12TH INTERNATIONAL ORGANIZTION OF CHINESE PHYSICISTS AND ASTRONOMERS ACCELERATOR SCHOOL
OCPA-2025

High-intensity High-Power Ion Accelerator Facility and Technical Challenge

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Outline

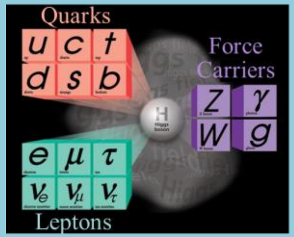
High-Intensity High-Power (HIHP) Ion Accelerator Facility

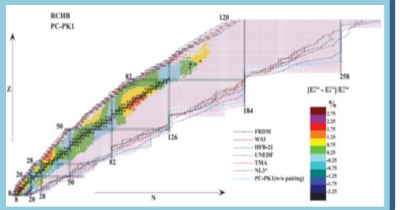
1. Challenge and key technologies of State-of-the-art
2. World-wide HIHP ion accelerators
3. HIAF&CiADS and key technology R&D
4. Summary

Applications of high-intensity high-power ion beams

Particle physics
Nuclear physics
HED physics
(Intens.& lumin. frontier)

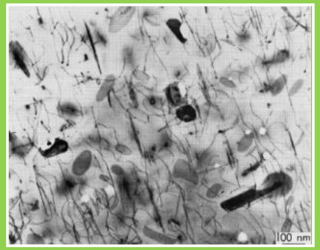
- Neutrino factory
- Muon source
- Collider
- Rare isotope facility
- Secondary beam
- .....

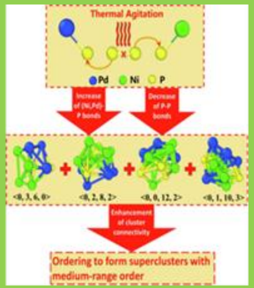


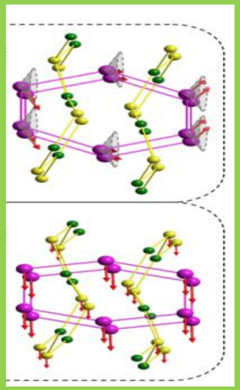


Material science
Bioscience and medicine
Condensed matter physics

- Neutron beam、neutron source
- Muon beam and muon source
- Detection and irradiation
- Isotope production
- Particle and radiation imaging
- .....

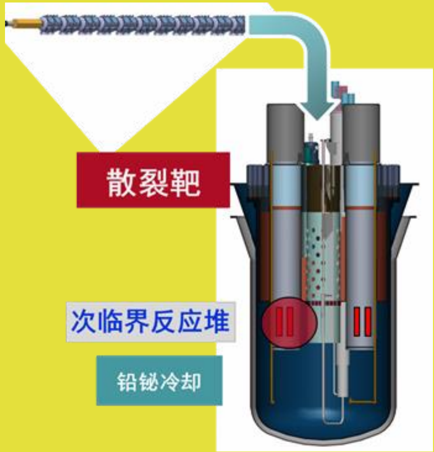






Advanced nuclear power

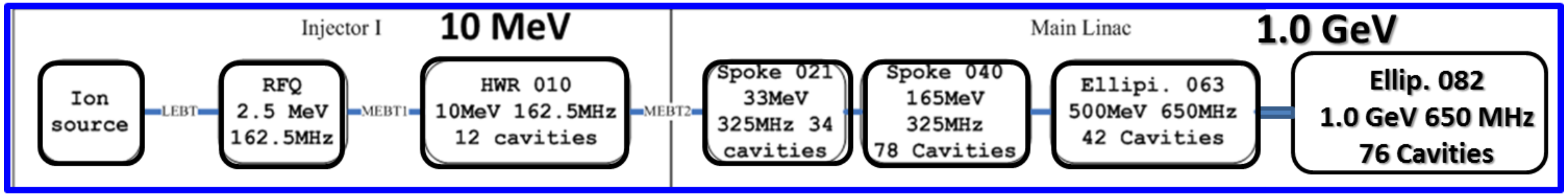
- ADS
- Advanced nuclear-fission power
- Heavy ion driven fusion
- Neutral beam for MCF
- Fusion material irradiation
- .....



Technical routes of high-intensity and high-power ion accelerators

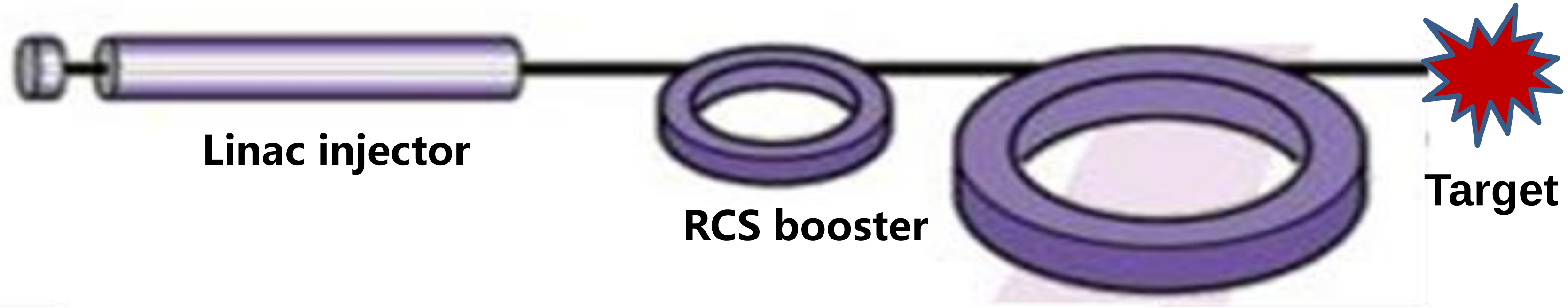
- **High-intensity and high-power (Frontier of intensity and luminosity)**

  -- SC ion linac (1-10 MW,< 3 GeV,>5 mA)



- **High-energy and high-power (Frontier of high energy)**

  -- RCS synchrotrons (1-3 MW, >3 GeV/A)



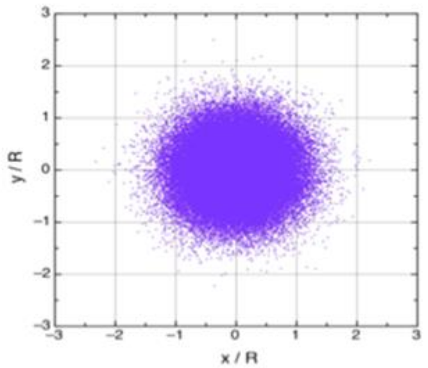
Several synchrotrons and storage rings for acceleration and accumulation, compression, and finally to the target

- **High-intensity and high-power cyclotrons** (1-3 MW, < 1 GeV/A, <5 mA)

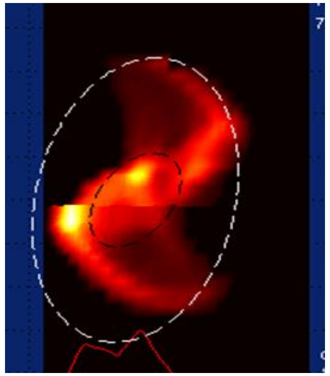
Key issues & challenges of beam dynamics and technologies

■ Key issues and challenges of beam dynamics

- Interactions between charged-particles;
- Interactions between ion beam and electric-magnetic elements
- Space-charge effect, instabilities, collective effect, wakefields …
- Extremely low beam-losses for HIHP ion beam, <1 W/m



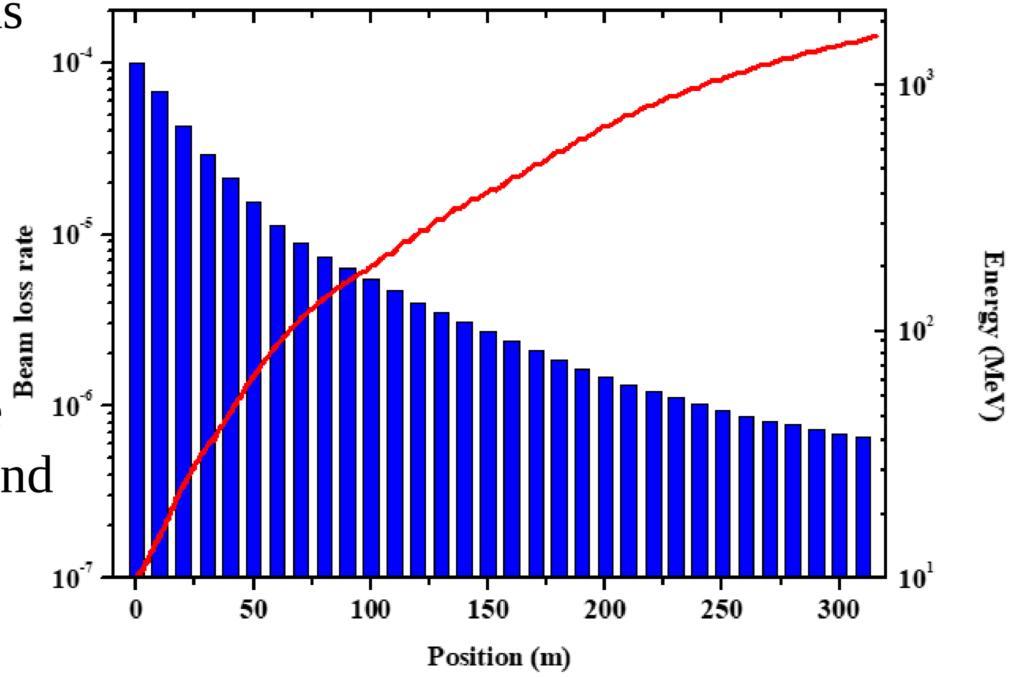
Beam halo



Beam distortion

■ Technical challenges

- A few accelerators coupled and connected together, or hundreds SRF cavities, stripping foil for H^- and heavy ions
- **Beam loss rate** 10^{-4}-10^{-6},
  CW: 10^{15}-10^{16} pps, pulsed: 10^{12}-10^{15} ppp
- Stabilization of RF frequency、phase and voltage amplitude (hundreds SRF cavities)
- Beam dynamics--LLRF control--beam loss detection--machine protection-- automatic recovery of beam trips – fast feedback and diagnostics （tens μs）, **for long-term operation**
- **Long-term stability and availability** with MW beam
- **AI&ML** …..



How to produce high-intensity ion beams --Ion source

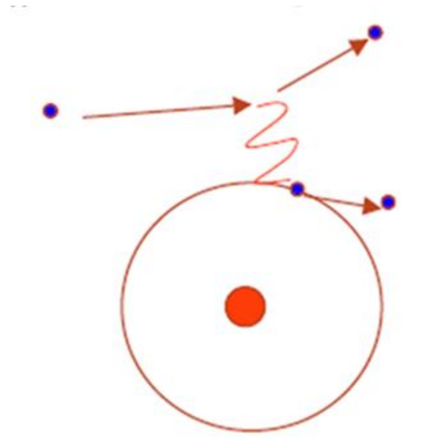
- **What is an ion source?**

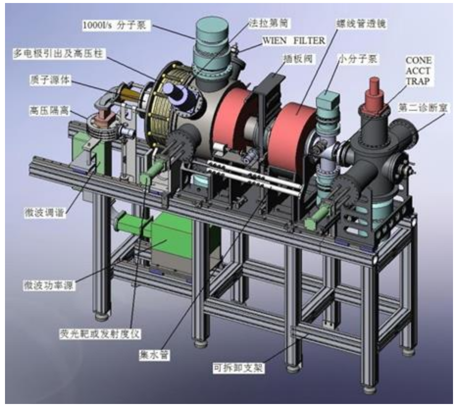
Ion source is a plasma device for producing ion beam. Ions can be produced by electron-impact ionization and the electrons are generated from plasma

- **What are the most important parameters for an ion-source user ?**

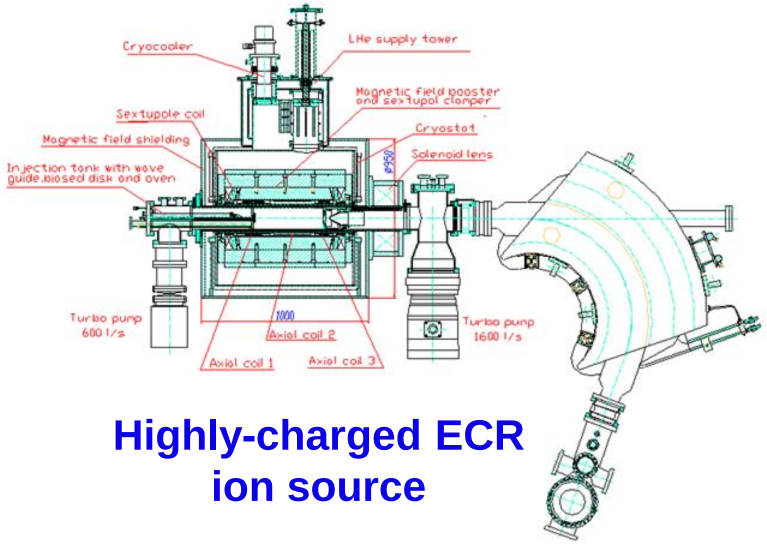
Beam intensity and beam emittance(beam brightness): related to ion source itself (plasma parameters), beam extraction system and LEBT.

- **Ion source system: ion source, extraction, beam transport and analyzing**, beam diagnostics, control, power supply, vacuum, …..





