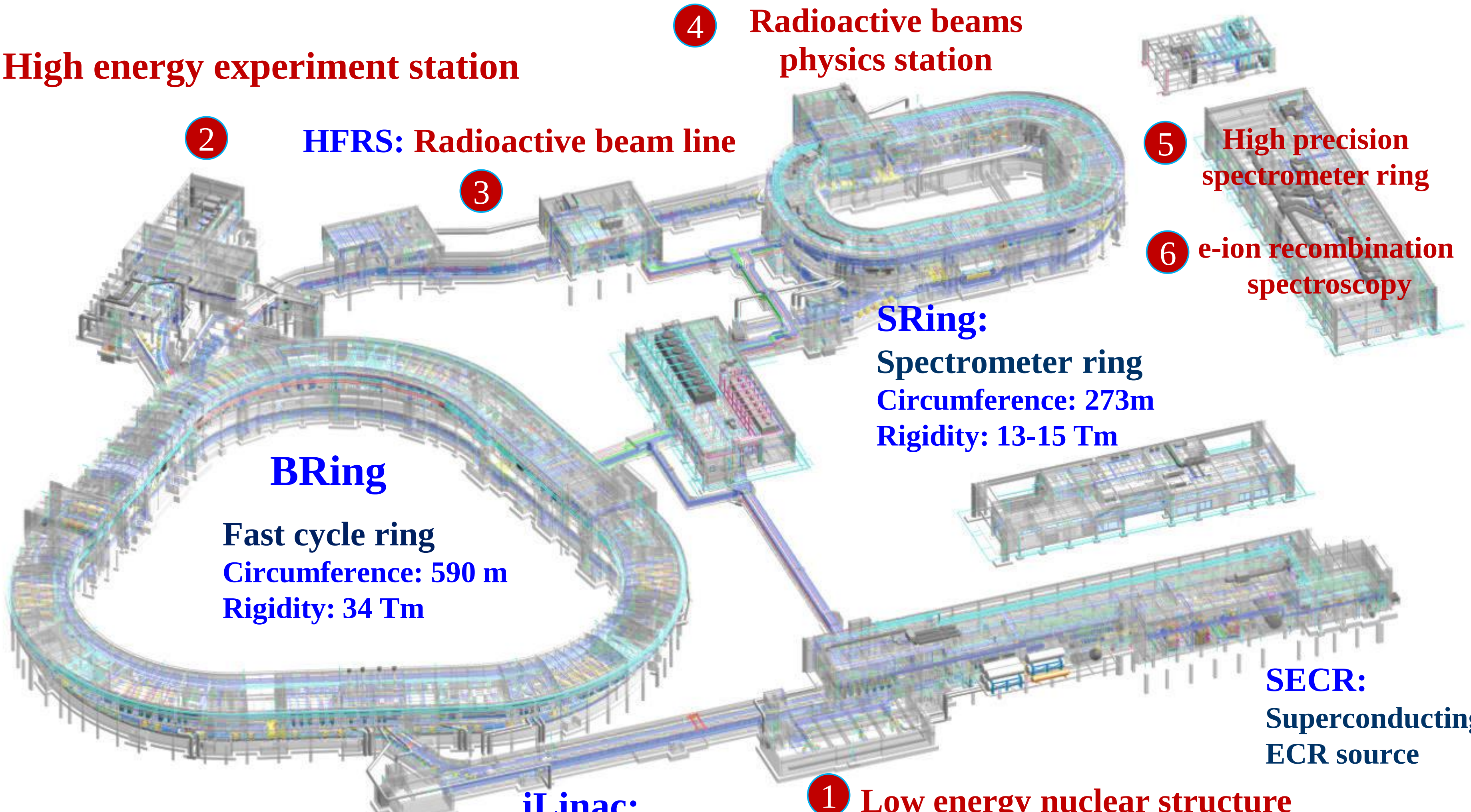
- SPIRAL2 at GANIL in Caen, France
- FAIR at GSI in Darmstadt, Germany
- FRIB at MSU in the U.S.
- NICA at JINR, Dubna, Russia
- EURISOL in Europe

High Intensity Heavy-ion Accelerator Facility

HIAF in China

Brief introduction of the HIAF

Accelerator components and experiment terminals



BIM (Building information model)

Brief introduction of the HIAF

- **HIAF main parameters**

To provide very high intensity heavy ion beam

	SECR	iLinac	BRing	HFRS	SRing
Length / circumference (m)	---	114	**569**	192	**277**
Final energy of U (MeV/u)	0.014 (U^{35+})	17 (U^{35+})	**835 (U^{35+})**	800 (U^{92+})	**800 (U^{92+})**
Max. magnetic rigidity (Tm)	---	---	**34**	25	**15**
Max. beam intensity of U	**50 pμA (U^{35+})**	**28 pμA (U^{35+})**	**2×10^{11}ppp 6×10^{11}pps (U^{35+})**	-------	**(0.5-1) $\times10^{12}$ppp (U^{92+})**
Operation mode	DC	CW or pulse	**fast ramping (12T/s, 3Hz)**	Momentum-resolution 1100	**DC, deceleration**
Emittance or Acceptance (H/V, π·mm·mrad, dp/p)		5 / 5	**200/100, 0.5%**	±30mrad(H)/±15 mrad(V), ±2%	**40/40, 1.5% (normal mode)**

Brief introduction of the HIAF

HIAF

HIAF construction time schedule

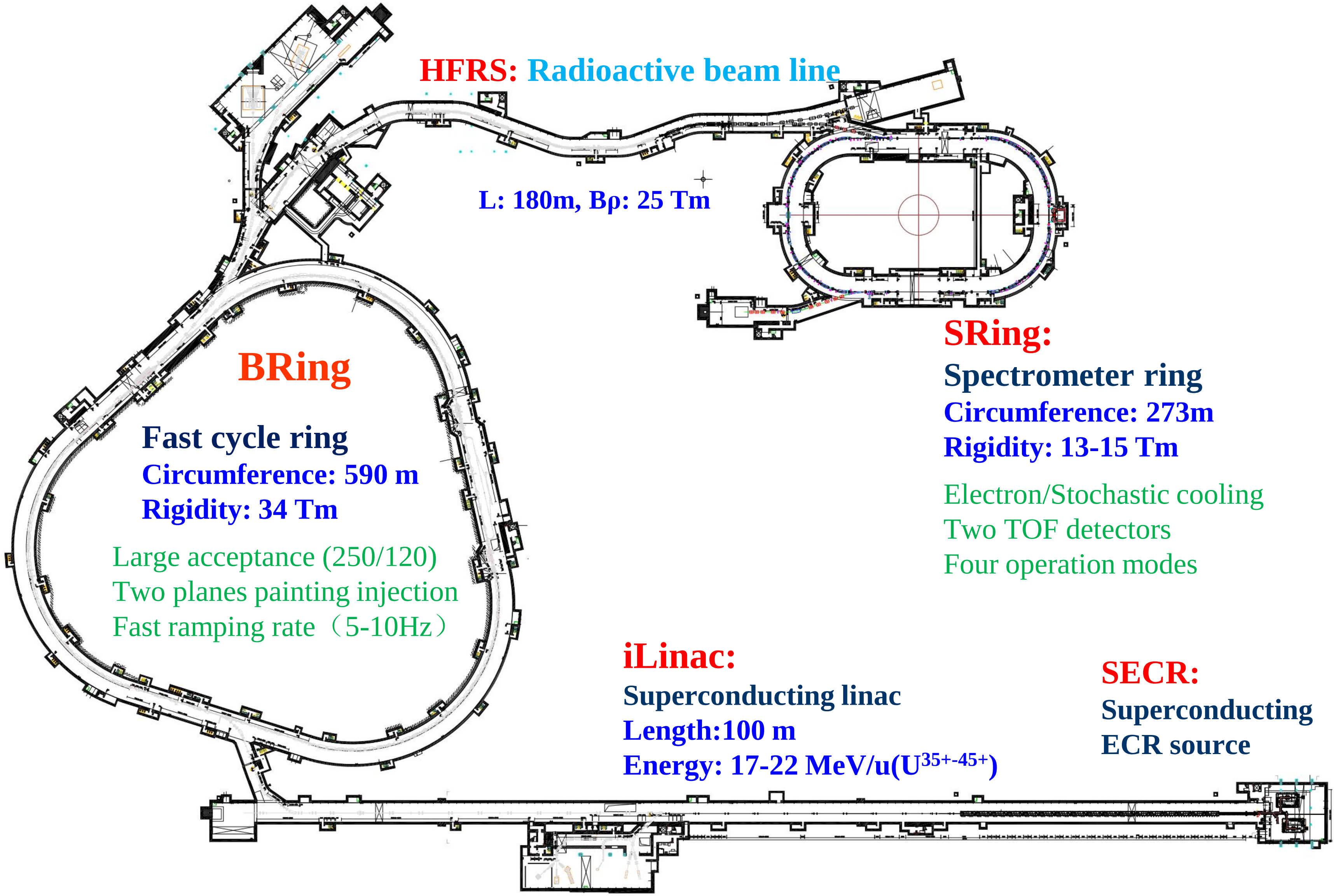
2019	2020	2021	2022	2023	2024	2025	2026
Civil construction							
		Electric power, cooling water, compressed air, network, cryogenic, supporting system, etc.					
ECR design & fabrication		SECR installation and commissioning					
	Linac design & fabrication			iLinac installation and commissioning		Day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

- The first ion beam provided by **FECR** is at the end of 2023;
- The low energy ion beam of **iLinac** is expected at 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 accelerator

Accelerator components

ECR + superconducting linac + fast ramping rate synchrotron



The Front End

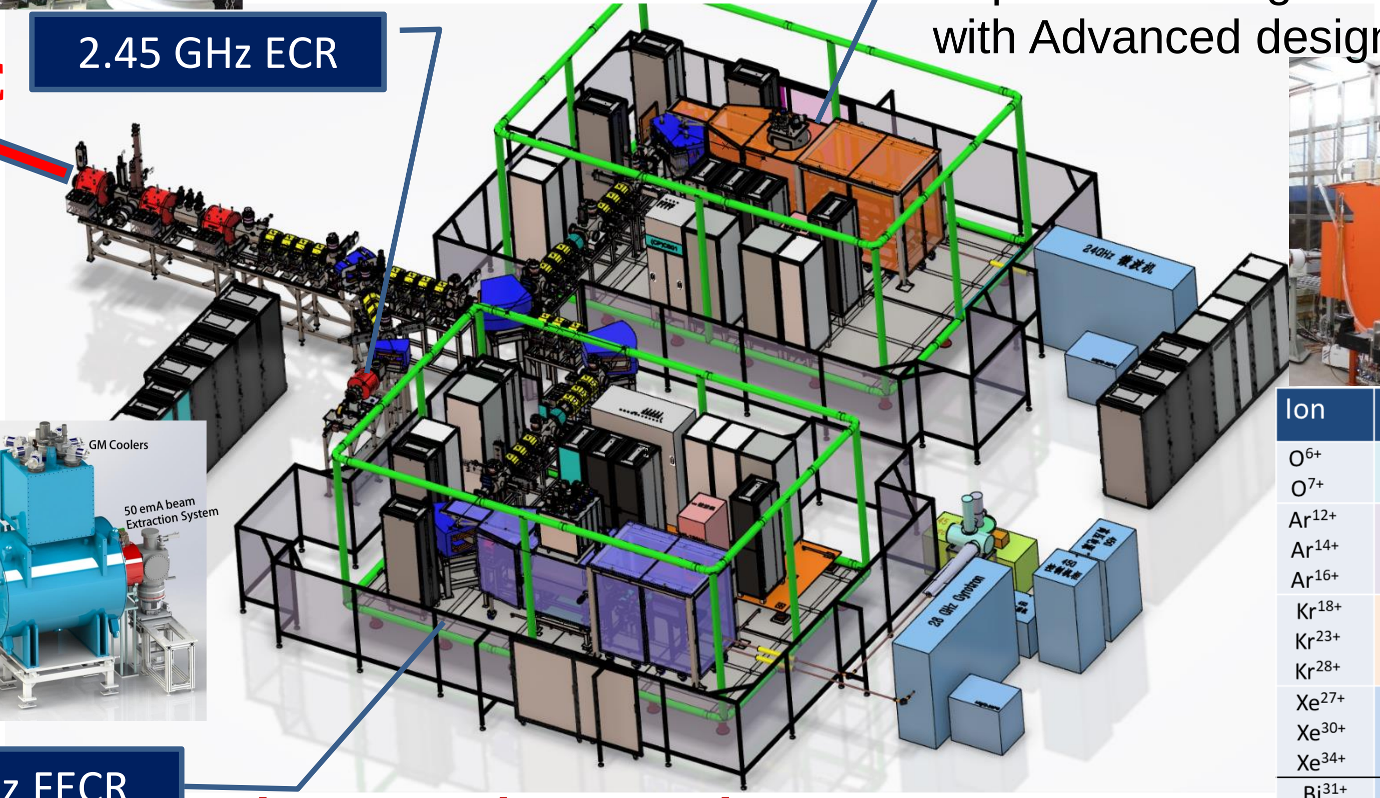
Permanent magnet structure and reliable beam production

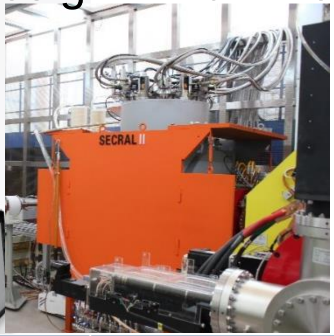
28 GHz SECRAL

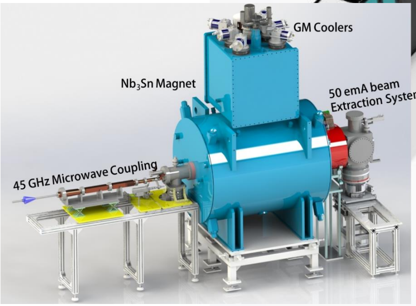
3rd generation,
Superconducting ECR ion source with Advanced design in Lanzhou