2.45 GHz microwave-driven ion source



Highly-charged ECR ion source

2.45 GHz microwave-driven ion source for single-charged ion beam

Chalk River

Taylor &Wills

Beginning of '90s

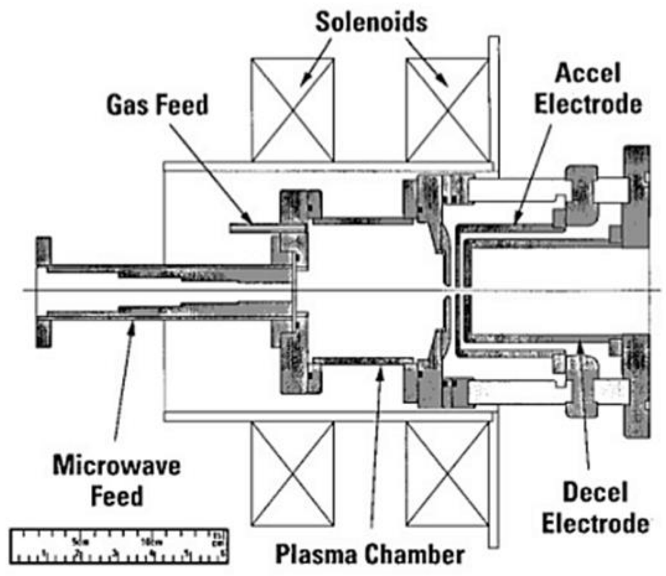
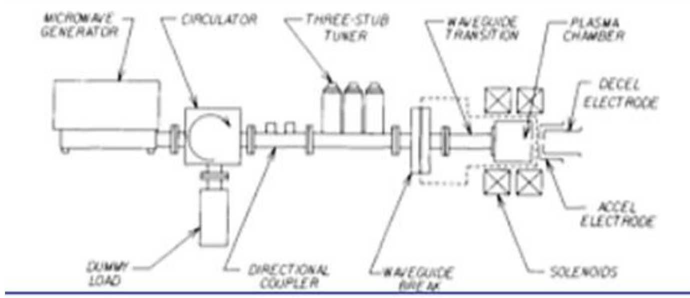


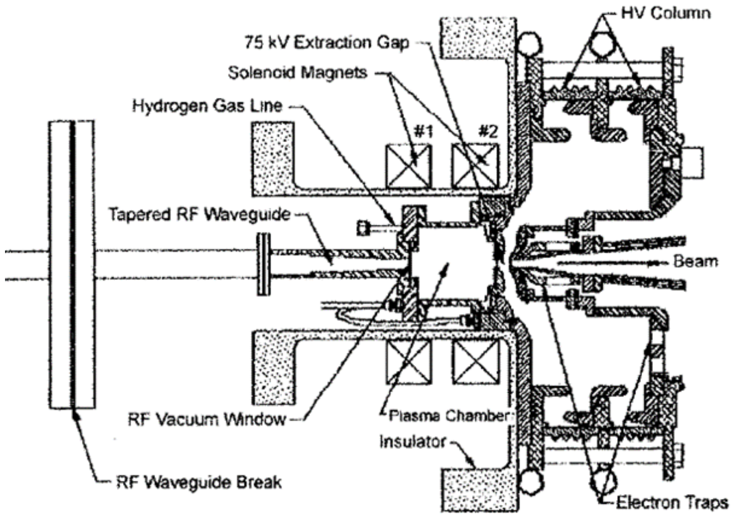
FIG. 1. Microwave-driven Chalk River proton source.



Breakthrough simple design

All successful sources are based on it

T. Taylor and J. Wills, Proc. Linac'92, Ottawa



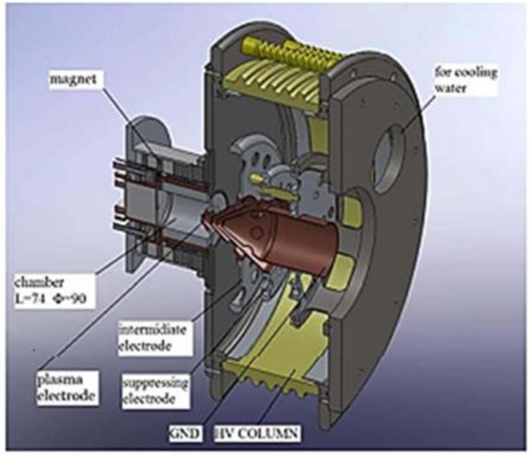
J. Sherman, et al., RSI, 69, 1003 (1998)

Table 1. Summary of the proton source operation.

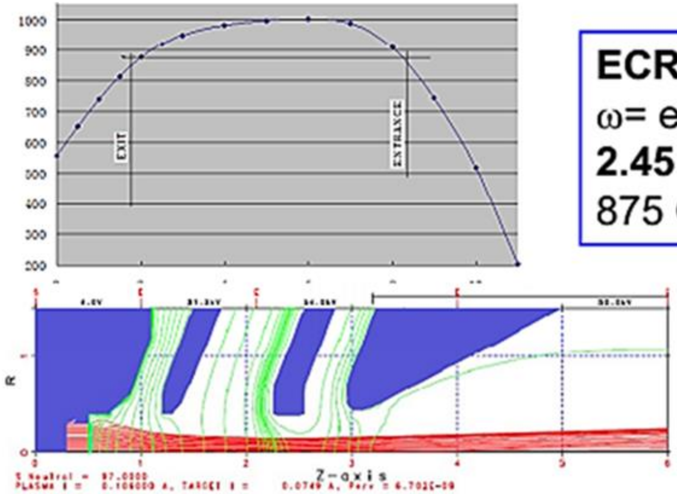
Ion Source Parameter	Value
H_2 gas flow, Q_{H2} (sccm)	4.1
Ion source pressure (mTorr)	2
Ion source gas efficiency (%)	24
Discharge power, 2.45 GHz (kW)	1.2
Ion source solenoid 1 (A)	87.2
Ion source solenoid 2 (A)	89.2
Axial magnetic field, calculated (G)	863
Beam energy (keV)	75
High voltage power supply current (mA)	165
Electron trap voltage (kV)	-1.95
DC1 current (mA)	154
Beam current density (mA/cm^2)	265
Beam power, cw mode (kW)	11.6
Proton current at DC1 (mA)	139
Duty factor (%)	100
DC2 current (mA)	120
Injector emittance, 1rms norm. (πmm-mrad)	0.18

IMP and PKU 2.45 GHz microwave-driven ion source

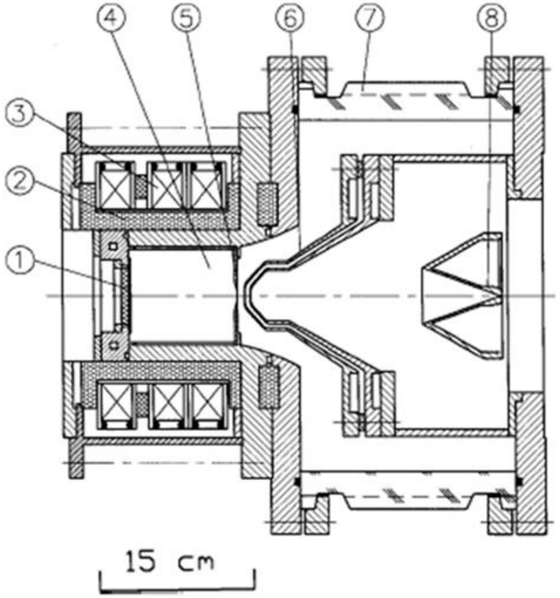
IMP China

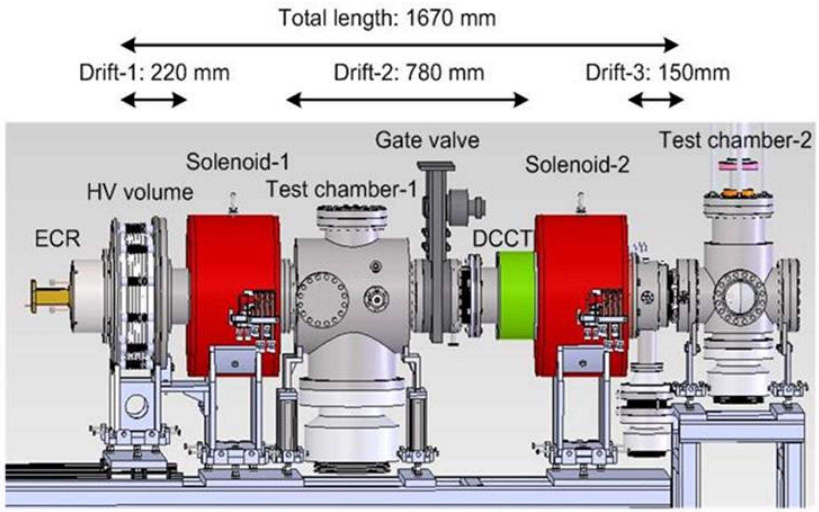


Proton source designed by IMP Lanzhou

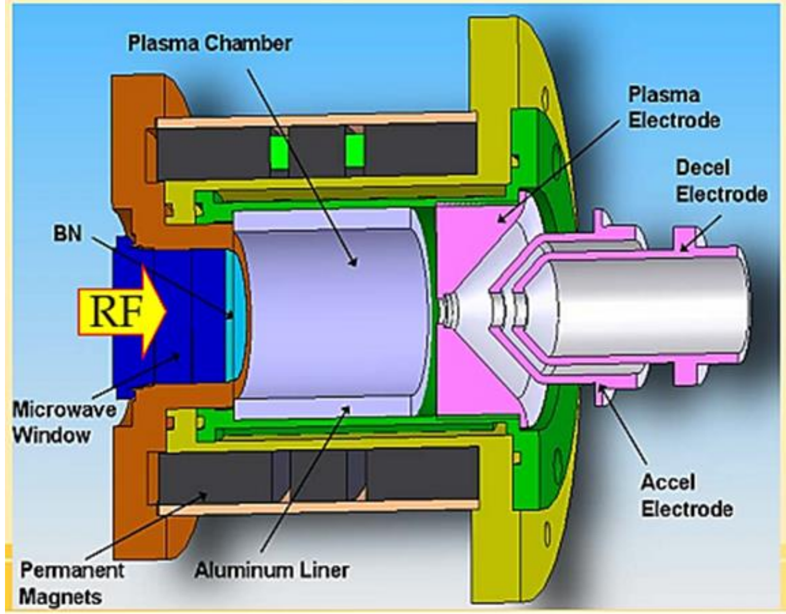


ECR Source
ω= e B / m
2.45 GHz ➔
875 Gauss



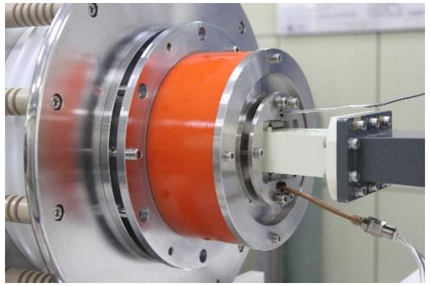


PKU China



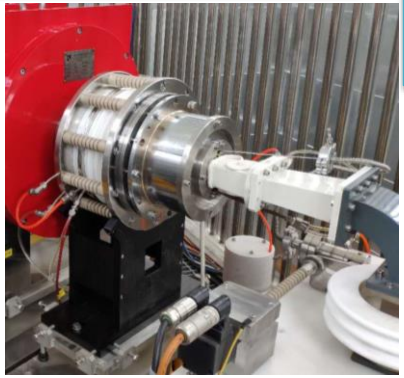
Development of IMP 2.45 GHz microwave-driven ion source

2017-2023



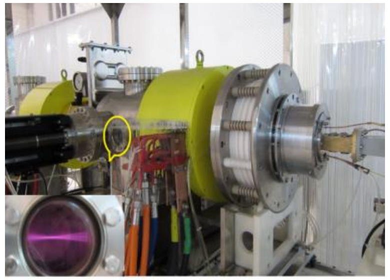
^{39}Ar Enrichment Neutron source

2016



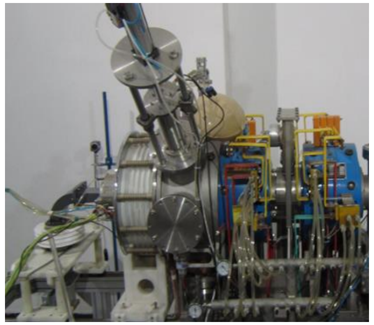
JUNA

2014



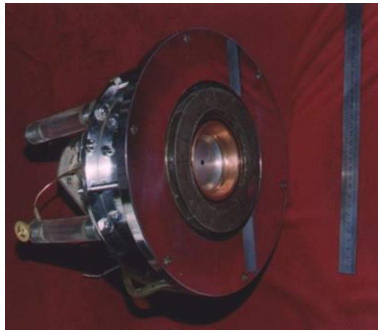
C-ADS

2011



Neutron Source

1999

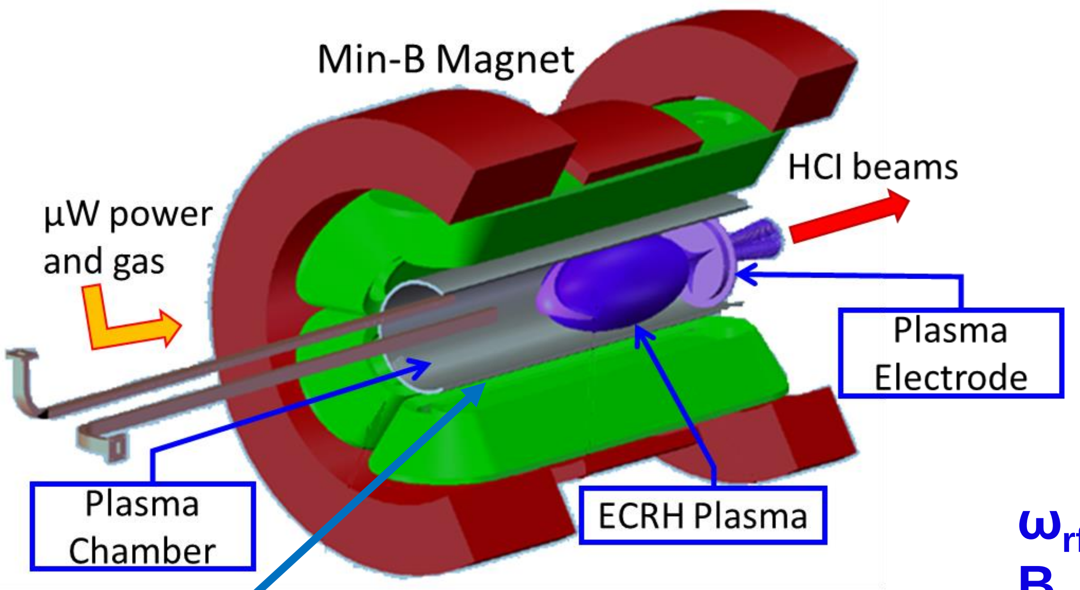


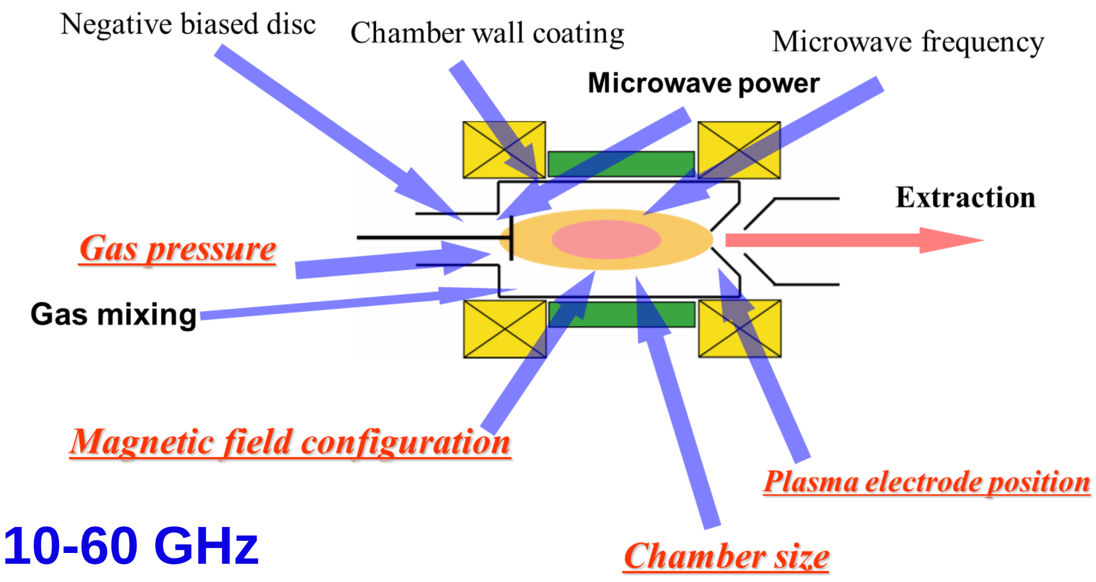
Neutron Source

H^+, H_2^+, H_3^+….
H^+ beam: 20-100 mA
Beam energy: a few tens keV
Emittance(rms): 0.1-0.2 πmmrad

ECR ion sources for highly-charged ion beam production

ECR: Electron Cyclotron Resonance

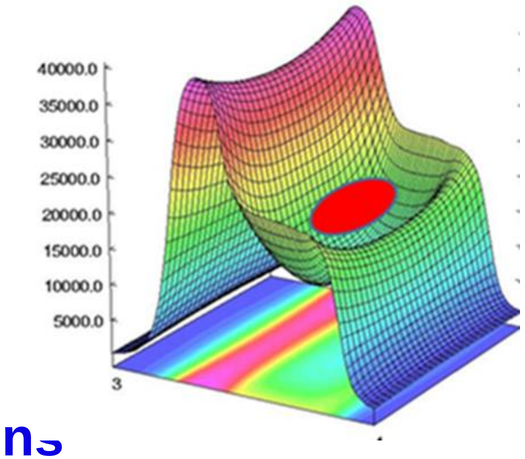




Multi-Mode Cavity ?

ω_{rf} = 10-60 GHz
B_{max} =1-16 T

$\omega_{rf}, P_{rf}, B, n_0 \Leftrightarrow n_e\, T_e\ \ \tau_e,\ n_i\, T_i\ \ \tau_i$

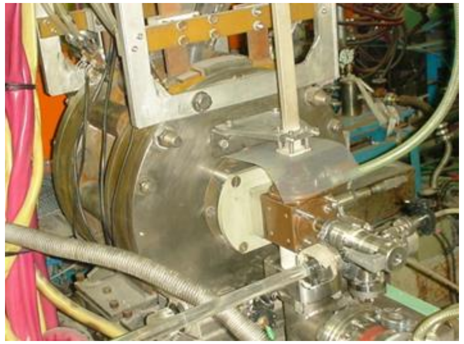


- **Confinement of high density highly-charged plasma**
  --- long-time confinement for electrons and ions ---Minimum B structure
- **Electron stepwise collisional ionization producing highly-charged ions**
  --- high density and hot elelctons with required energy distribution --- high power microwave ECR heating

Development of IMP highly-charged ECRIS

IMP ECRIS

1986-1995
(10GHz)



LECR1

LECR0

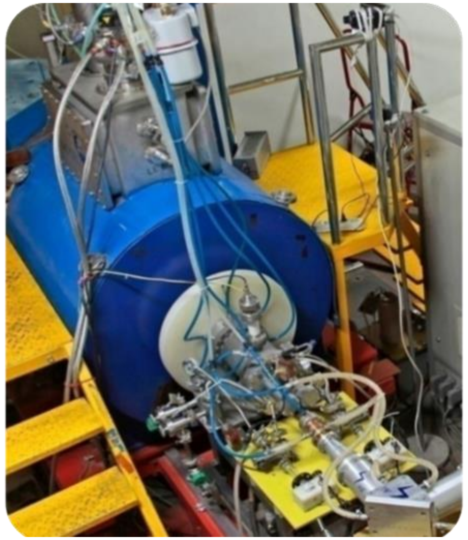
1996-2002- present
(14-18 GHz)

LECR3

LECR2

2000-2016-present
(24-28 GHz)

SECRAL II



SECRAL

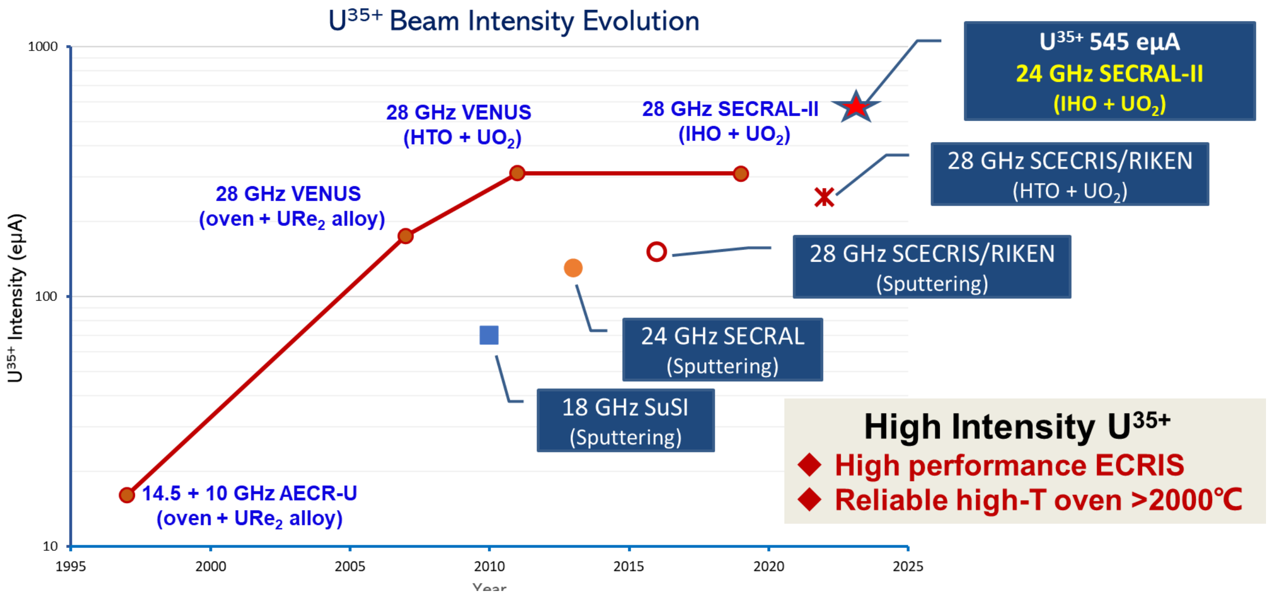
2015-2024-present
(45 GHz--)

FECR

The world leading >10 years

Record beam intensities produced by SECRAL&SECRAL-II

Ion species	Charge state	SECRAL& SECRAL-II 24~28 +18 GHz 6-10 kW [eμA]
^{40}Ar	12+	1420
	16+	620
	18+	15
^{78}Kr	18+	1030
	28+	145
^{129}Xe	26+	1100
	30+	365
	42+	16
^{209}Bi	31+	680
	41+	100
^{238}U	34+	620
	35+	545
	46+	61
	55+	13



SECRAL-II
24-28GHz

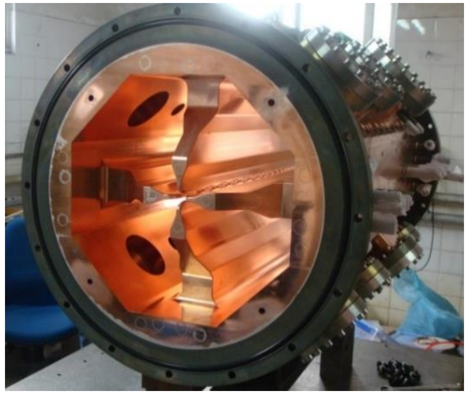
Acceleration of high-intensity low-energy ion beam by RFQ

RFQ is a typical low-energy accelerator for high intensity ion beam acceleration

Transversal match	Beam Focusing and shaping	Longitudinal bunching	Acceleration

Beam match、focusing、bunching and acceleration in the RFQ cavity

Four rods RFQ

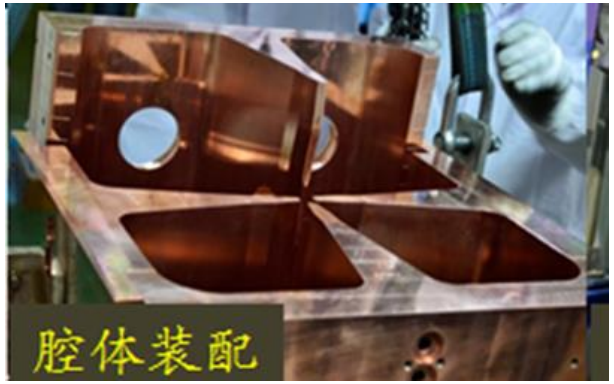


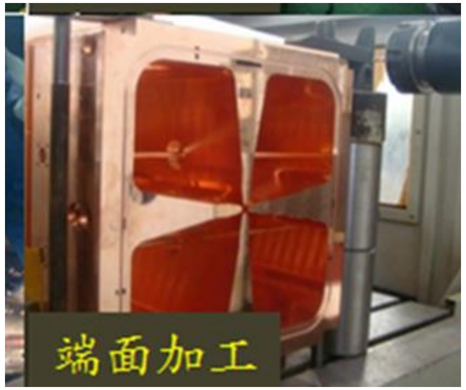
Four vane RFQ

Key issues

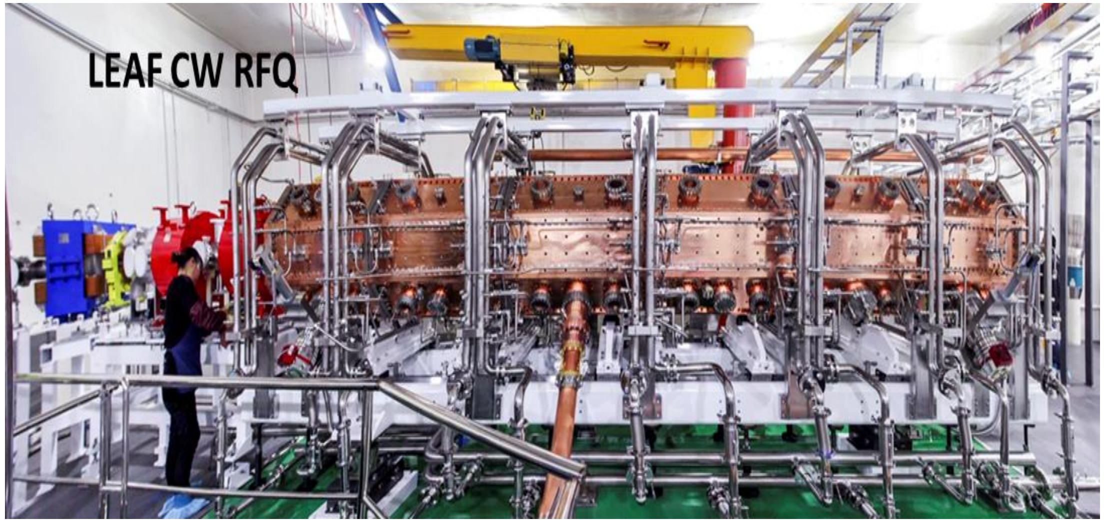
- **Stable and high-power electric-magnetic fields for beam focusing, bunching and acceleration**
- **Interaction between the electric-magnetic fields and the high intensity ion beam in RFQ**