2.45 GHz ECR

iLINAC







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

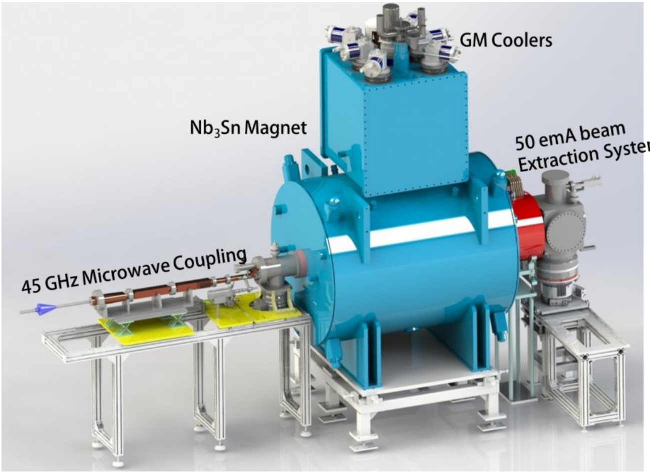
45 GHz FECR

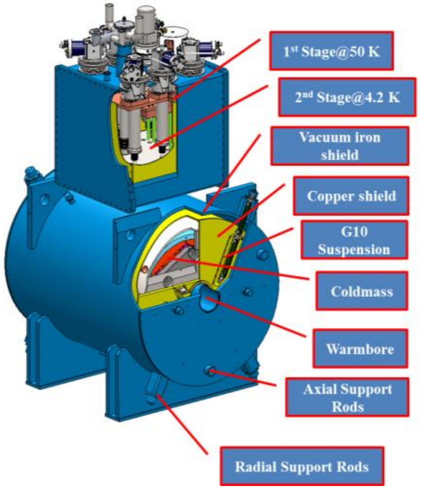
4th generation ECR ion source

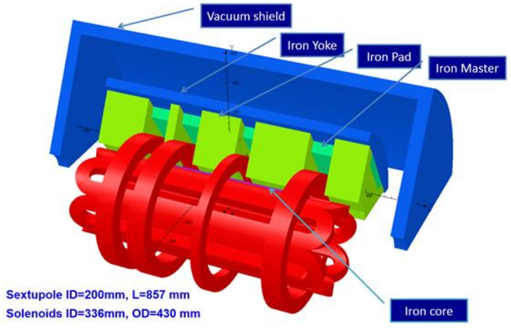
Solutions to the stringent needs of the superconducting linac capable of accelerating very intense beams with broad A/Q ratios.

The Front End

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



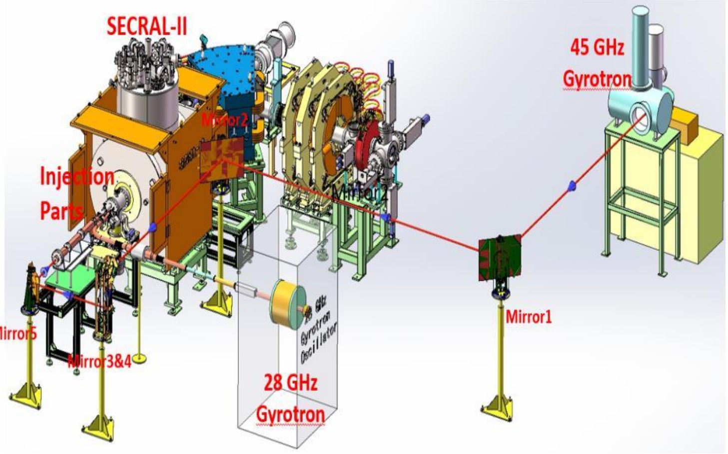




Most technical challenges have been verified, system integration is under progress

Sextupole Coils

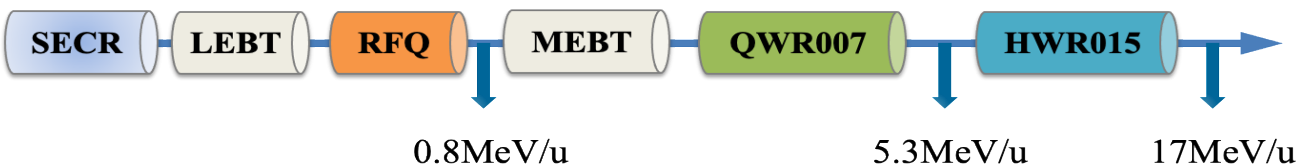

Full-sized cold mass



45 GHz microwave coupling

The first plasma at 45 GHz is expected in 2023

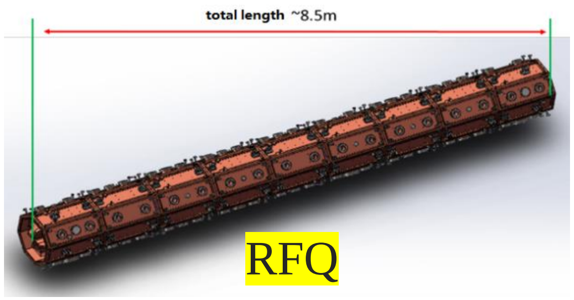
High current superconducting ion linac



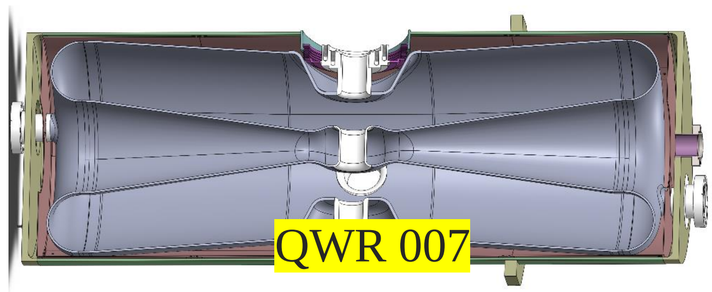
- **Pulsed**
  28 pμA U^{35+}
- **CW**
  15 pμA U^{35+}

3HB+RFQ MEBT QWR007 HWR015

To BRing or Terminal 1

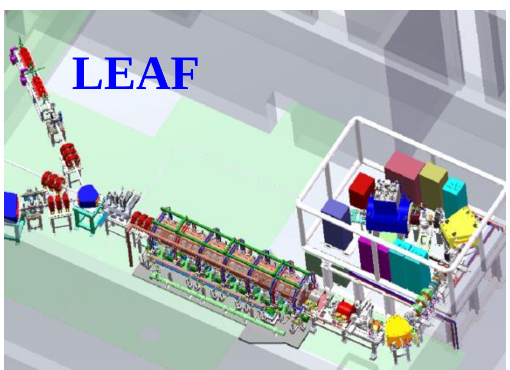


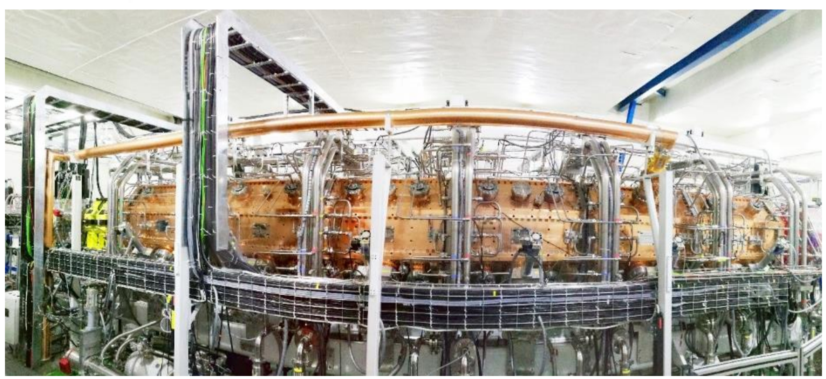
RFQ

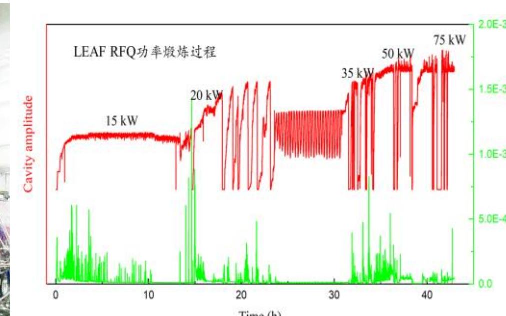


QWR 007

HWR 015





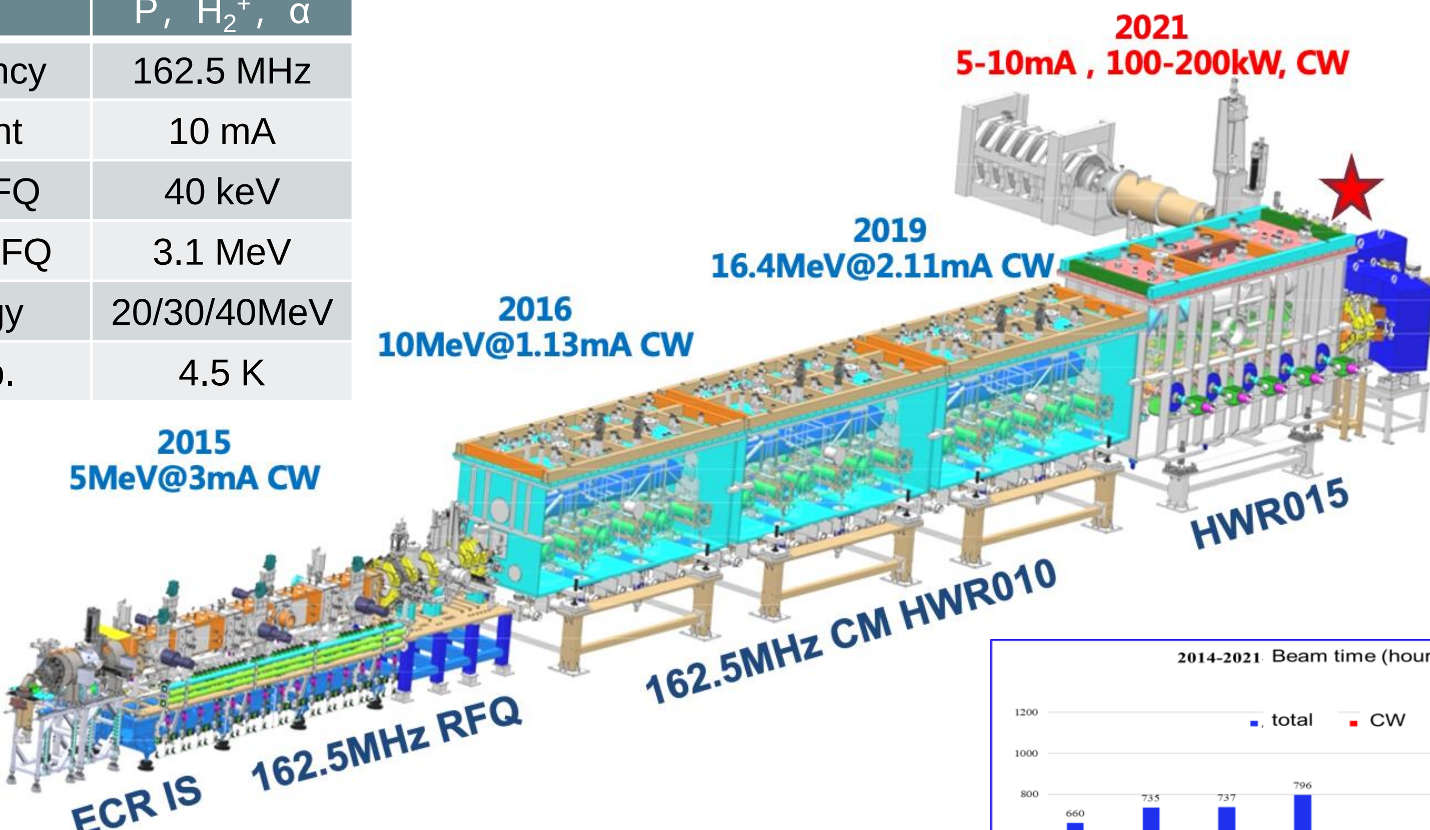


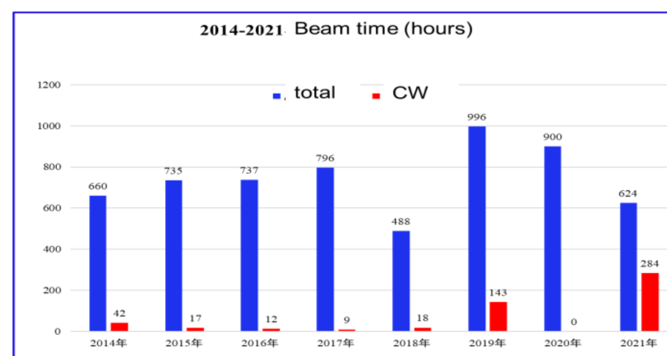
L-RFQ RF training log

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



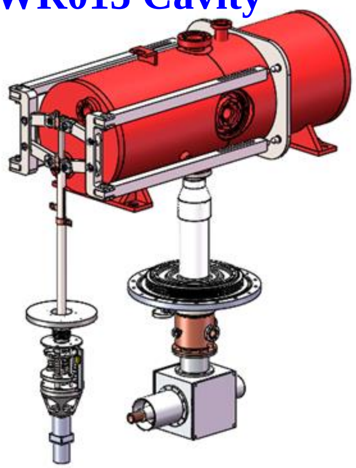


Supported by "strategic Priority research Program" of the Chinese Academy of Sciences