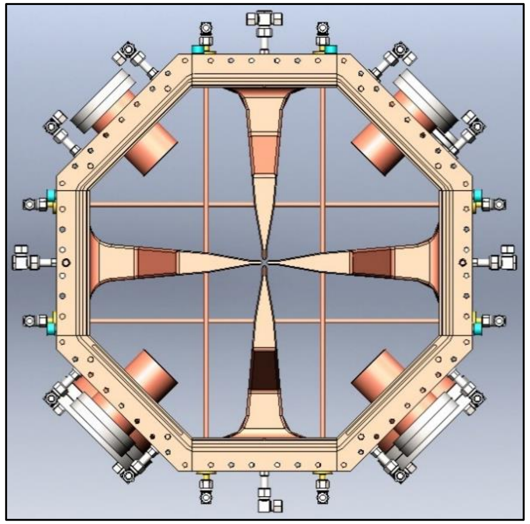
Proton and heavy ion RFQ accelerators developed by IMP

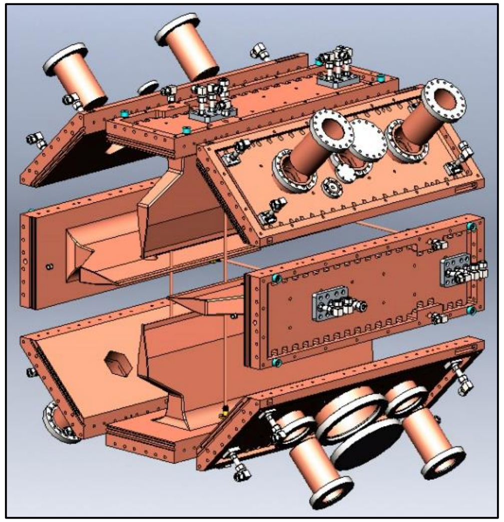




2.1 MeV/H^+ 10 mA, 2011-2014, 3 such RFQs were built and being operated at IMP







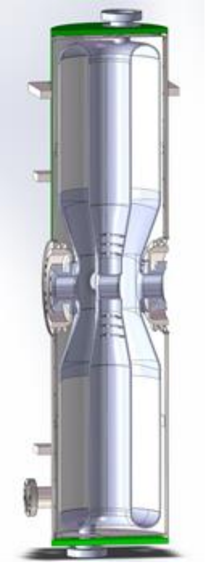
0.5 MeV/A, A/Q=2-7, 2015-2024, 1 mA O^{6+}, 0.2 mA Bi^{35+}, 2 such heavy ion RFQs were built for LEAF and HIAF

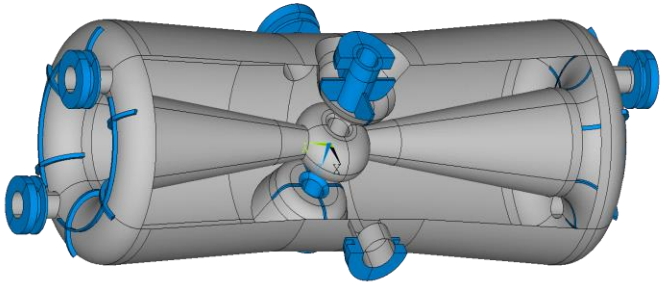
The world best-performance proton and heavy ion RFQs in terms of beam intensity

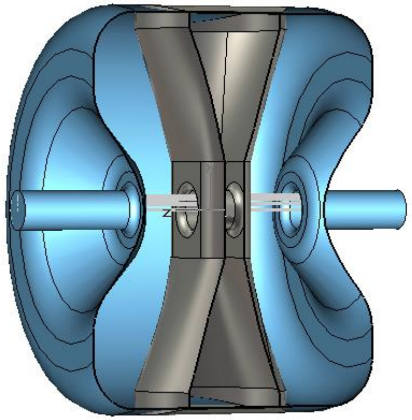
SRF cavities for high intensity beam acceleration achieving higher E

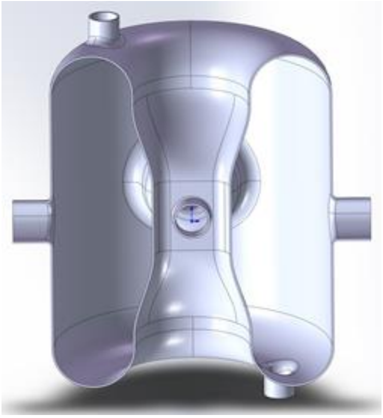
Key issues

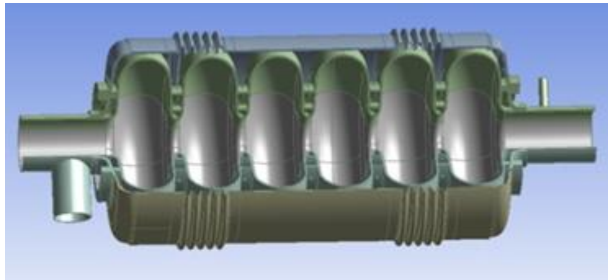
- Generate high electric-field gradient （E_{acc}） with high Q 、low RF power loss、low electric and magnetic peak field (E_{peak}、 B_{peak}) and stable RF frequency、phase and voltage amplitude by optimization of cavity structure and cavity surface processing.
- Realize acceleration and transmission of high intensity ion beam almost no any beam loss.







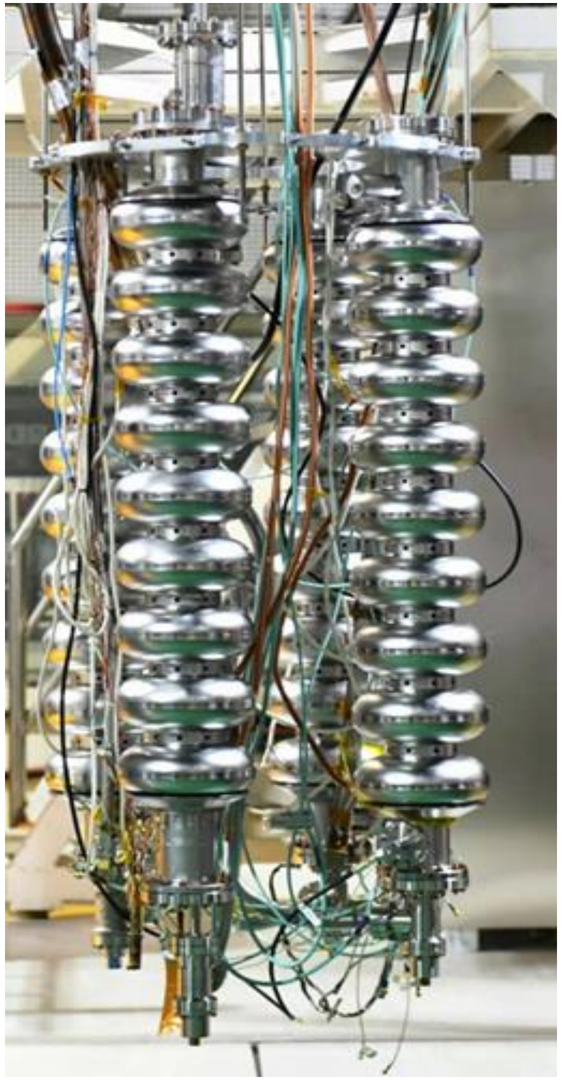


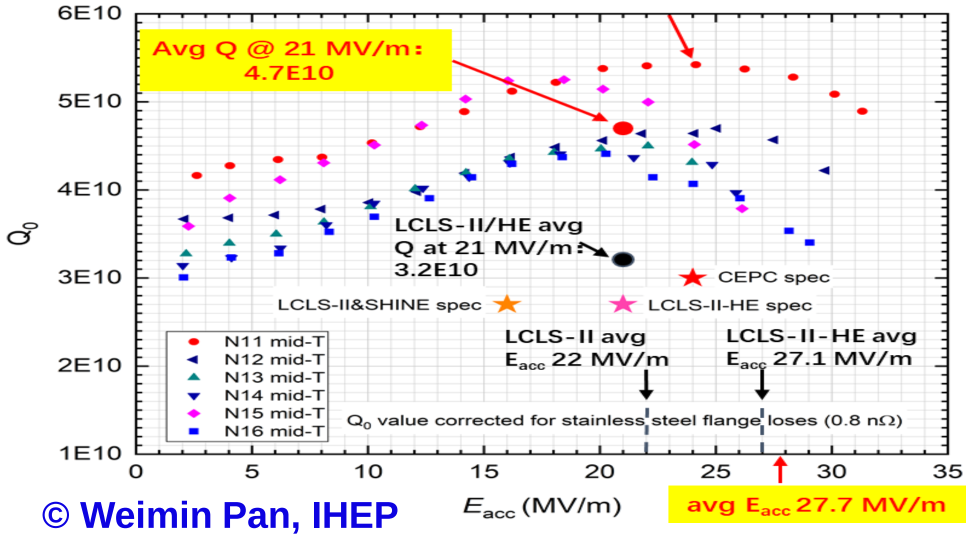


Typical SRF cavities for ion acceleration

Multi-cell SRF cavity for electron and proton beams

Bulk-Nb





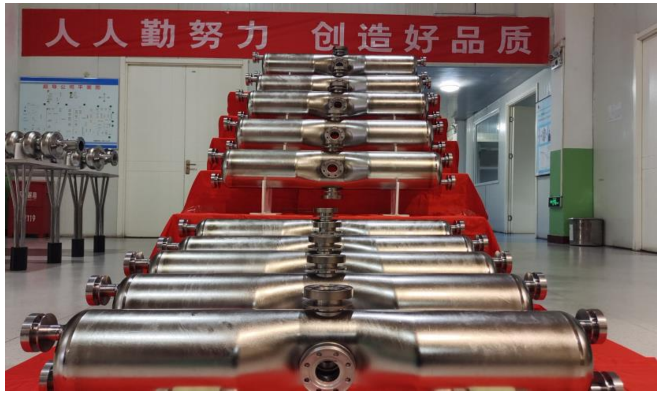
- 1.3 GHz 9-cell prototype built by IHEP
  Q_0 4.9 x 10^{10}, E_{acc}~31 MV/m in VT.

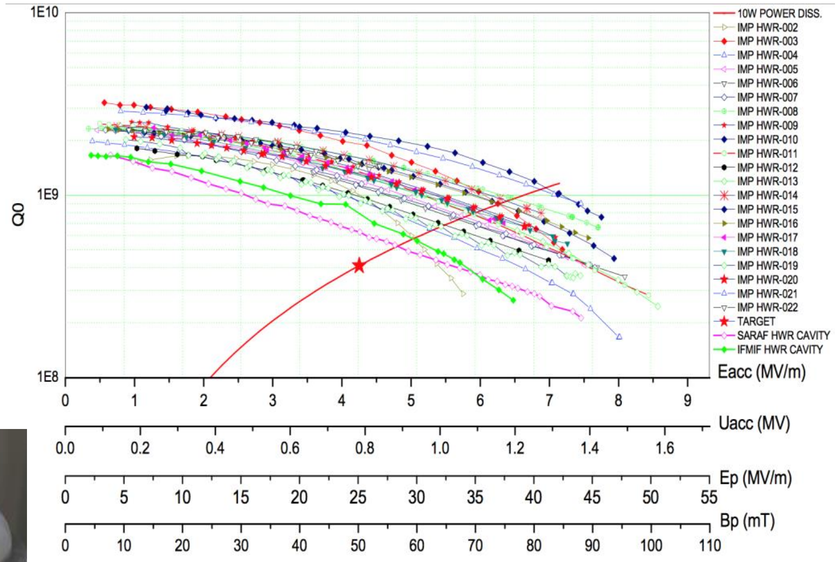
- β= 0.82. 5-cell prototype built by IMP
  Q_0 1 x 10^{10}, ~30 MV/m in VT. 650 MHz

- Gradient E_{acc} and Q_0 to be improved, for both bulk-Nb, and thin films:
  higher-T operation (less He + cryo power)

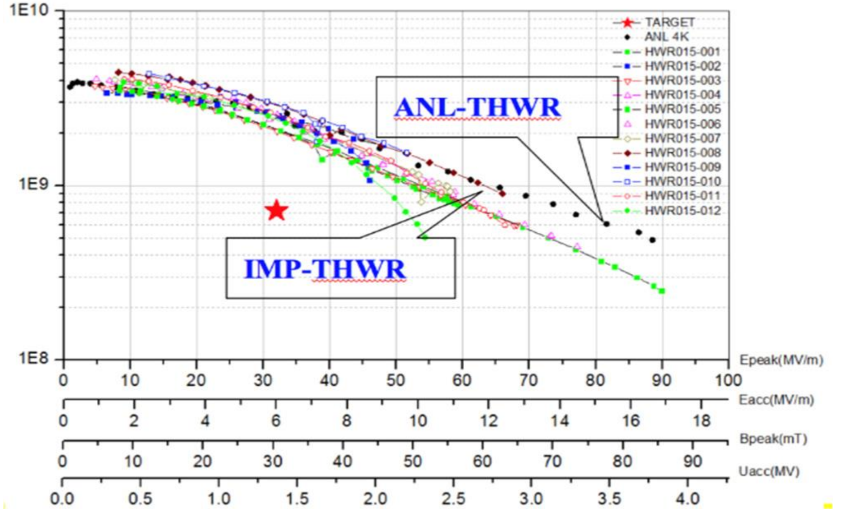
- Recent surface processing and thin film advances (surface coating Nb & Nb_3Sn, electro-polishing, N-doping/infusion …) potentially enable much higher performance

Low and medium β SRF cavity for proton and heavy ions





HWR010 by IMP

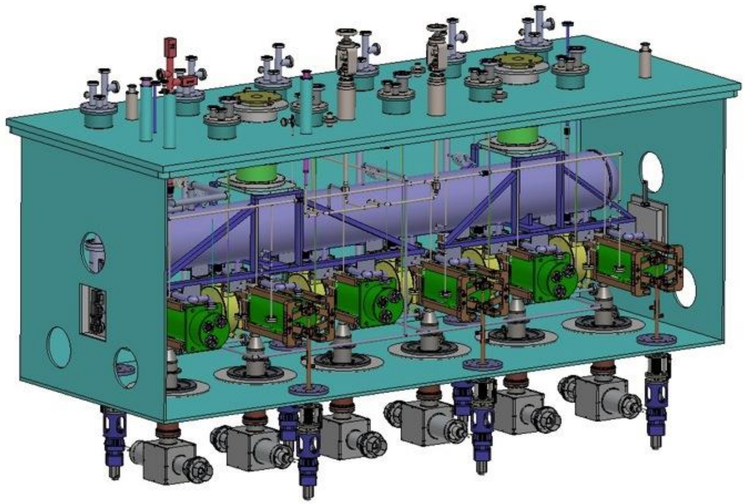


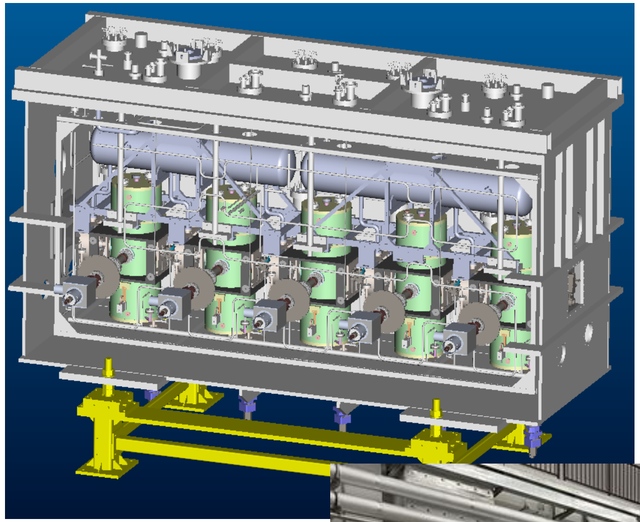
HWR015 by IMP

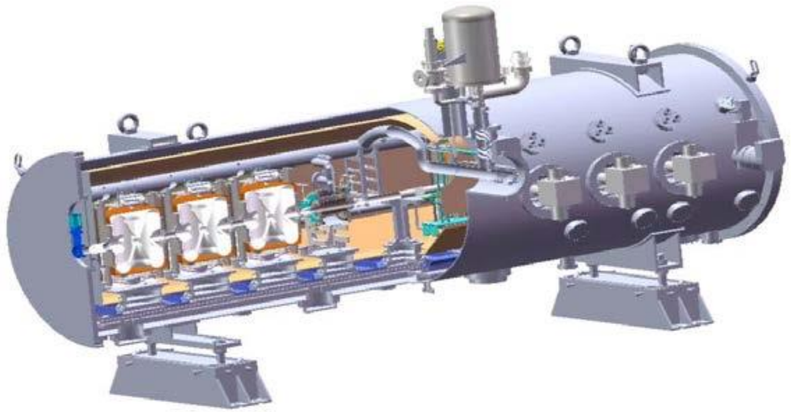
- Gradient E_{acc} and Q_0 to be improved, for both bulk-Nb, and thin films being developed by IMP
- New structure, new material and surface coating Nb & Nb_3Sn may further advance the performance

SRF Cryomodule

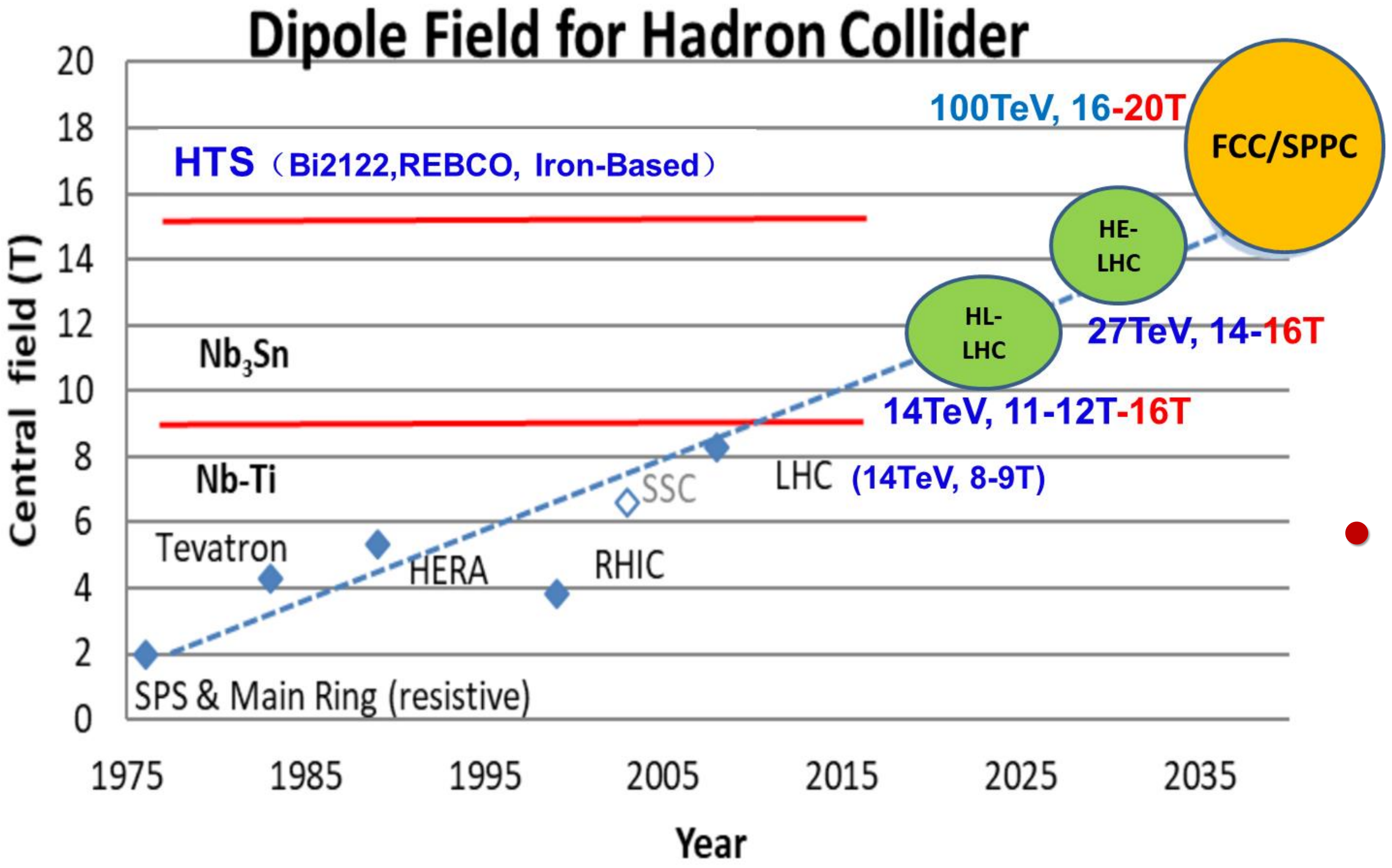
Integration of SRF cavities, SC solenoids, BPM, powers couplers, frequency tuners, LHe vessel, cavity support, magnetic shielding, multi-layer thermal shielding, …..







Accelerator SC magnet： Development and State-of-the-Art



Two approaches

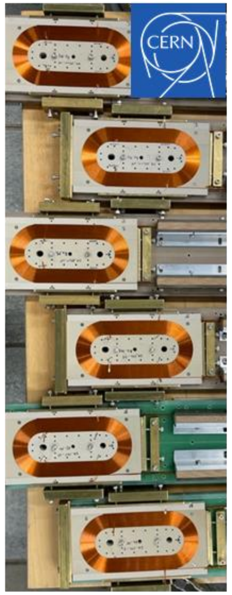
- LTS (Nb3Sn)
- HTS (REBCO) conductors

- **High field SC magnet Tech. in China not as advanced as those in US and EU !!!**

- **Nb_3Sn Q-magnet：11-12T，in small series production；12-16T dipole in prototyping**
- **HTS Bi2212、REBCO, solenoids >20T，16-20T dipole in prototyping**

Future high field SC magnets: HTS magnet

- Possible to realize J >1000 A/mm2 , B > 20T, T > 20K
- HTS conductors: ReBCO, BSCCO(Bi-2223,2221), IBS
- Key issues: degradation, quench losses and quench protection, cost
- Accelerator demands: field quality, reproducibility, stability, uniformity
- HTS/LTS hybrid technology: Possible cost saving but still need 1.9 or 4.5K for LTS

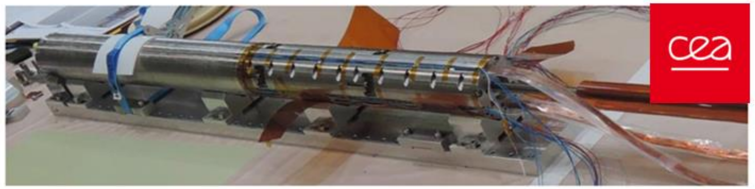


CERN insulated tape-stack cable racetracks

So many labs involved

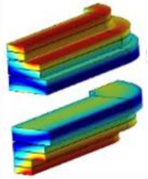
EUCARD2 Feather M2 (CERN)

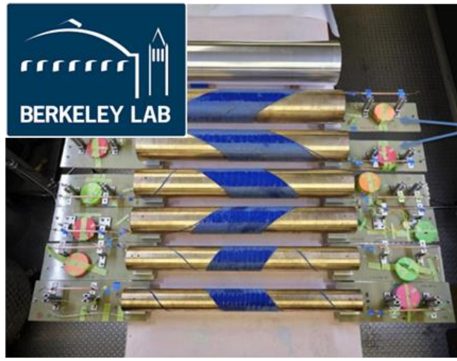
EUCARD2 Cos Theta (CEA)



CEA MI Racetrack

6 T insert coils by IHEP





REBCO CCT with CORC ® Cable

Outline

High-Intensity High-Power (HIHP) Ion Accelerator Facility

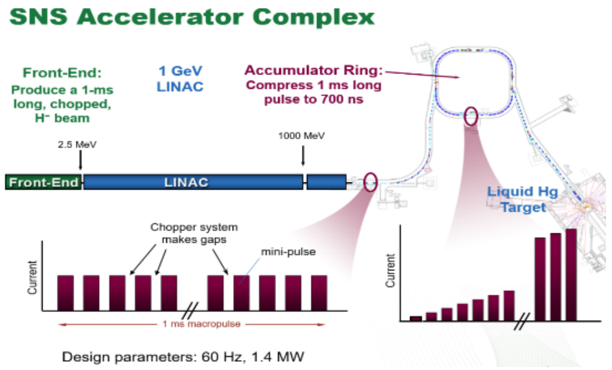
1. Challenge and key technologies

2. World-wide HIHP ion accelerators

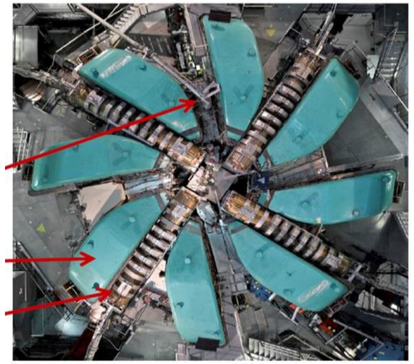
3. HIAF&CiADS and key technology R&D

4. Summary

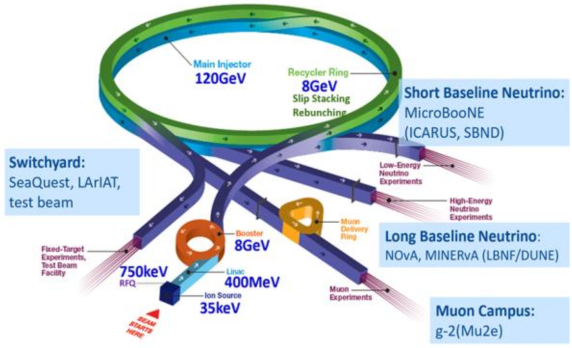
World-wide high-intensity and high-power ion accelerators （kW-MW）