SRF Main Hardware Progress

QWR007 Cavity

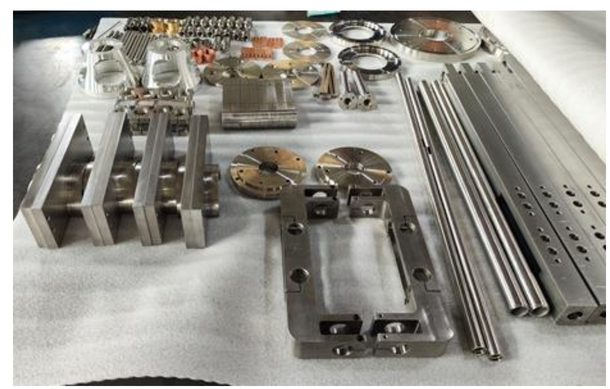
HWR015 Cavity



QWR007 Cavity Parts

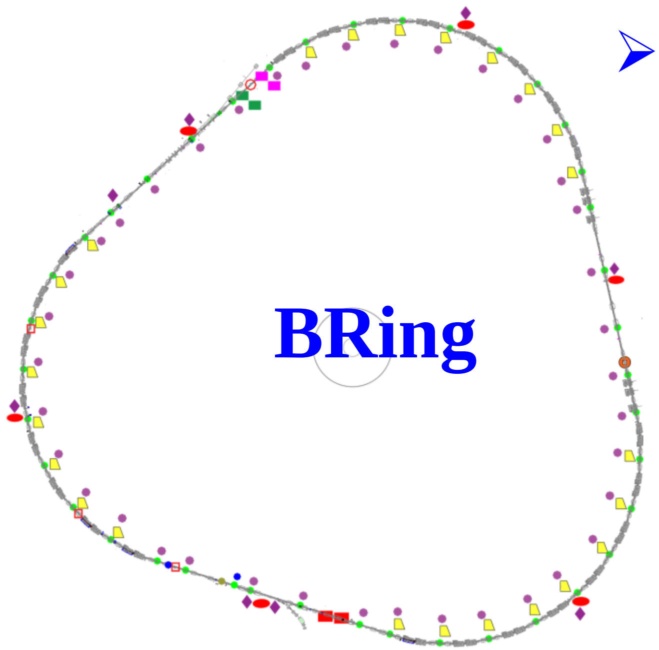
HWR015 Cavity Production

QWR Couplers

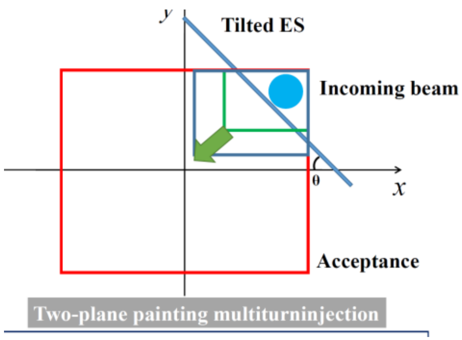


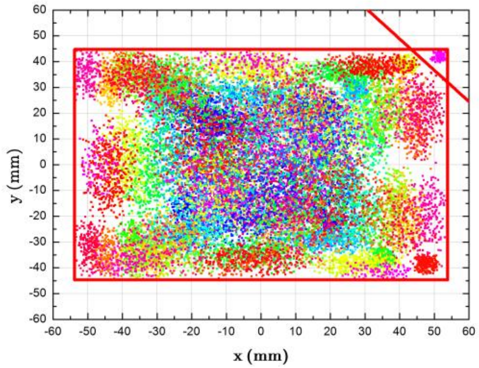
QWR/HWR Tuners

Fast ramping booster synchrotron BRing

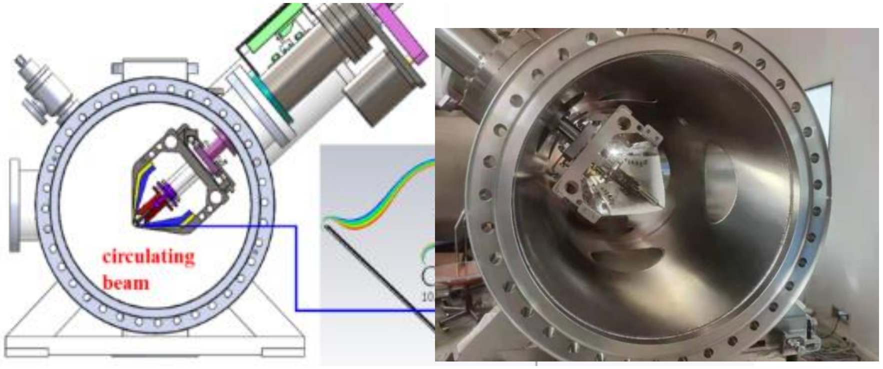


- **4-D painting injection**





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**

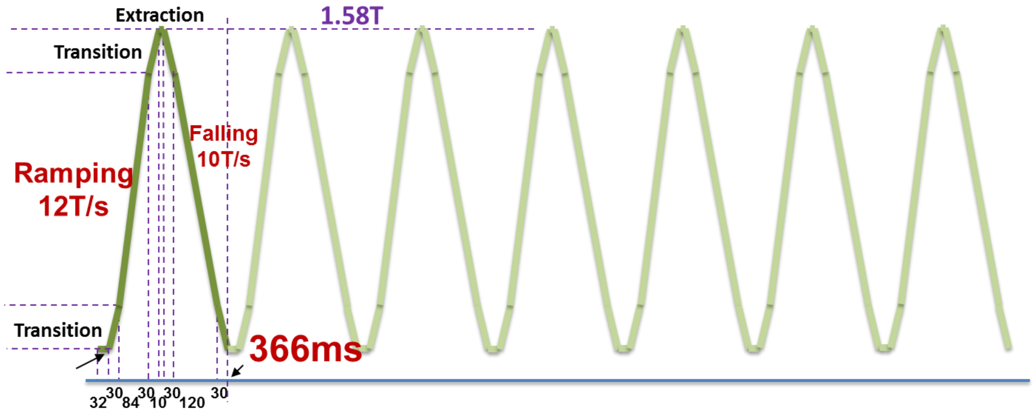
Nearly 10 times over the conventional single-plane injection.

Fast ramping booster synchrotron BRing

➢ Fast ramping rate mode

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

The highest ramping rate for heavy ion synchrotron, challenges for key system, such as power supply、RF and vacuum chamber

A major breakthrough through innovative technologies:

1. Fast ramping rate full energy storage power supply

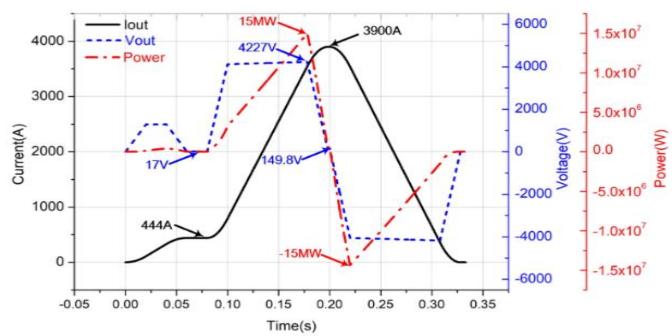
2. Magnetic alloy core loaded RF system

3. Ceramic-lined thin wall vacuum chamber

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**

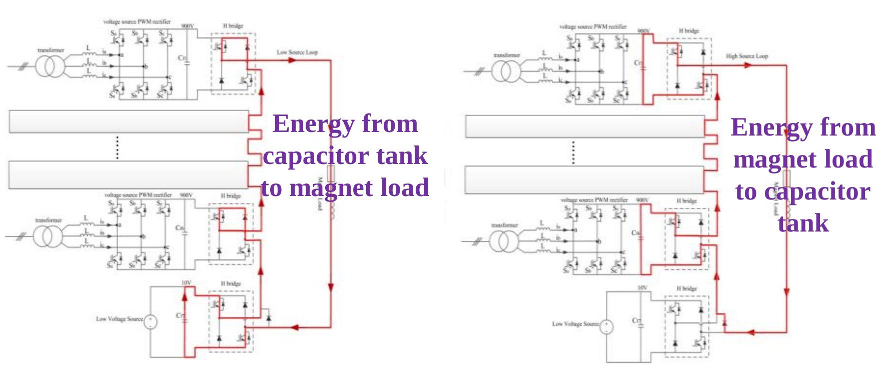
Excitation current/voltage	3900A/4300V
load inductance	116mH
Load Resistance	36.4mΩ
Current changing rate	≤±38000A/s
Flat bottom error	≤±0.2A
tracking error	≤±0.2A
Flat top error	≤±0.2A



Peak power reaches ±180MW totally at full load

Challenges: **High tracking precision and low current ripple, especially strong un-allowable line voltage fluctuation due to very large cyclic variation of reactive power**

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



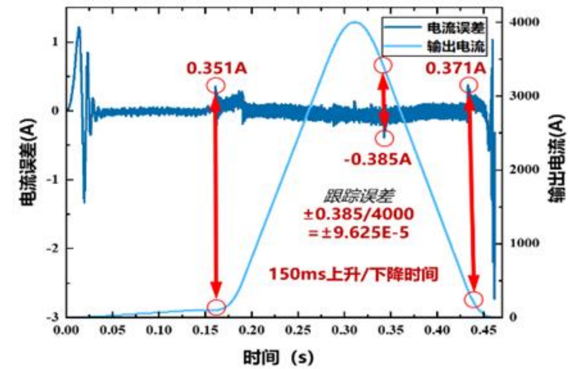
Block diagram of dipole power supply

- 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

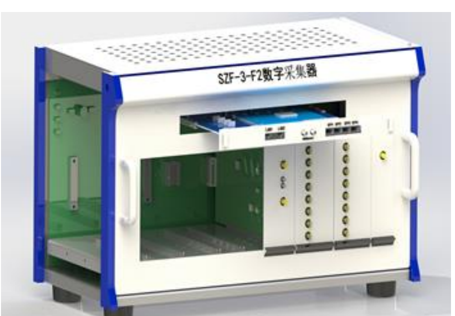
- **A full size prototype has been developed successful， the key technology and design of the power supply have been verified**



Leading level performance has been achieved, output results on the real magnet loads:

Current 3900A, ramping rate > 38000A/s, tracking error< ±9.625e-5, power requirement of dipoles will reduce from 180MVA to 15MVA

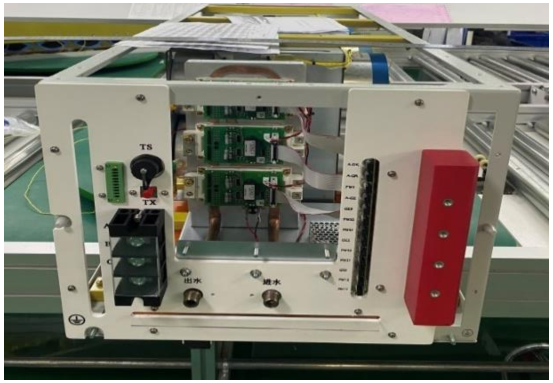
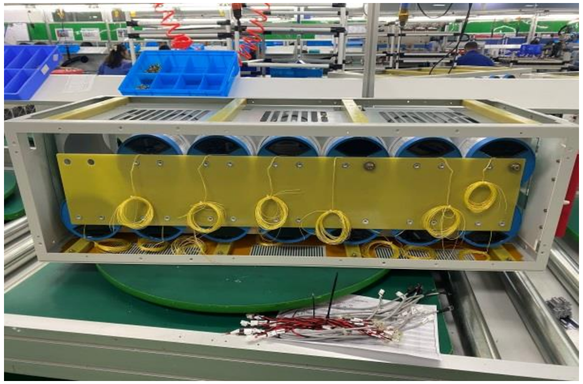
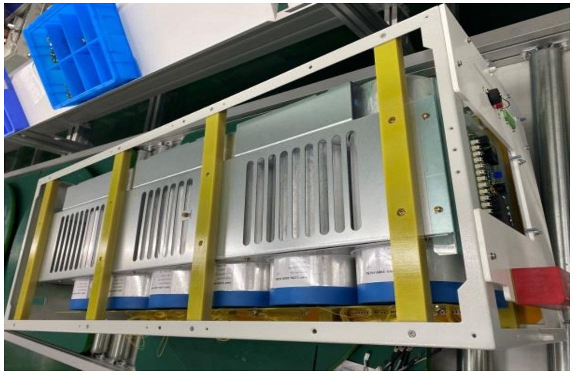
- **New generation of FPGA-based full digital controllers:** High-speed serial communication, distributed real-time high computing performance control system



The series of full digital controller SZF-3 for HIAF

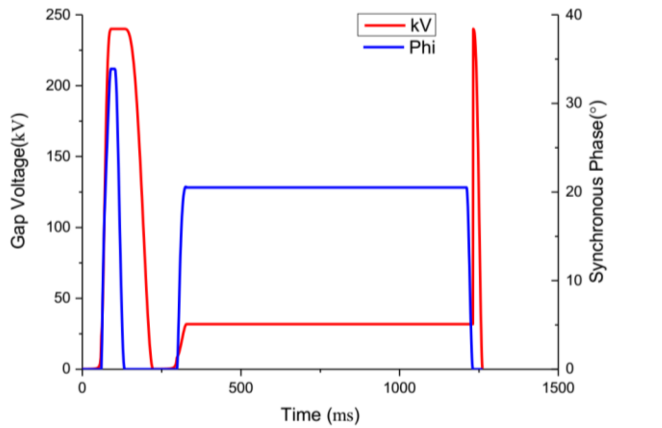
1. Fast ramping full energy storage power supply

- 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

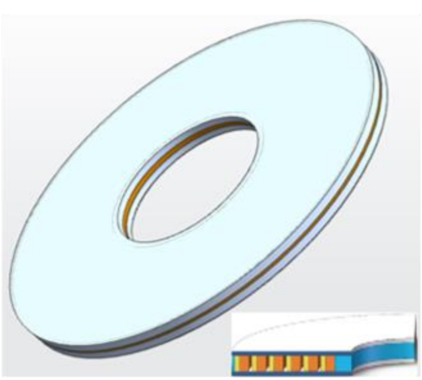
Not yet well established:

Fabrication of MA core module

Cooling of MA-loaded cavities operating at intense power dissipation

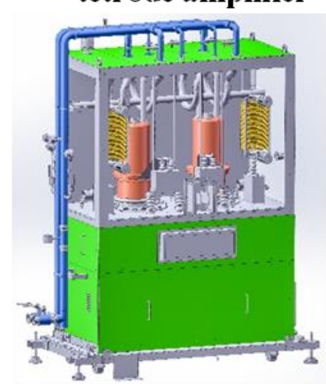
MA loaded RF system:

Large size oil cooled MA core

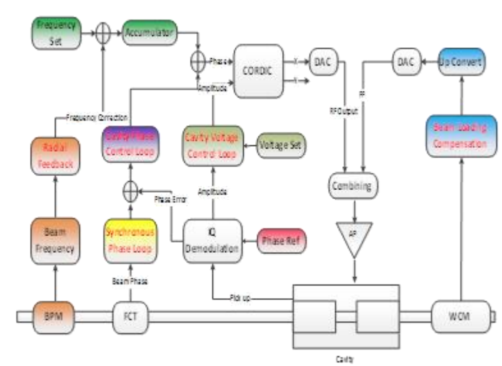


High gradient direct cooling MA- loaded cavity

Broadband push-pull tetrode amplifier



Multi harmonic digital LLRF



2. Magnetic alloy core loaded RF system

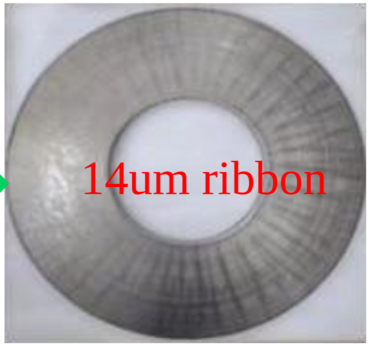
HIAF

- **Independent research and development of MA core**
  - Over ten years exploration from small(φ90), medium (φ460), to large (φ780) MA core.