ORNL SNS

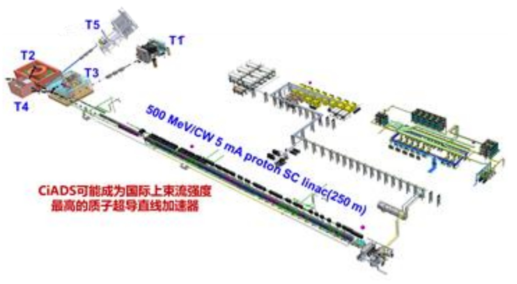


PSI cyclotrons

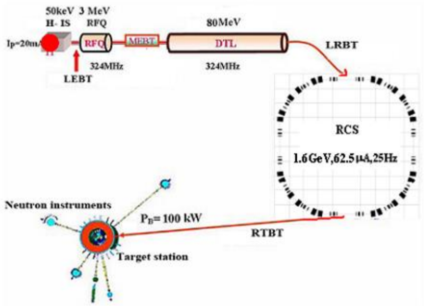


FNAL proton accelerator complex

JPARC

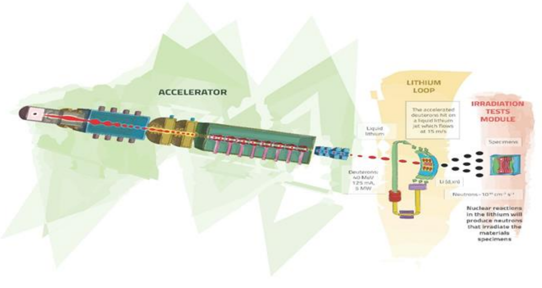


IMP CIADS（construction）

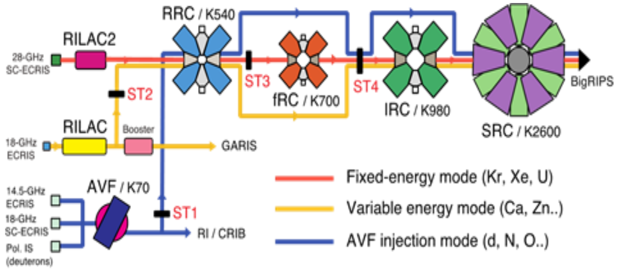


IHEP CSNS

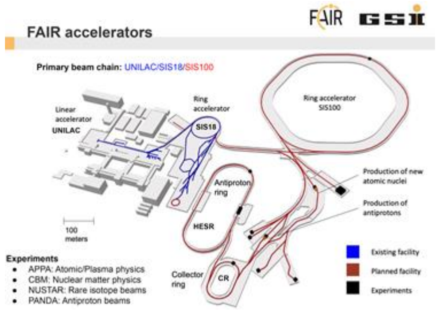
ESS（construction and commiss.）



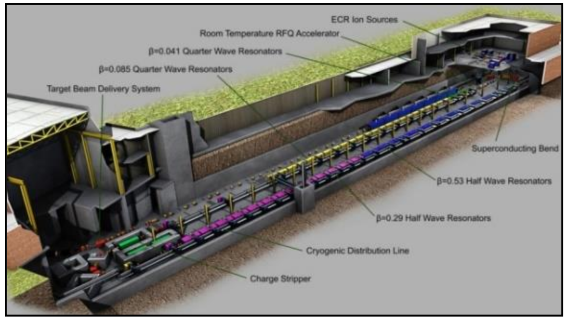
IFMIF（Plan）



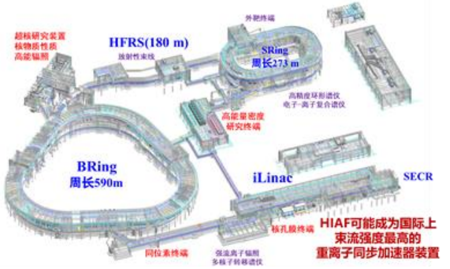
RIKEN-RIBF



GSI FAIR（construction）

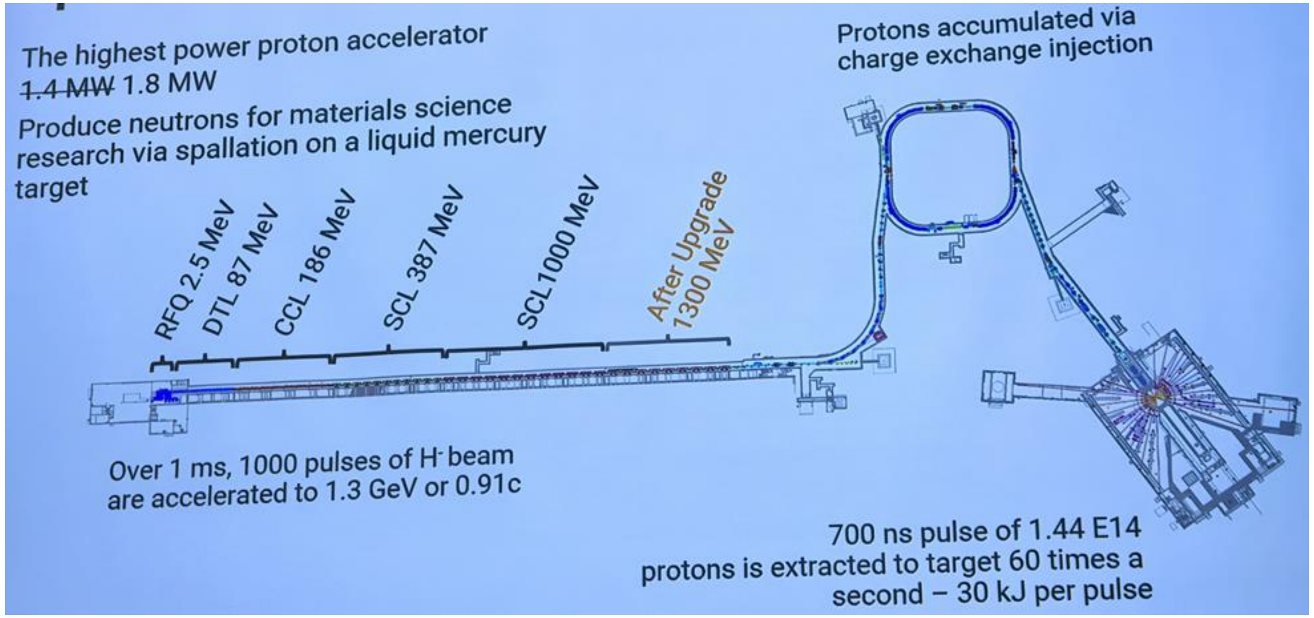


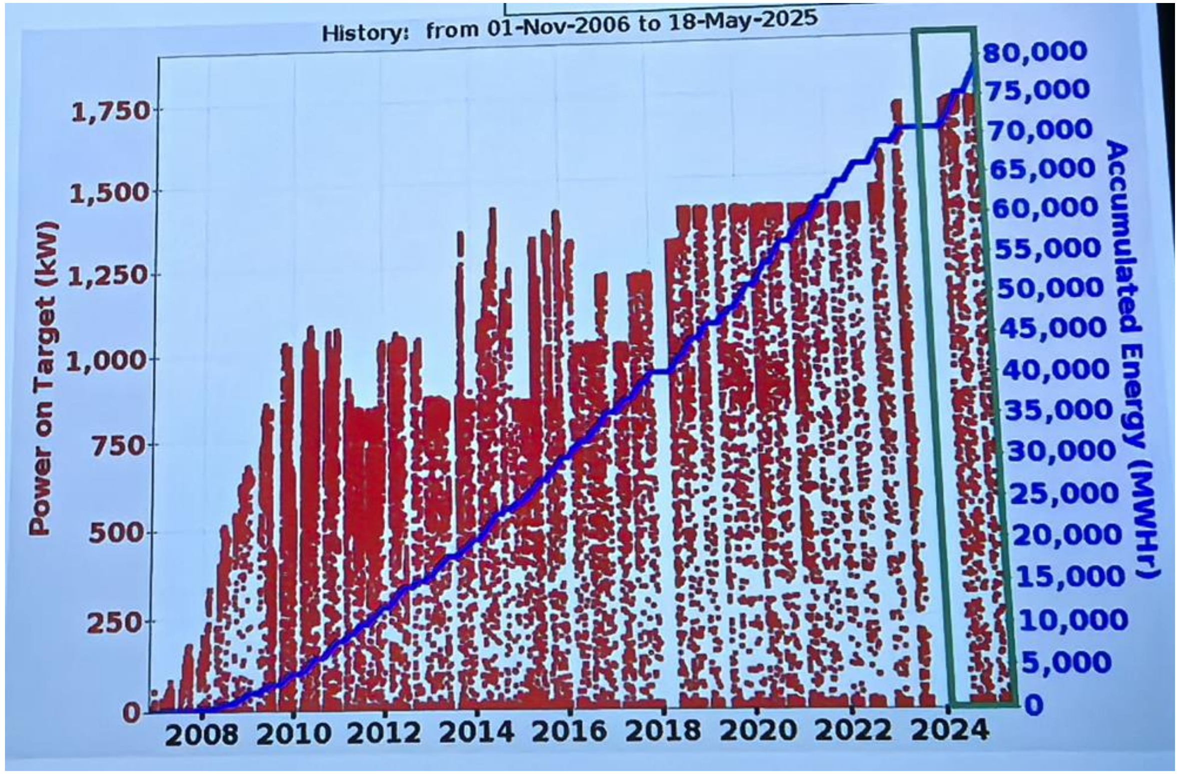
MSU FRIB



IMP HIAF（construction）

ORNL-SNS average beam power 1.7 MW



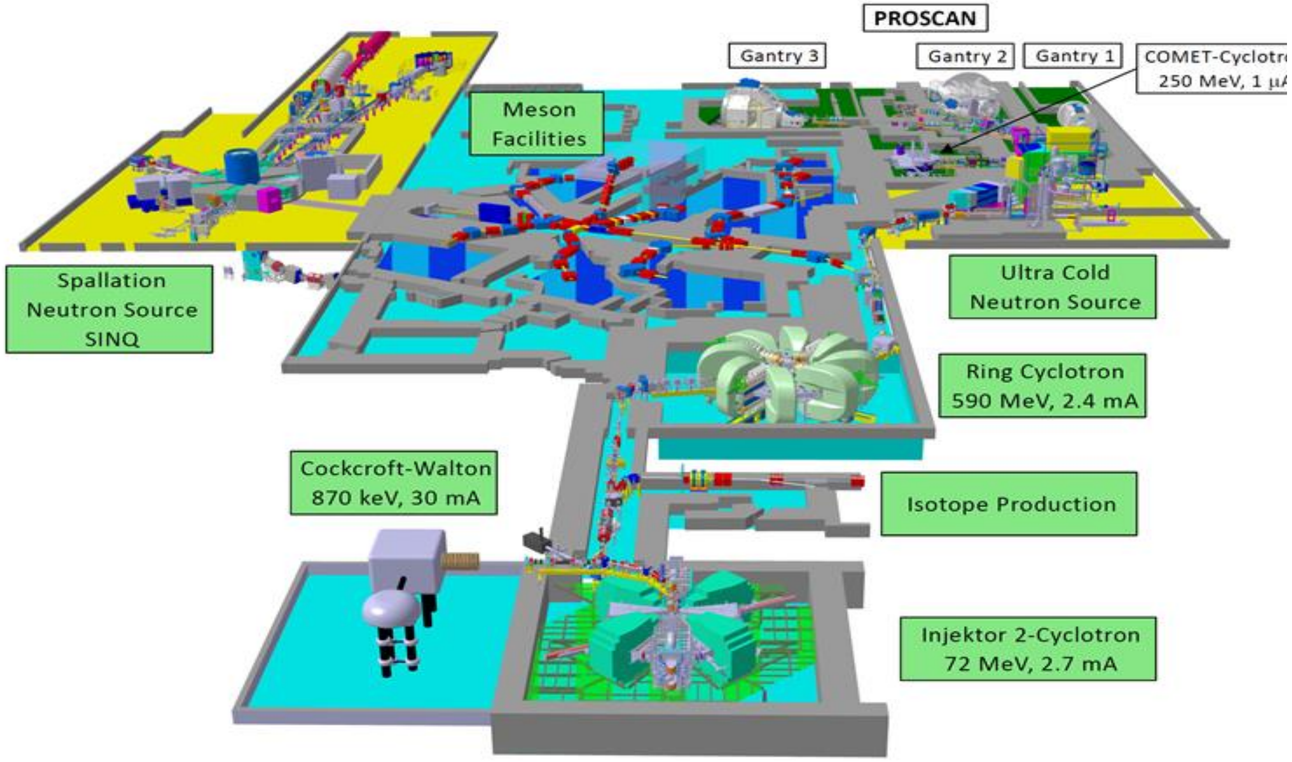


To be upgraded to 2.8 MW

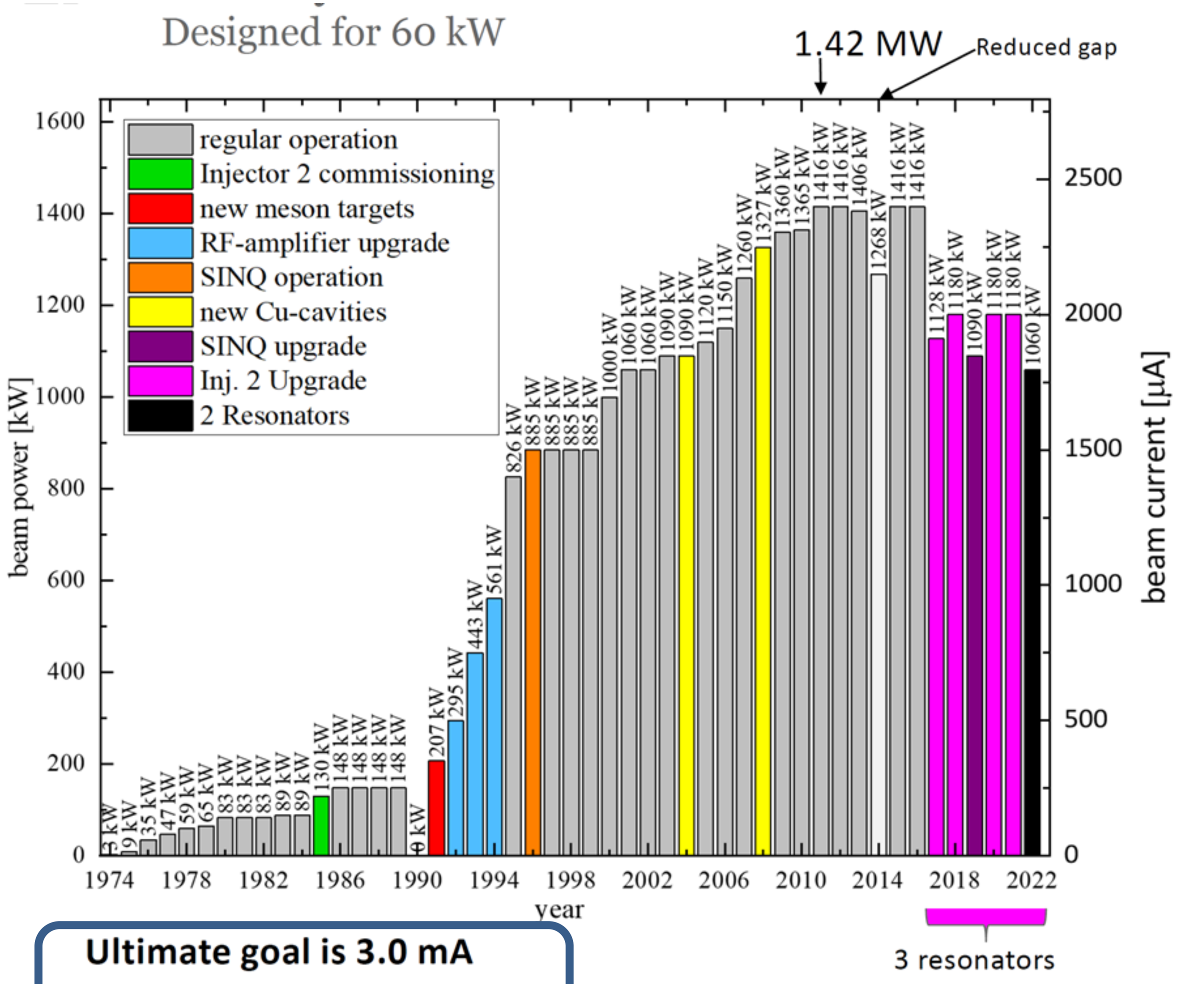
The world most powerful proton accelerator facility

N. Evans, ORNL-SNS, IPAC’25 talk

PSI proton cyclotron complex 1.4 MW



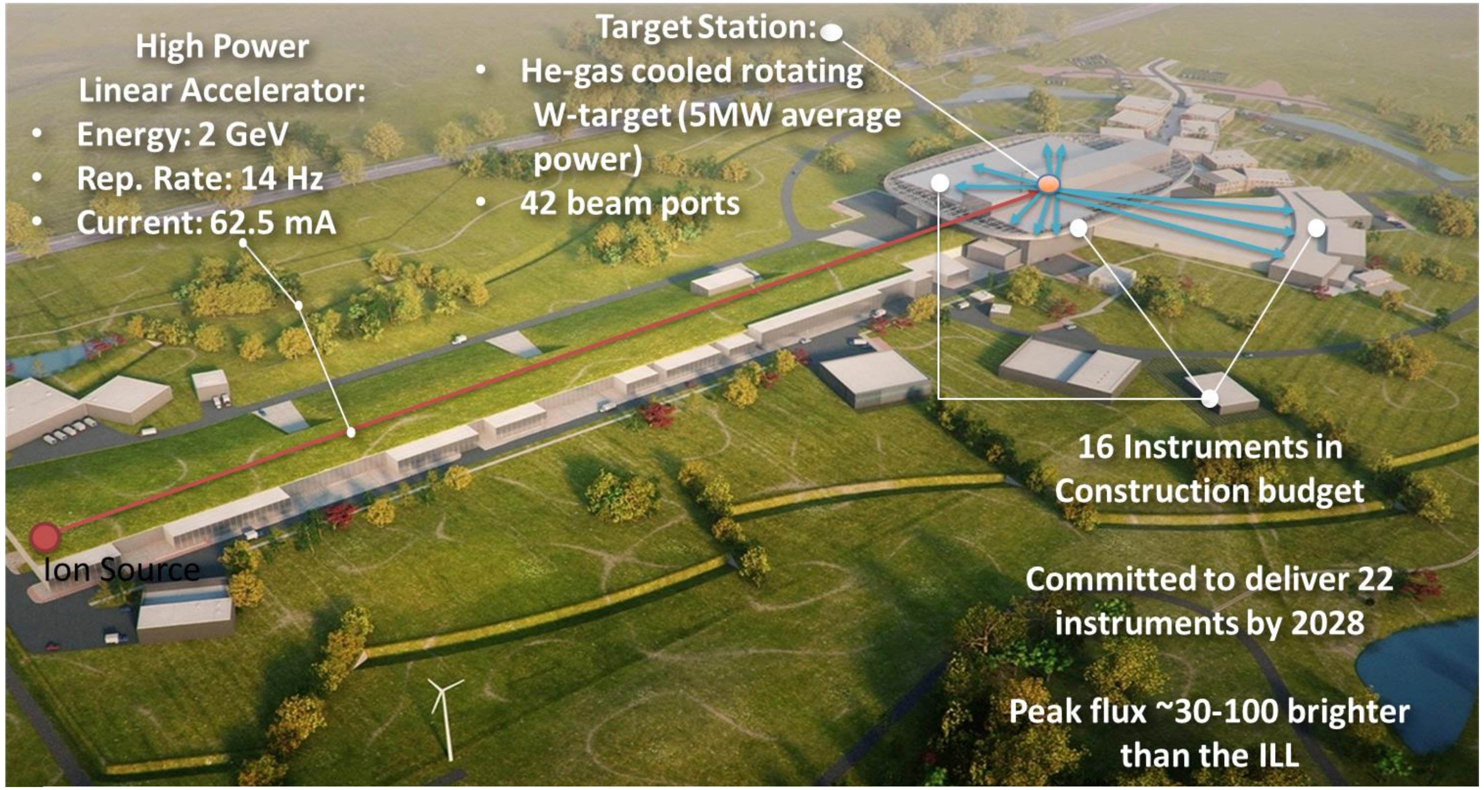
©Joachim Grillenberger, PSI, talk at HB2023