95×65×25mm

460×230×25mm

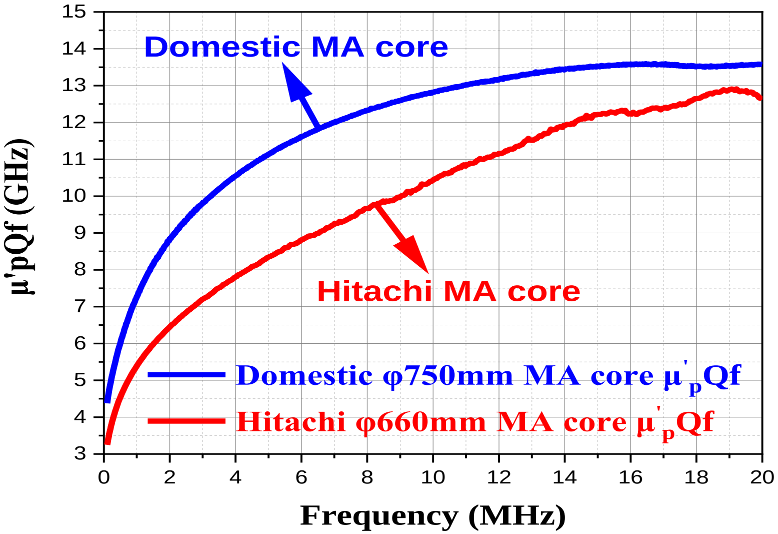
750×345×35mm



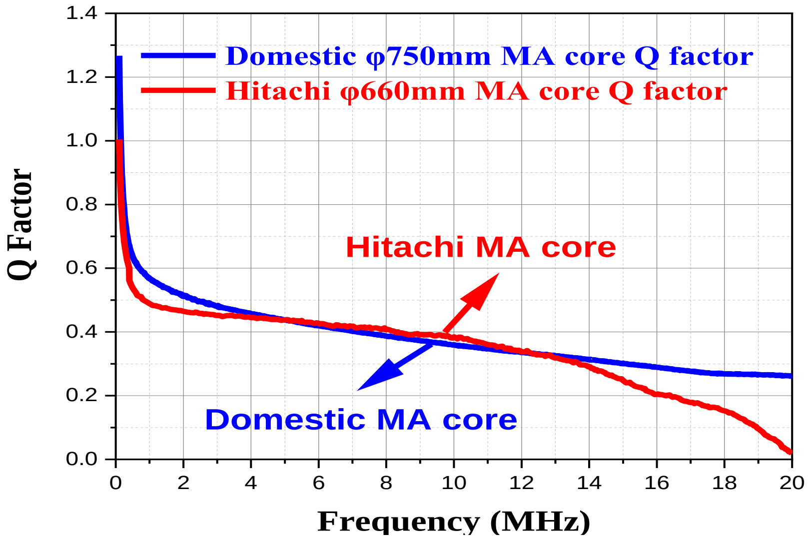
780×360×35mm

- **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

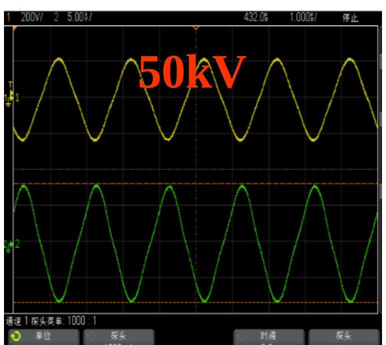
HIAF

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

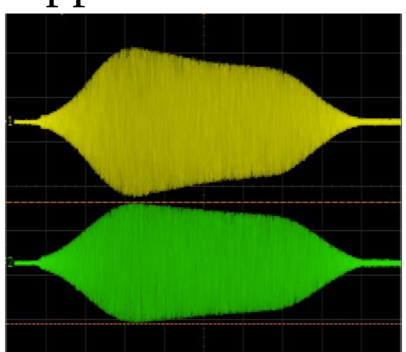
MA RF system

TH558 final stage

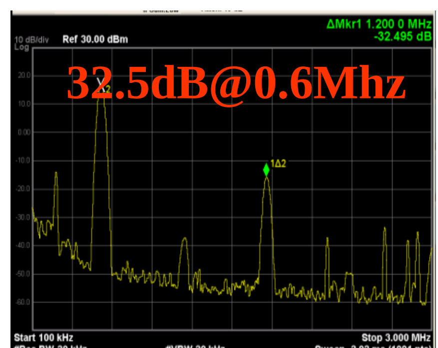
- ☐ The power test is carried out, voltage can reach 50kV@0.3~2.1MHz, and the third harmonic suppression is better than 25dB



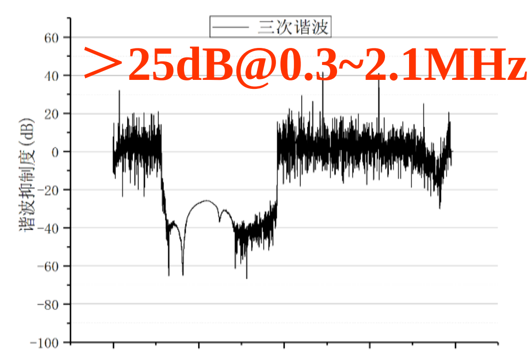
Cavity pick-up voltage



Voltage of ramping mode



Harmonic suppression



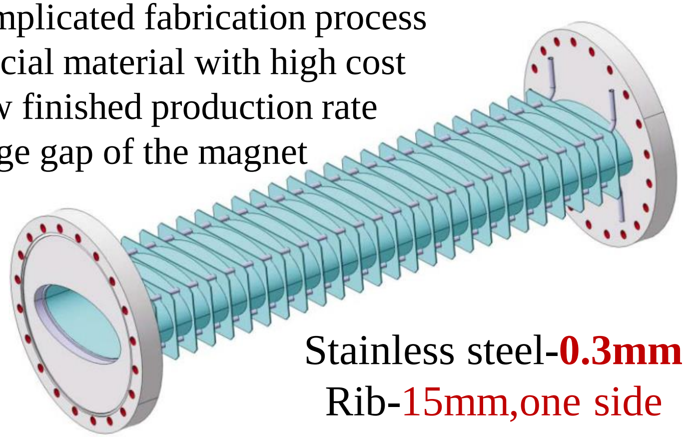
Harmonic at ramping mode

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

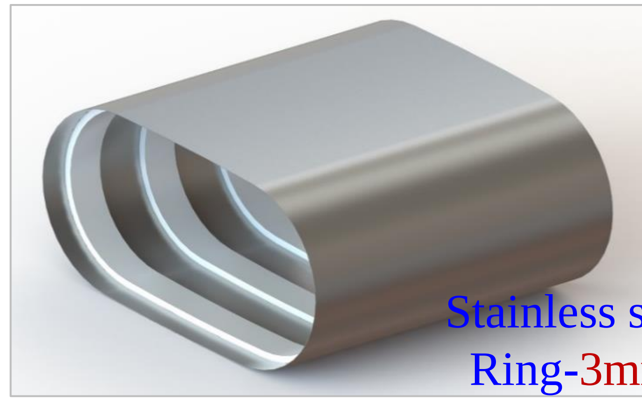
Complicated fabrication process
Special material with high cost
Low finished production rate
Large gap of the magnet



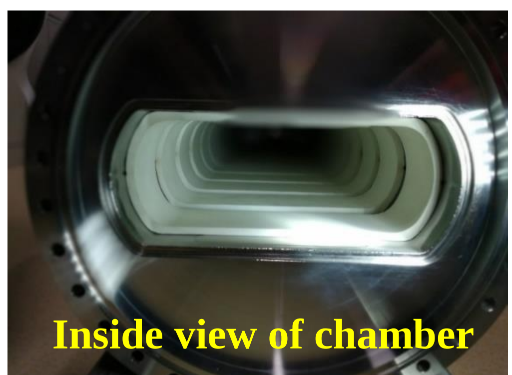
Stainless steel-**0.3mm**
Rib-15mm,one side

■ New scheme:

Thin-wall chamber supported by ceramic rings



Stainless steel-**0.3mm**
Ring-3mm,one side



Inside view of chamber

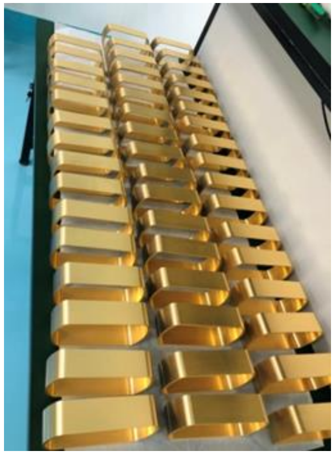
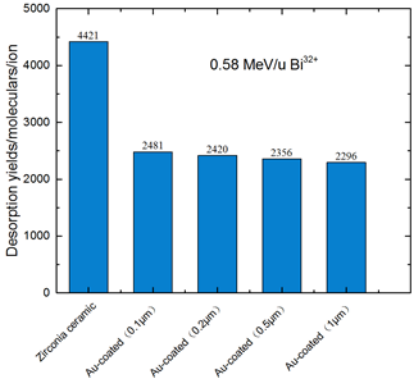
Vacuum pressure is 4.3×10^{-12} mbar after baking (250 ºC, 72 h)

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

3. The ceramic-lined thin-wall vacuum chamber

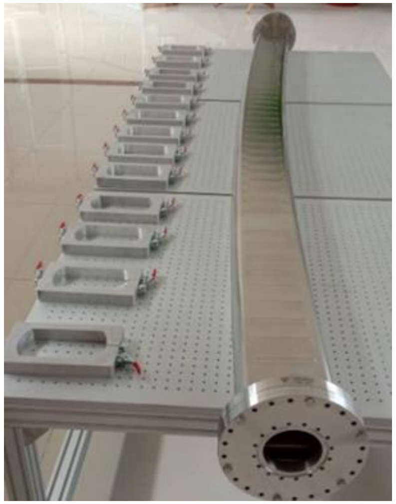
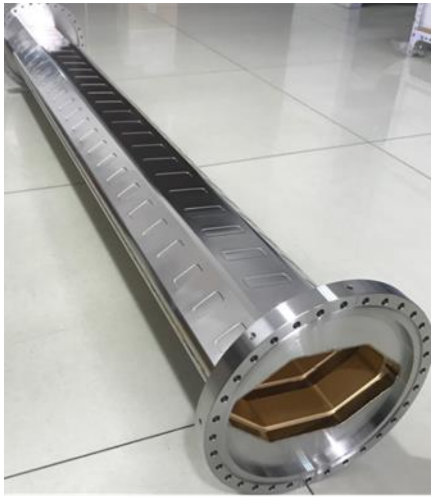
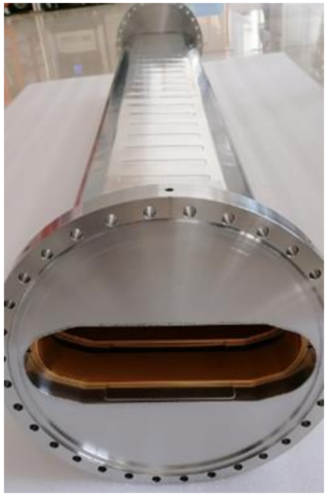
- Ti/Cu/Ti/Au coating process was proposed to reduce the desorption yield and the impedance, magnetron sputtering coating machine has been built to mass-produce

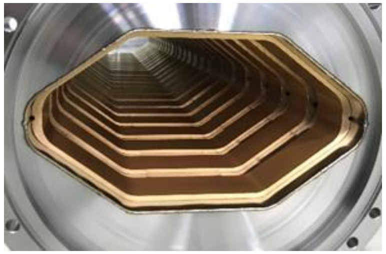


Desorption yield decreased significantly after Au-coated

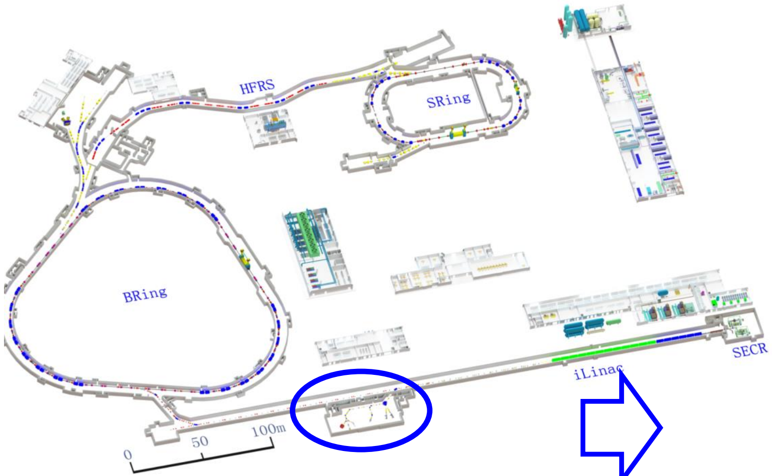
- A serial of full size chambers have been fabricated and key technology has been verified after several rounds of baking , the mechanical and vacuum performance test



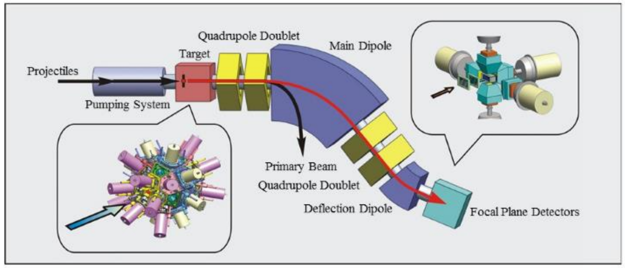
Experimental terminals & stations

1. Low energy nuclear structure terminal

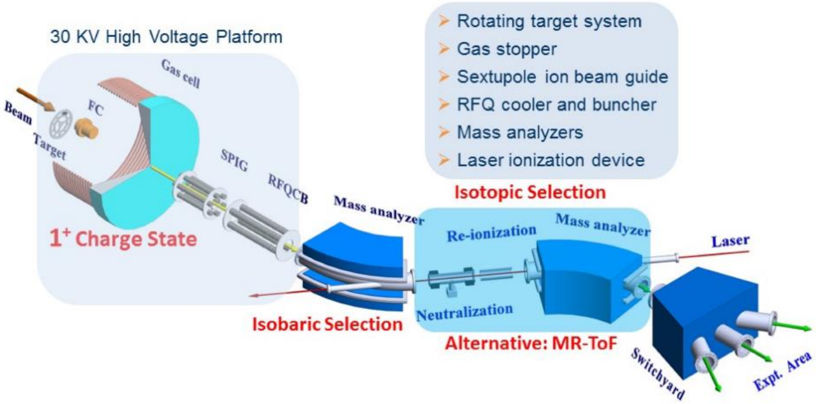


Very high intense beam from iLinac

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



The gas-filled recoil separator



Multi-nucleon transfer reaction separator

New gas-filled recoil separator, SHANS2

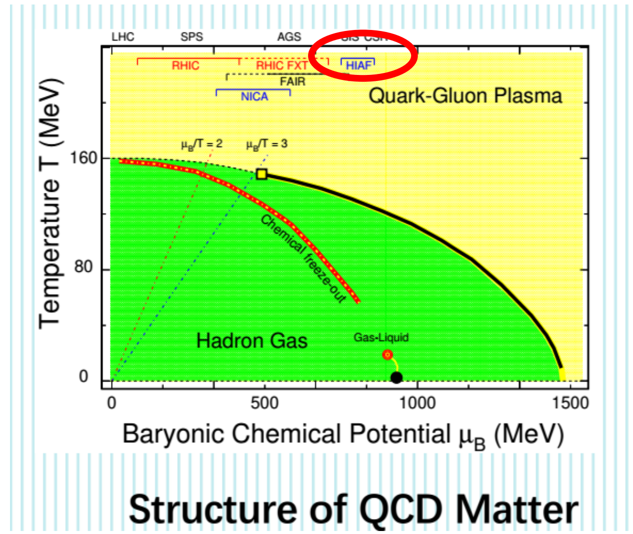
- **Synthesize new elements and isotopes**
- **Study nuclear decay properties**
- **Measure nuclear masses and lifetimes**
- **Determine nuclear charge radii and moments**

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

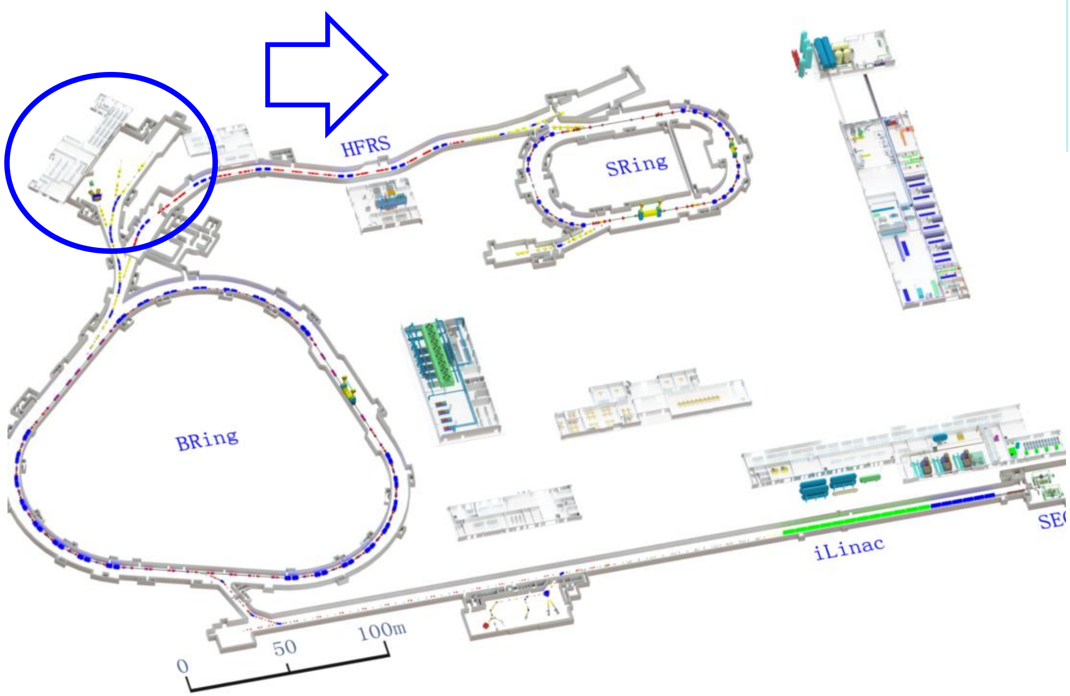
2. High-energy experimental station

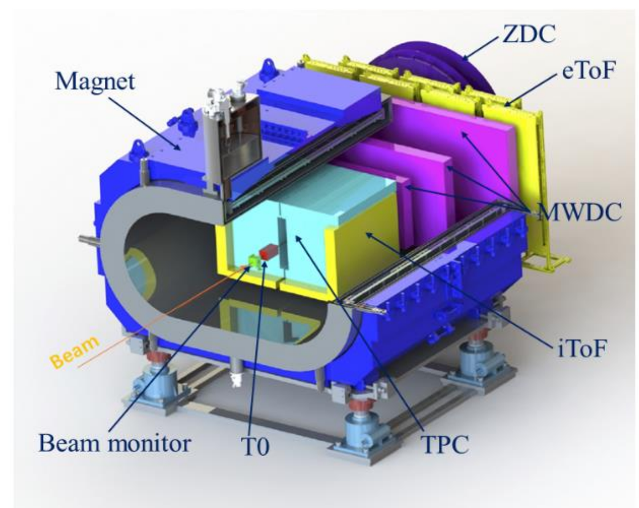
Ion species	Energy (GeV/u)	Intensity (ppp)
p	9.3	2.0×10^{12}
$^{12}C^{6+}$	4.2	6.0×10^{11}
$^{78}Kr^{19+}$	1.7	3.0×10^{11}
$^{209}Bi^{31+}$	0.85	1.2×10^{11}
$^{238}U^{35+}$	0.835	1.0×10^{11}

- Hyper nuclear physics
- **Phase diagram of strongly interacting matter**

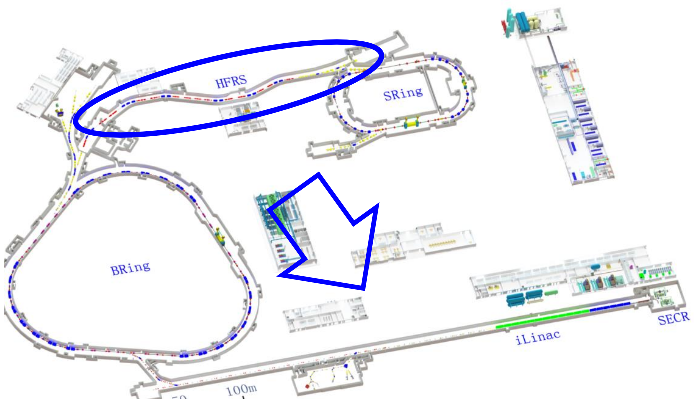


- **Several GeV/u, high quality slow extraction**

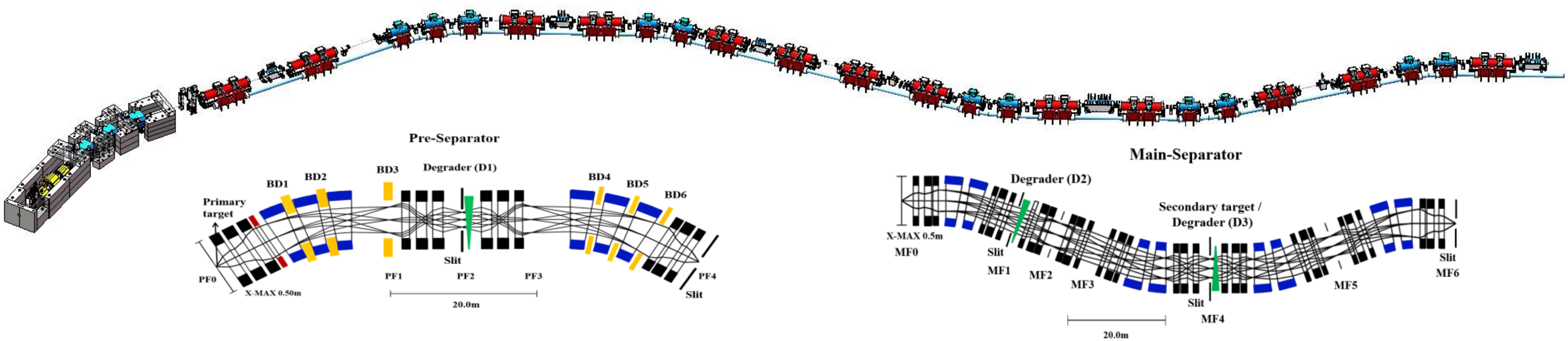




3. High energy fragment separator (HFRS)



Rigidity /Tm	Spot size at target/mm	Angular acceptance/ mrad	Momentum acceptance	First order Momentum resolution
25	x=±1; y=±2	x'=±30; y'=±15	±2.0%	1100 (emittance=30 π·mm·mrad and x=±1mm)



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 suppression power and excellent separation power**
- **Versatile spectrometer, dispersive or achromatic mode ion-optical settings**

3. High energy fragment separator (HFRS)

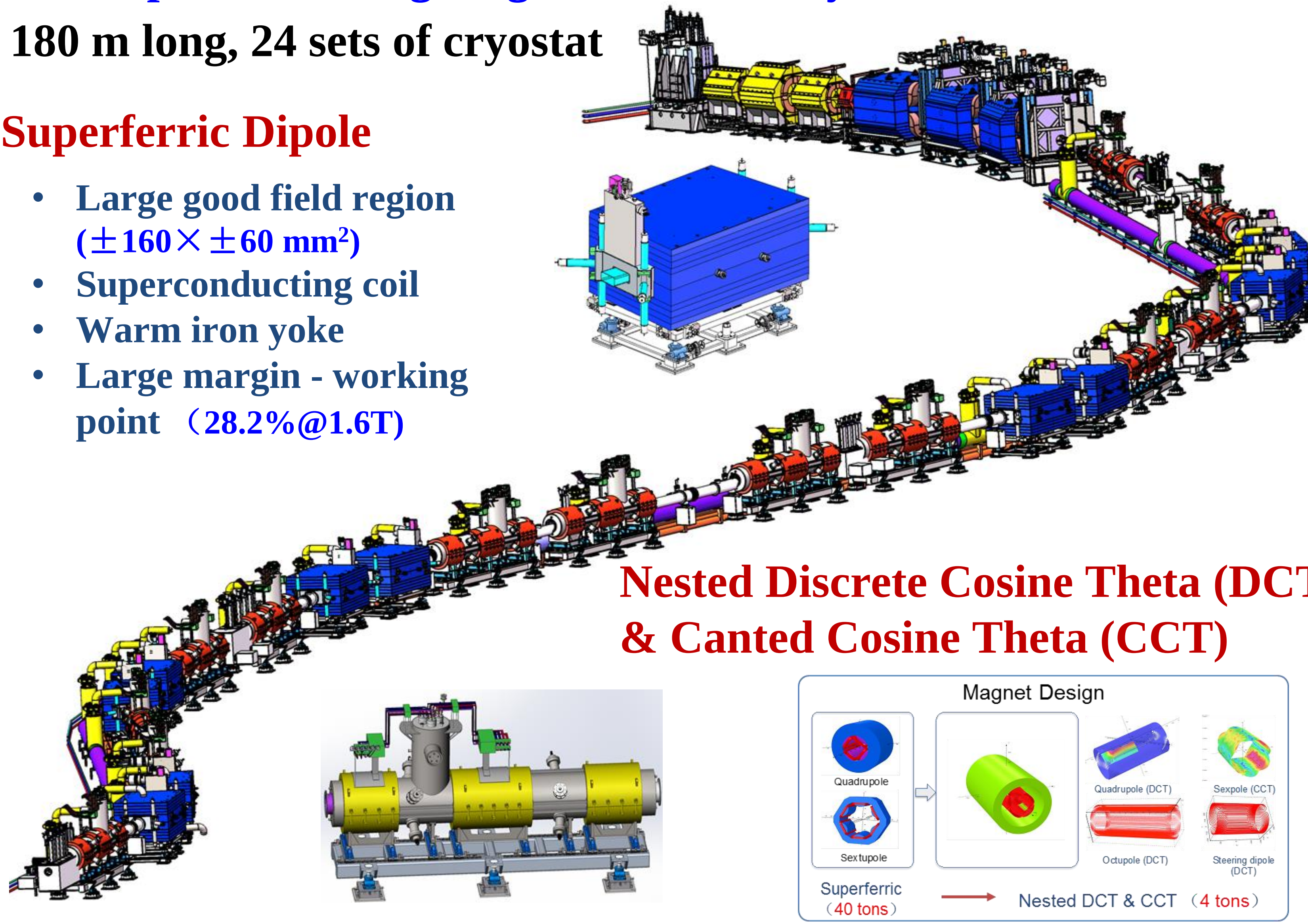
➢ Full superconducting magnet beam line system

180 m long, 24 sets of cryostat

Superferric Dipole

- Large good field region ($\pm160\times\pm60$ mm^2)
- Superconducting coil
- Warm iron yoke
- Large margin - working point （28.2%@1.6T)

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

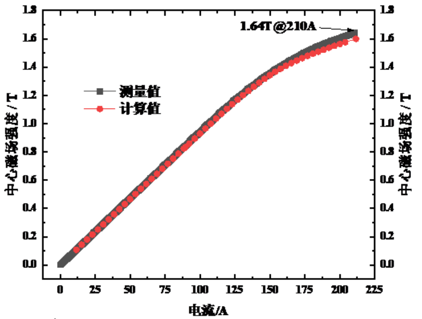


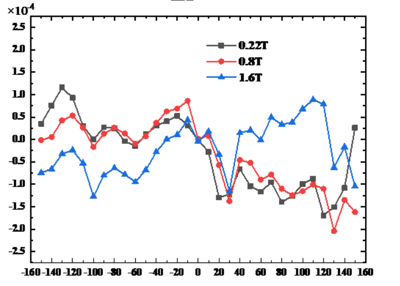
3. High energy fragment separator (HFRS)

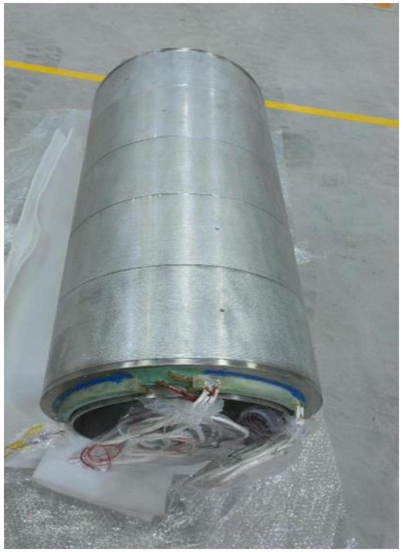
Design parameters of HFRS dipole

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

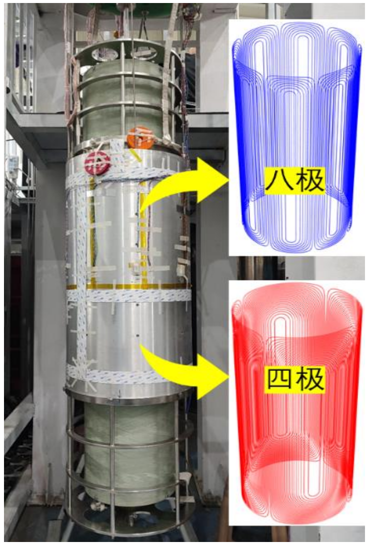
Superferric Dipole







L800-1



L800-2

L1200

4. Multi-function storage ring

Key devices

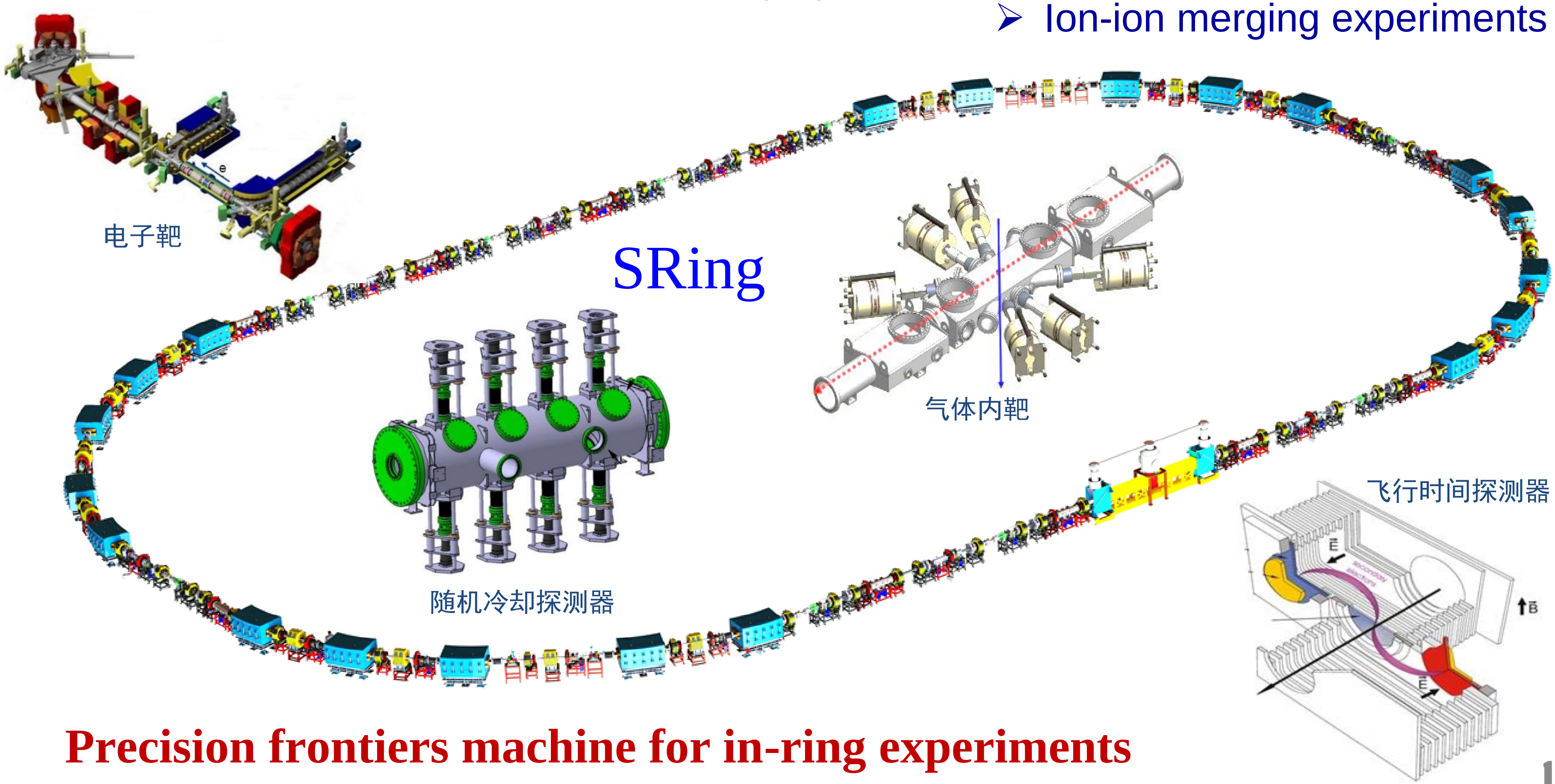
- Electron cooling
- Stochastic cooling
- Two TOF detectors
- Electron target

Operation modes

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

Experiment programs

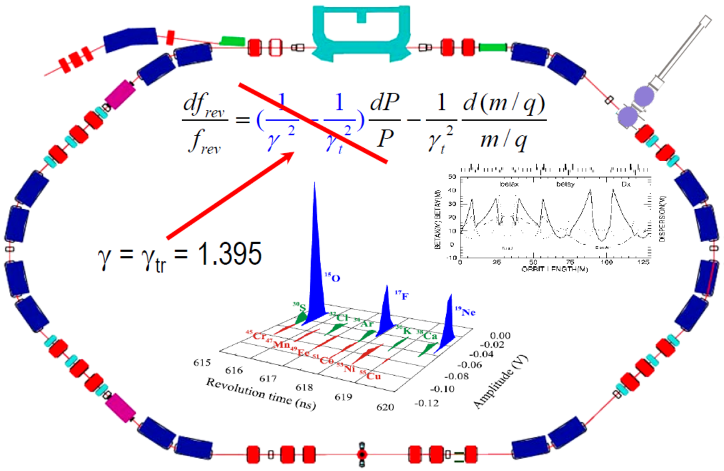
- Gas-jet target experiments
- DR experiments
- IMS & SMS
- Laser cooling
- Ion-ion merging experiments



Precision frontiers machine for in-ring experiments

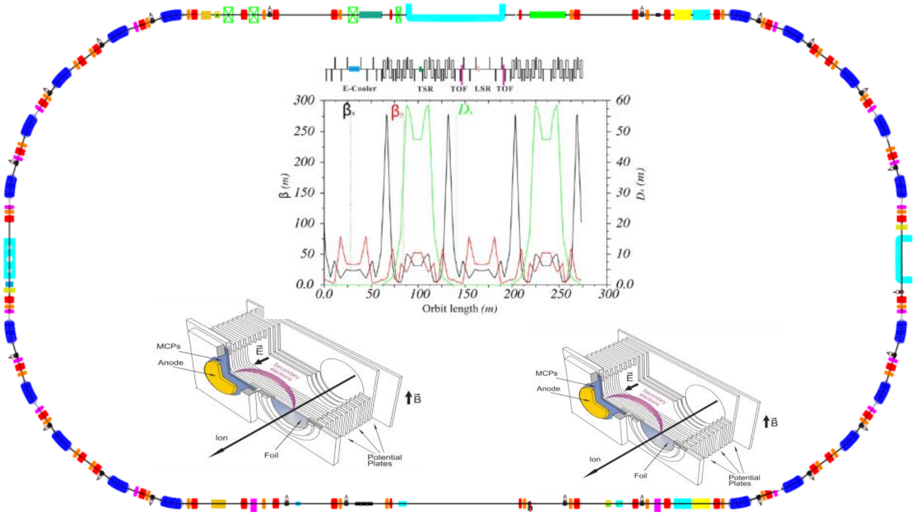
4. Multi-function storage ring

Isochronous mode with two TOF



$$\frac{df_{rev}}{f_{rev}} = \left(\frac{1}{\gamma^2} - \frac{1}{\gamma_t^2}\right)\frac{dP}{P} - \frac{1}{\gamma_t^2}\frac{d(m/q)}{m/q}$$

HIRFL-CSRe



HIAF-SRing

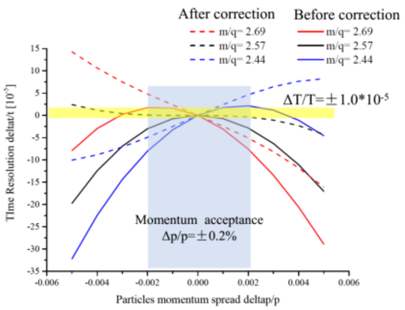
43 masses are measured

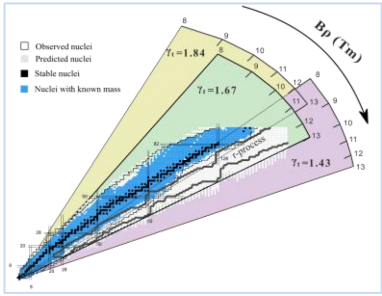
Measured for the first time: 16

Precision improved: 27

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

Demonstrated the two TOF mode first time in the world



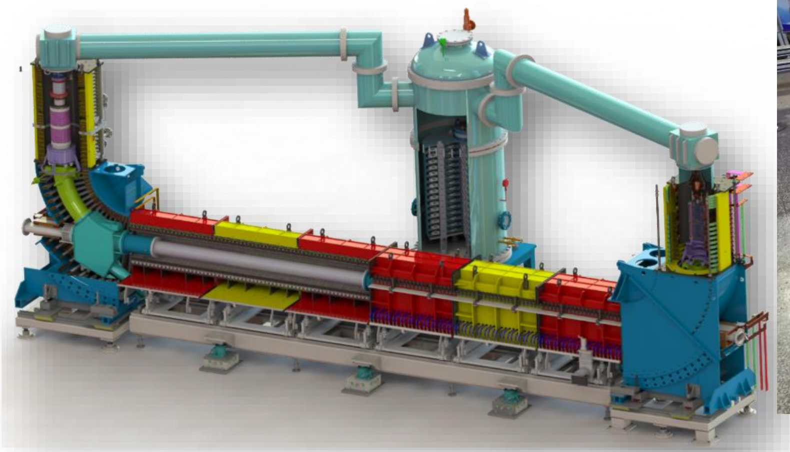


$\Delta M/M \sim 10^{-7}$-10^{-8}

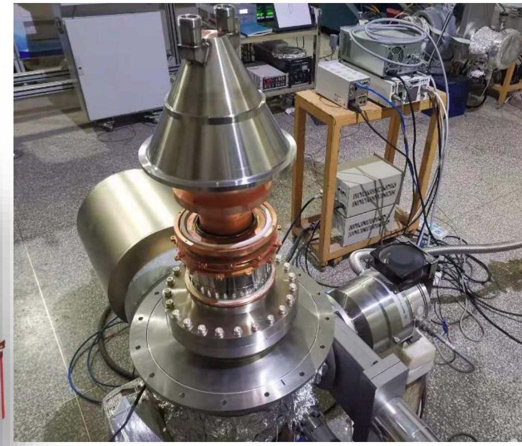
The highest precision of isochronous mass measurement

4. Multi-function storage ring

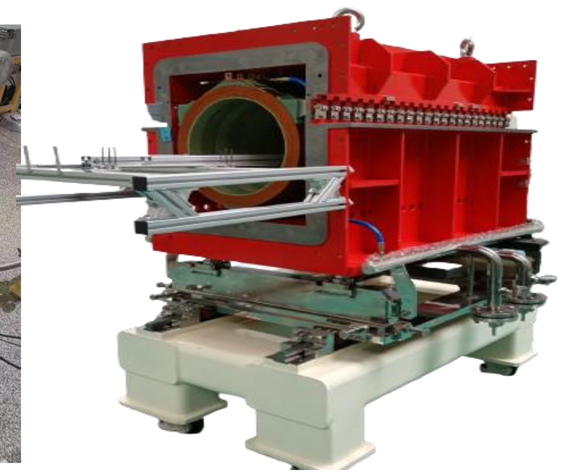
■ Electron cooler in SRing



450 keV DC magnetized electron cooler



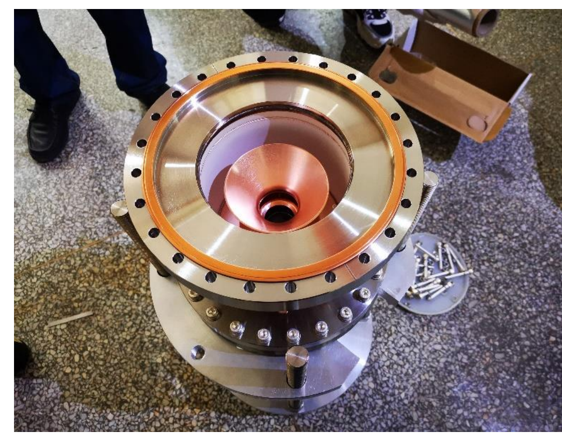
Collector



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

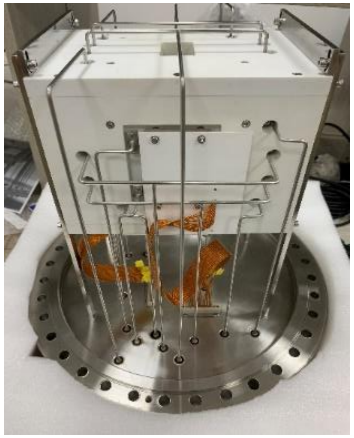
- **Most of the hardware are in mass production**

Dipole magnet

Quadrupole magnet

Primary target

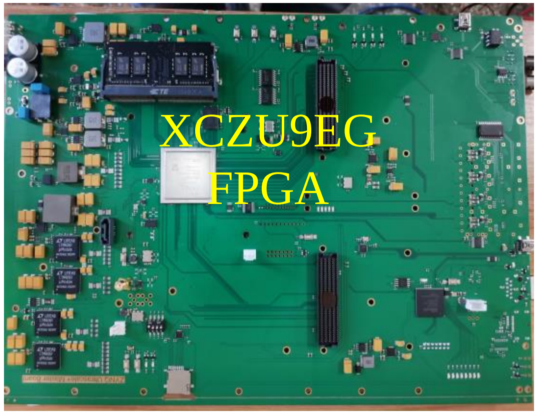
Collimator

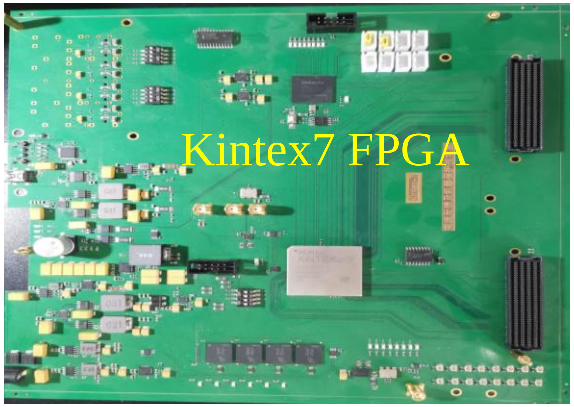


Beam instruments

Hardware fabrication

- **Most of the hardware are in mass production**





Civil construction

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 the summer of 2023.**
- **The early completion of project is expected at end 2025**

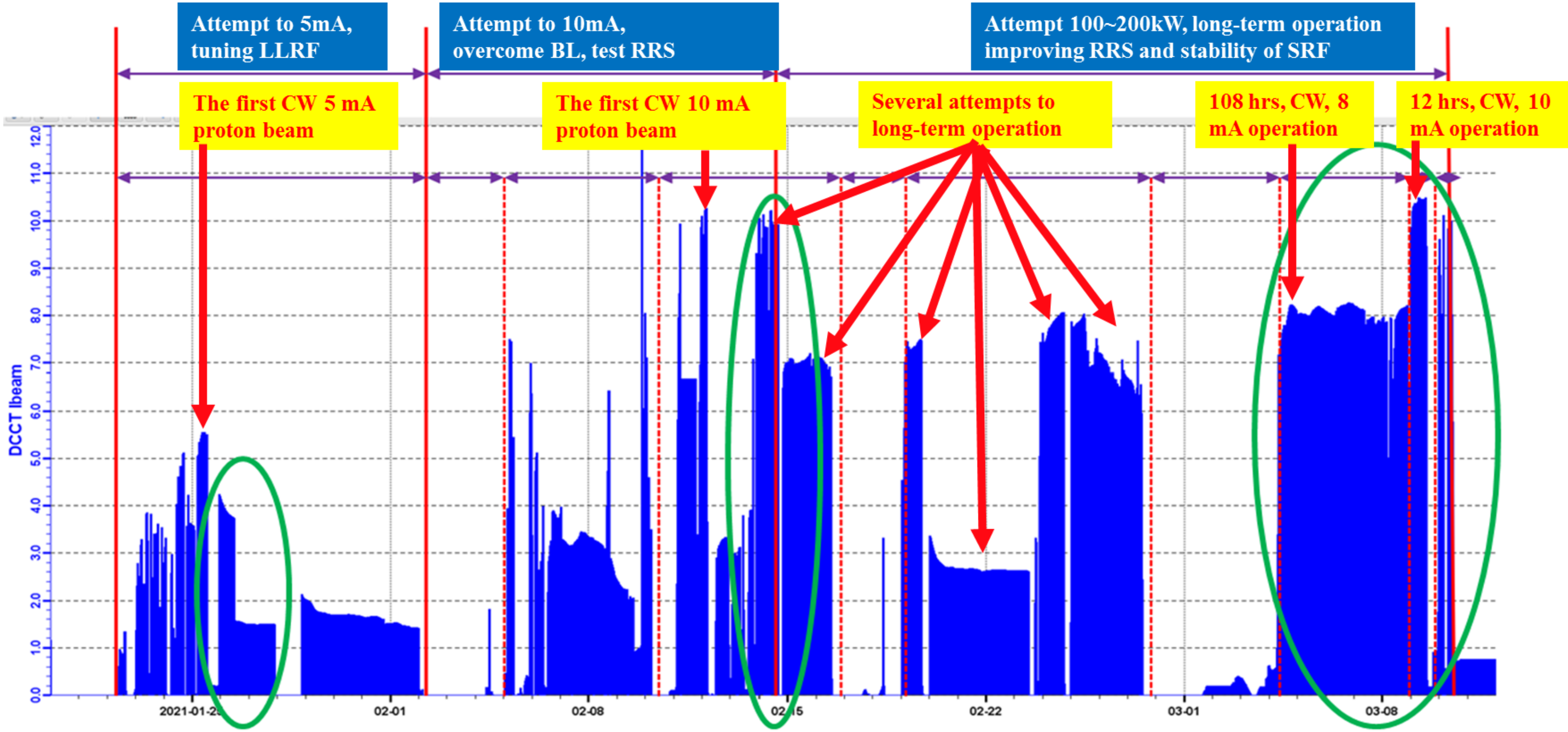
Present status and summary

High-Intensity Heavy Ion Accelerator Facility-HIAF

Thanks for your attention!

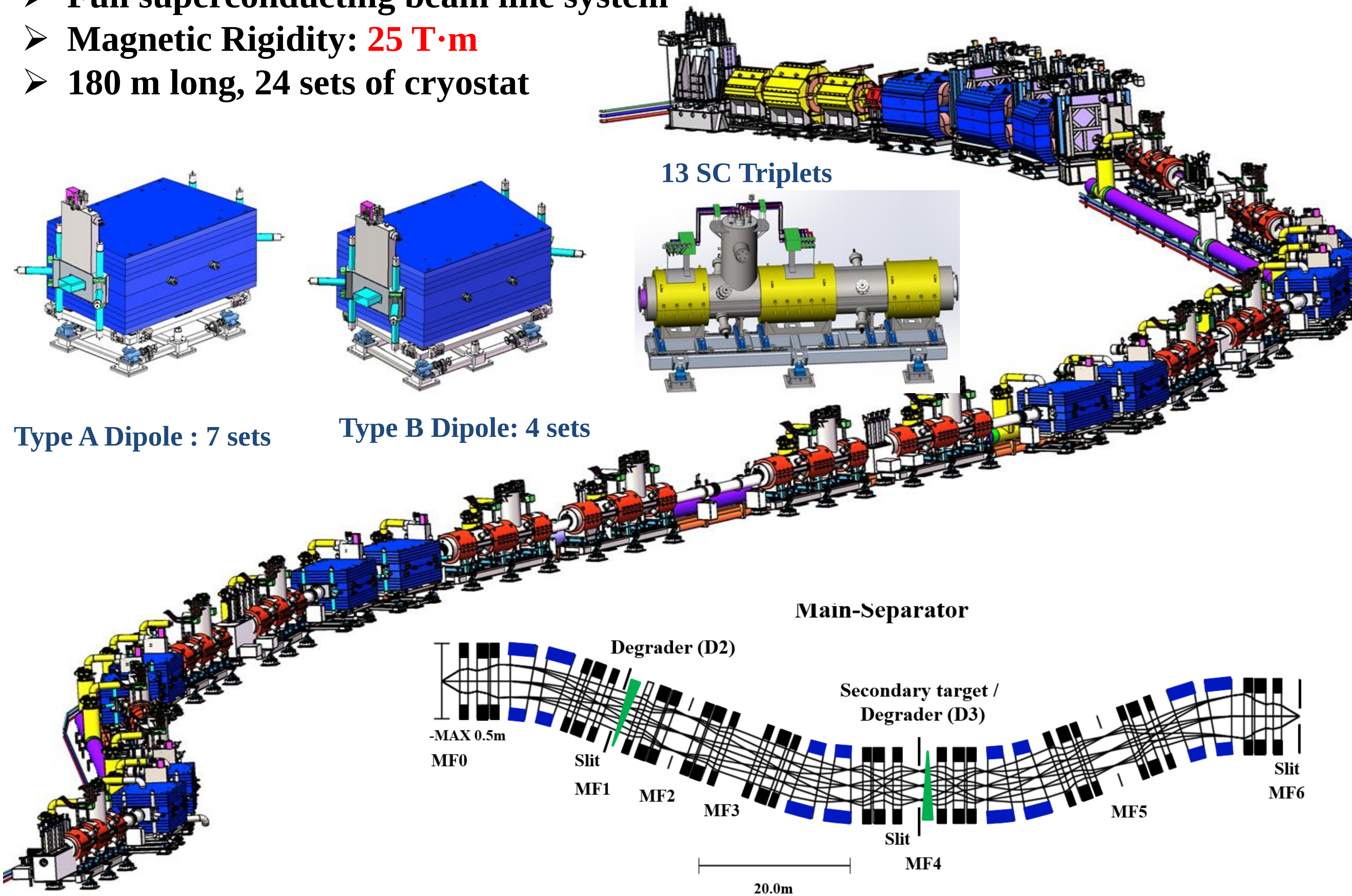
High current superconducting ion linac

- **Operation from Jan. 20 to Mar. 10, 2021**



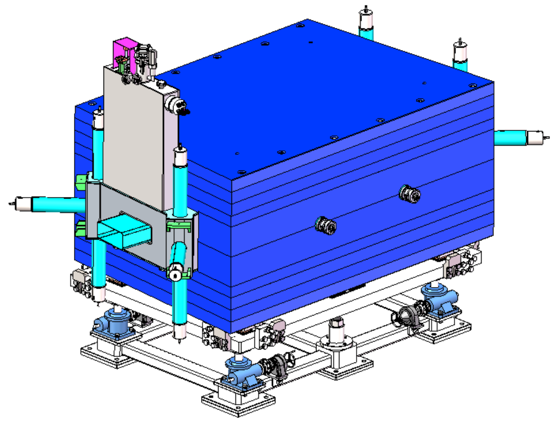
Superconducting magnets for HFRS

- Full superconducting beam line system
- Magnetic Rigidity: 25 T·m
- 180 m long, 24 sets of cryostat



High energy fragment separator (HFRS)

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



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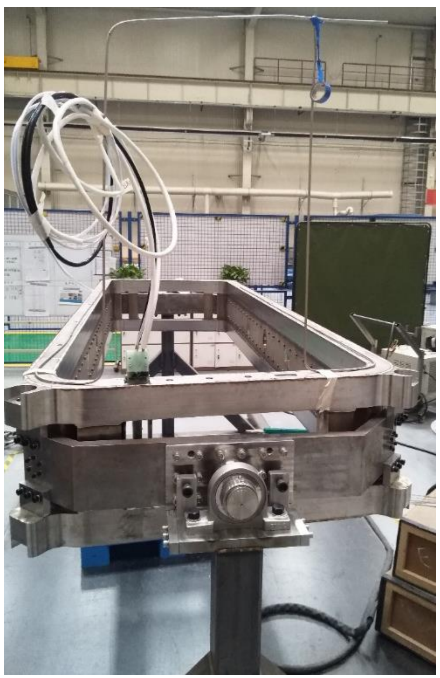
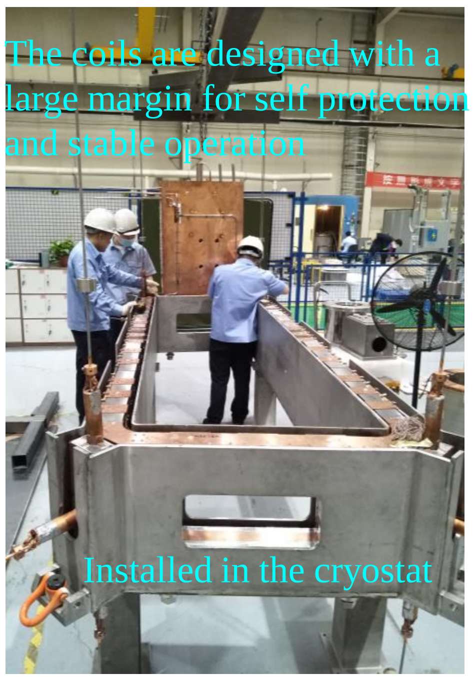
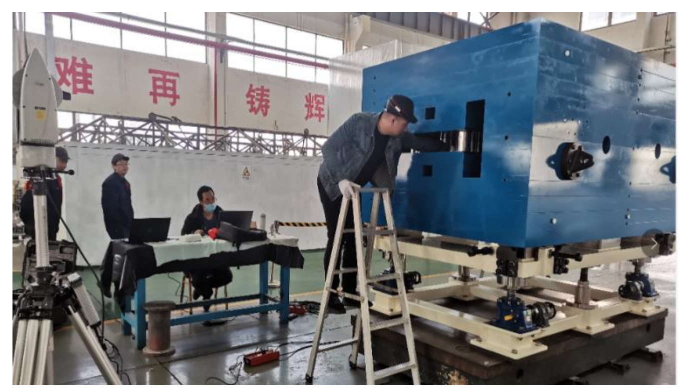




The final assembly of the cryostat is to be completed



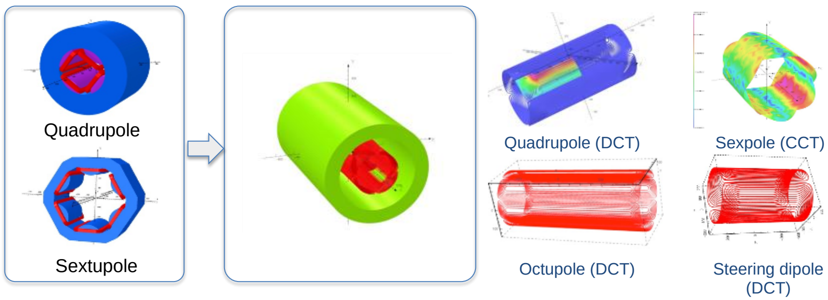
Finished iron yoke

Superconducting magnets for HFRS

HIAF

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

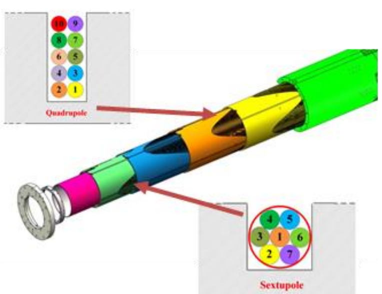
Magnet Design

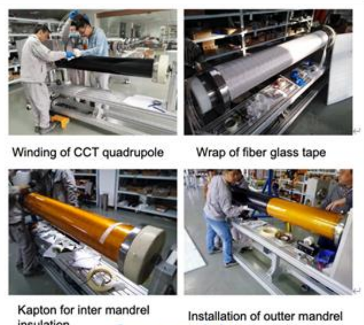


Superferric （40 tons） → Nested DCT & CCT （4 tons）

- DCT quadrupole: shorter ends and higher efficiency
- CCT sextupole: easier fabrication and winding
- Warm iron: field shielding, good field linearity and smaller cold mass
- Nested design reduce the beam line length

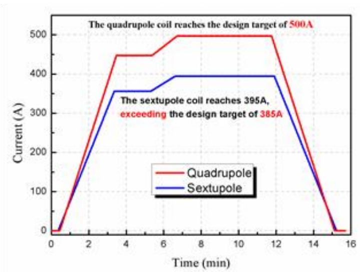
Half-aperture CCT Prototype（Quad + Sext）





Assembly

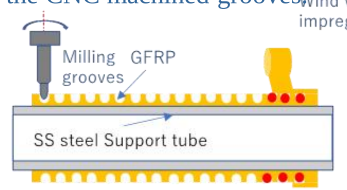
Winding Process

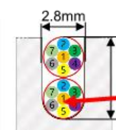


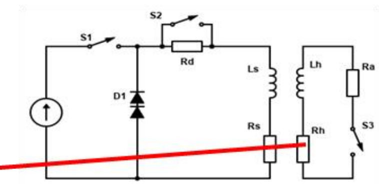
Energized to design current

Full-scale Prototype（Oct + Quad）

The rope cables with 6 insulated NbTi strands and 1 copper wire are embedded into the CNC machined grooves.



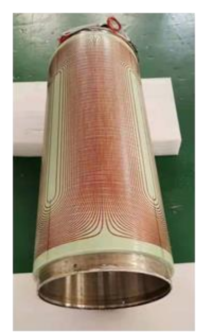




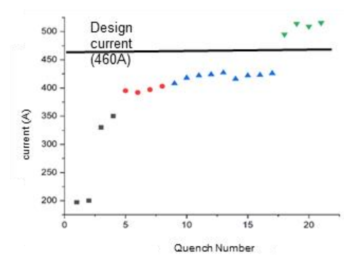
Non-linear quench back protection

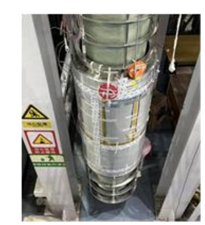
Center copper heater for quench protection

Octupole



Quadrupole



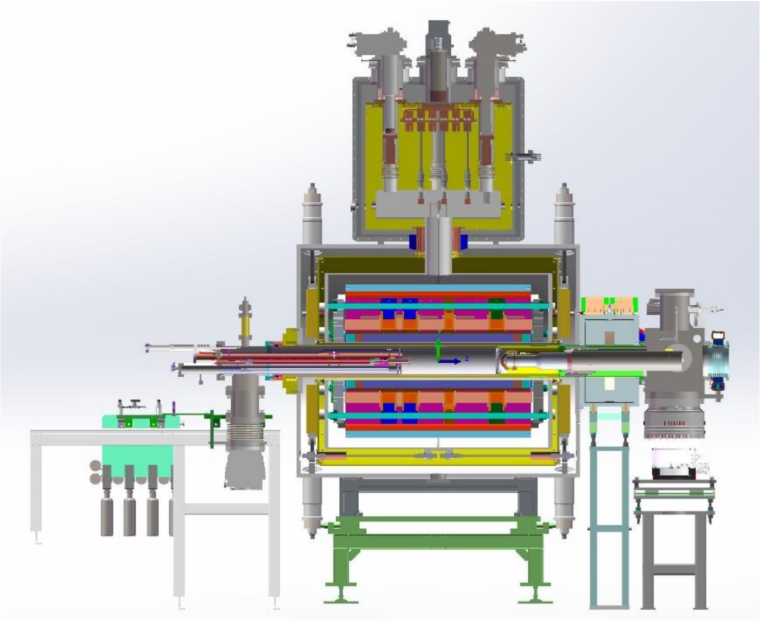


Trained to 112% of nominal current

45 GHz superconducting ECR ion source

Main Challenges in FECR ion source

- Reliable SC-magnet for 45 GHz plasma confinement
- Effective coupling to the plasma of 20 kW/45 GHz microwave power
- 20 kW microwave heated plasma operation reliability and stability: Plasma chamber and dynamic stability
- Strong bremsstrahlung radiation problems
- Intense high charge state ion beam (20-40 emA) extraction, transport and beam quality control
- Intense refractory ion beam production: U, W, Ta, Mo, Ti, Ni…

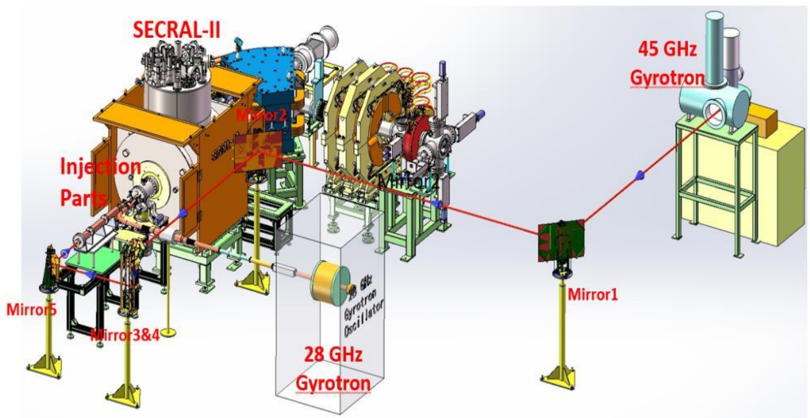


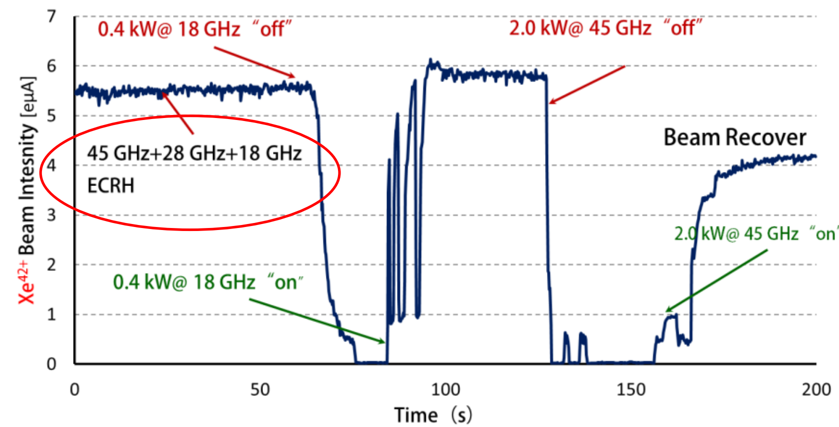
Specs.	Unit	3rd G ECRIS	FECR
frequency	GHz	24-28	45
Operational RF Power	kW	4~10	20
B_{ECR}	T	0.86~1.0	1.6
B_{rad}	T	1.8~2.2	≥3.2
B_{inj}	T	3.4~4.0	≥6.4
B_{min}	T	0.5~0.7	0.5~1.1
B_{ext}	T	1.8~2.2	≥3.4
Plasma Chamber ID	mm	100~150	≥140
Mirror Length	mm	420~500	500

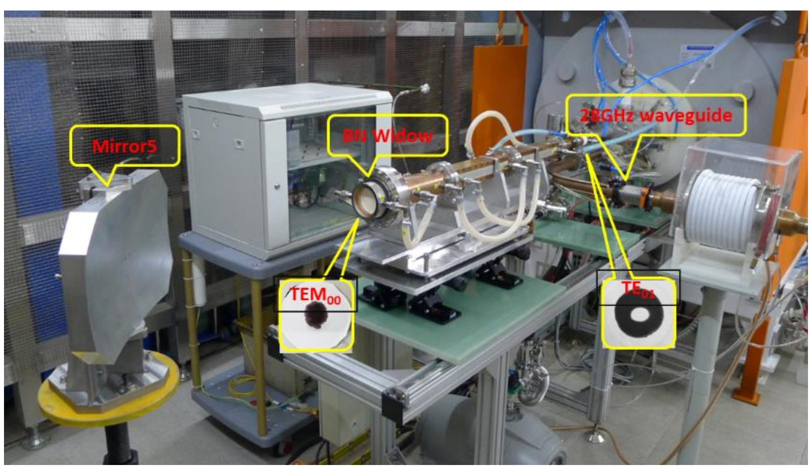
45 GHz superconducting ECR ion source

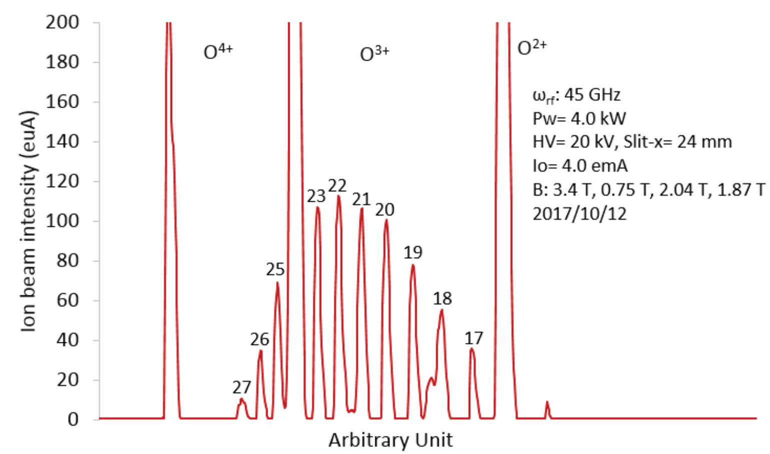
■ 45 GHz microwave coupling

- ➢ 45 GHz/20 kW microwave transmission system based on Quasi-optical design
- ➢ First 45 GHz ECR plasma with SECRAL-II ion source
- ➢ Efficient transmission and coupling demonstrated







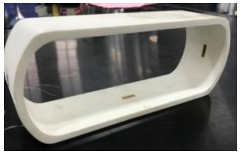


Xe beam with 45 GHz

The ceramic-lined thin-wall vacuum chamber

- **Cerium-stabilized zirconia ceramics with better mechanical properties are developed, based on mechanical properties test and long-term baking stability test**

Ceramic-lined (Al_2O_3)

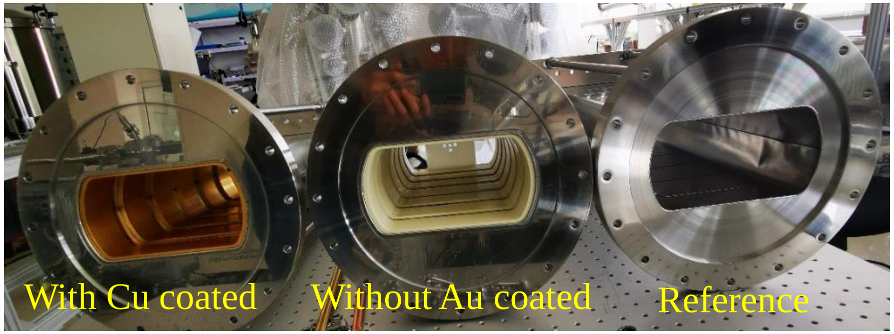


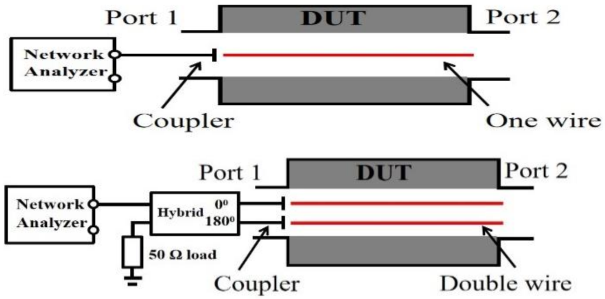
Thickness of 5mm

Ceramic-lined (Zirconia)

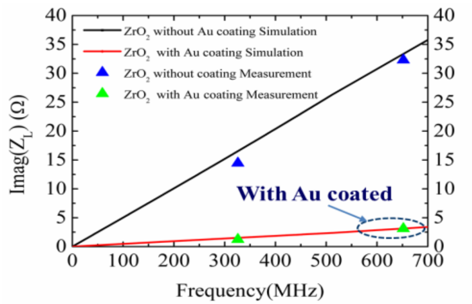
Thickness of 3mm

- **Based on the test of desorption yields and impedance, a scheme of Ti/Cu/Ti/Au coating process on the surface of the ceramic ring was proposed to reduce the desorption yield and the impedance of the vacuum chamber.**

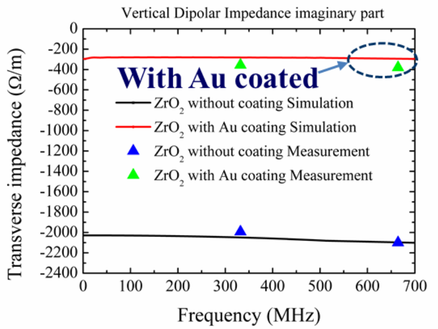


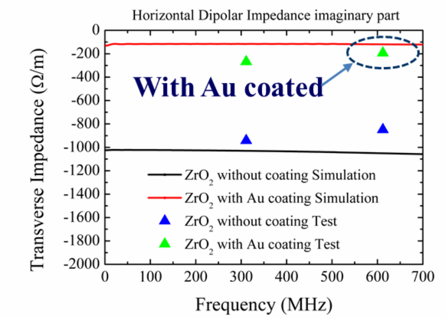


"λ/2" resonant method setup for impedance test



Longitudinal impedance reduced by 90% with Au coated





Transverse impedance reduced by 85% with Au coated