Ultimate goal is 3.0 mA
Corresponds to 1.8 MW

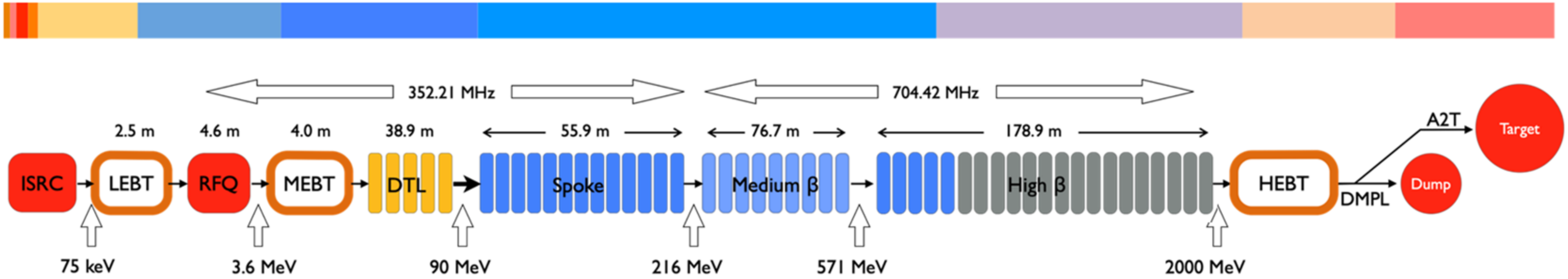
Being upgraded to 1.8 MW

ESS 5MW average beam power Commissioning



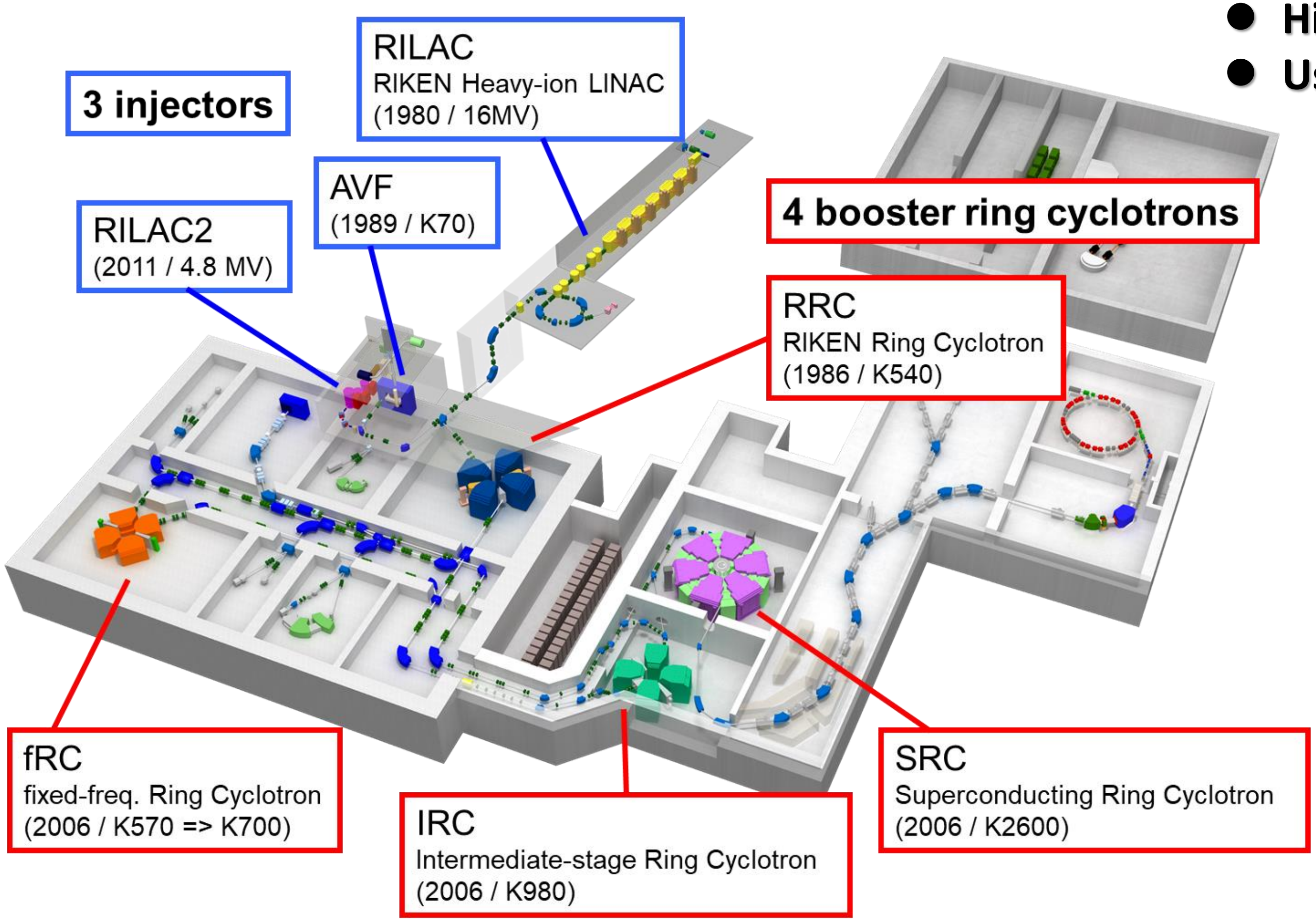
SC linac 2 GeV/5 MW

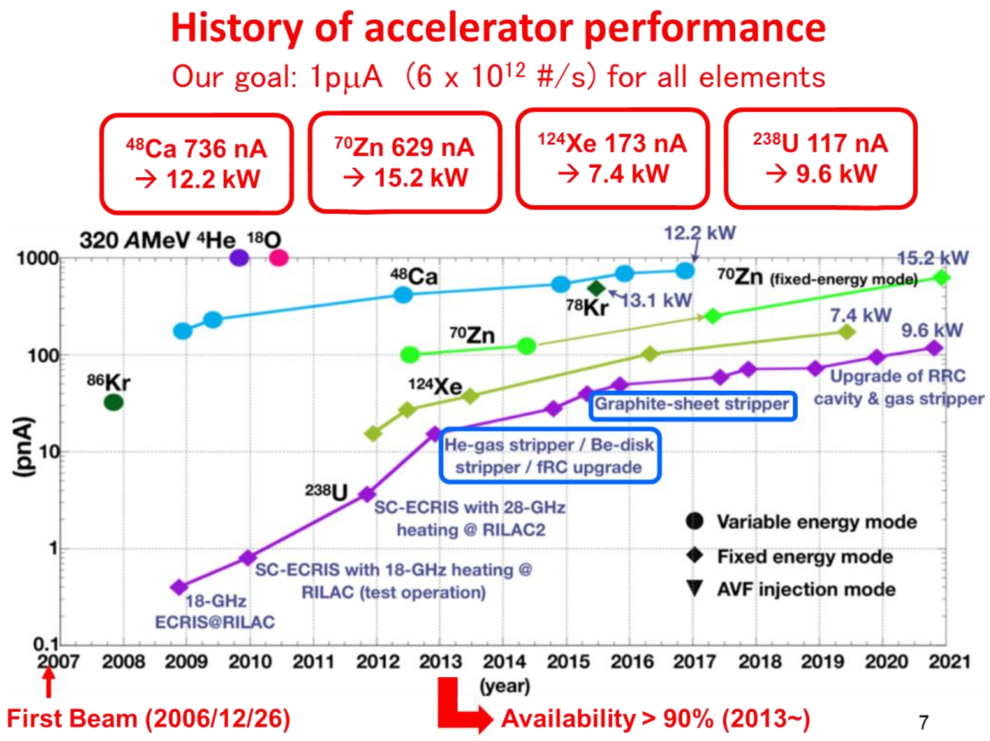
- 2014 start construction, 3 phases.
- **Beam on target milestone requires capability for 1.4 MW at 571 MeV with nominal pulse structure**
- Start Of User Operation requires capability for 2 MW at 870 MeV with nominal pulse structure
- Full scope is 5 MW at 2 GeV with 2.86 ms long pulses at 14 Hz



RIKEN RIBF heavy ion cyclotron complex

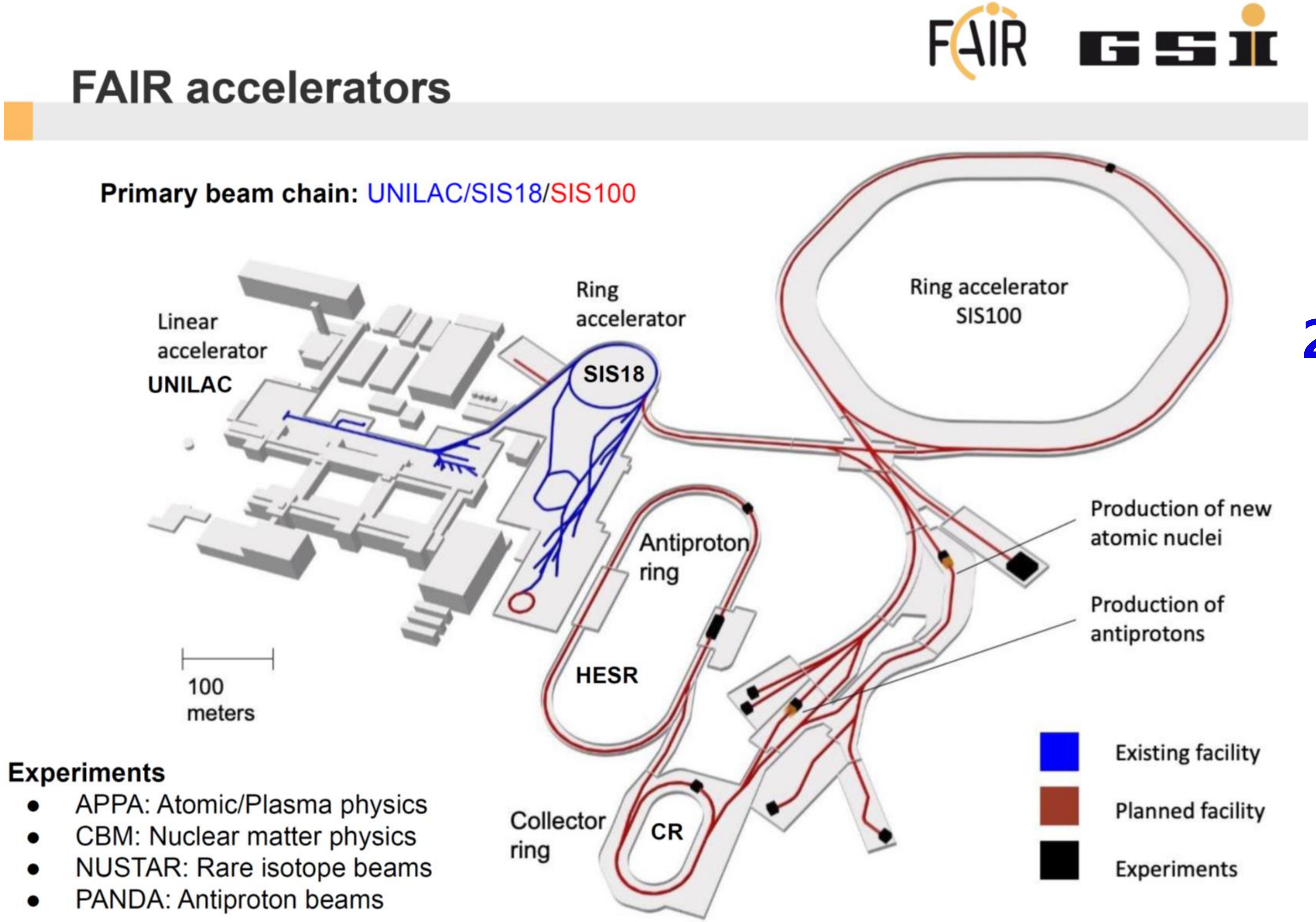
- **Highest energy of CW heavy ion accelerator complex**
- **Used to be a highest power heavy ion accelerator**





1) AVF-injection mode (< 440 MeV/u) : d, He, O, …
2) Variable-energy mode (< 400 MeV/u) : Ar, Ca, Zn, Kr, …
3) Fixed-energy mode (345 MeV/u) : Xe, U …

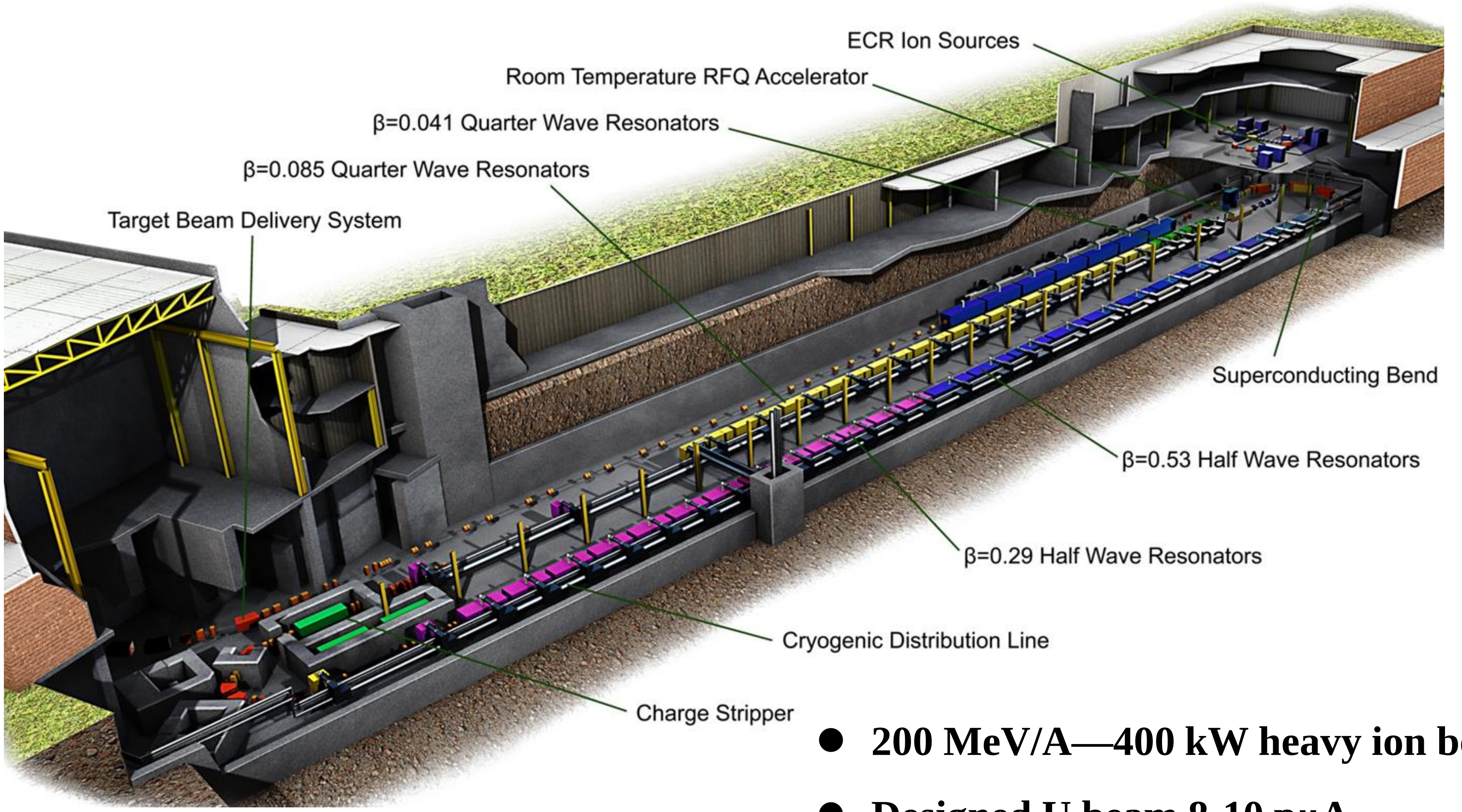
GSI-FAIR heavy ion accelerator complex Construction



2028-2030 operation

- $^{238}U^{28+}$ 1.5 GeV/A, 5×10^{11} ppp

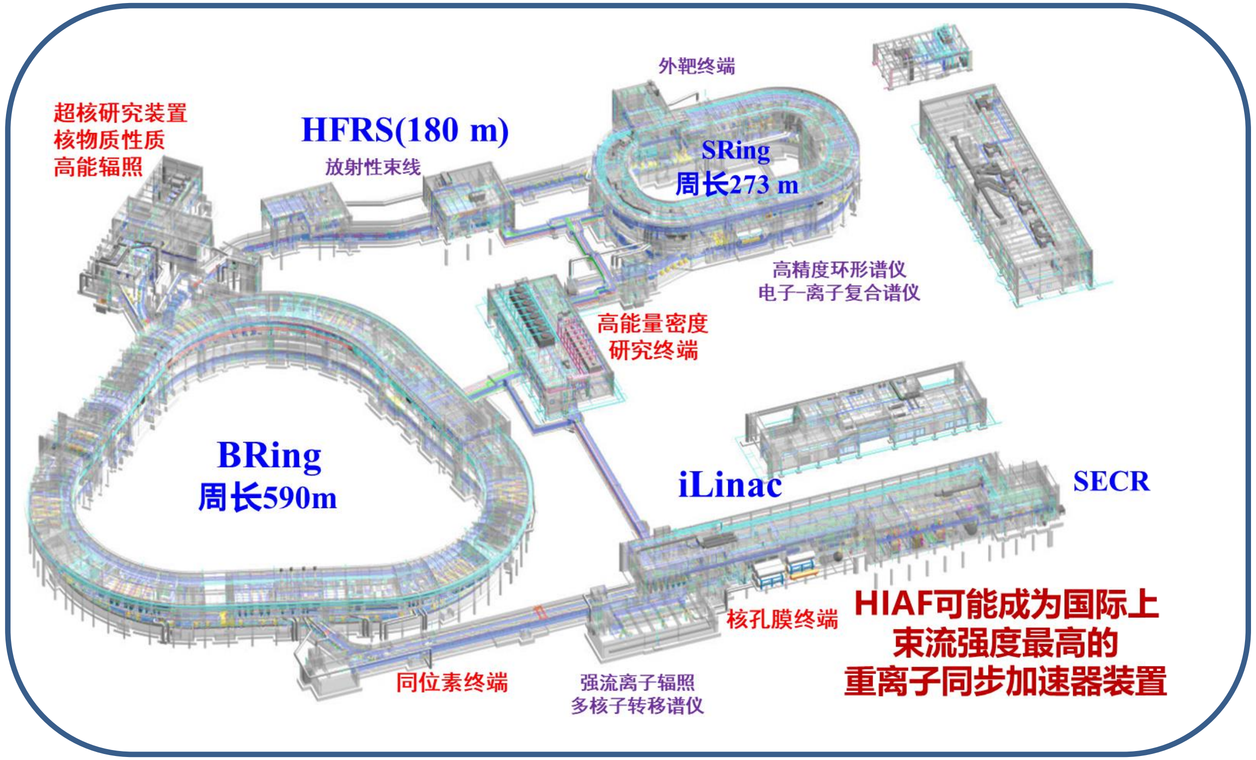
MSU-FRIB Heavy ion SC linac



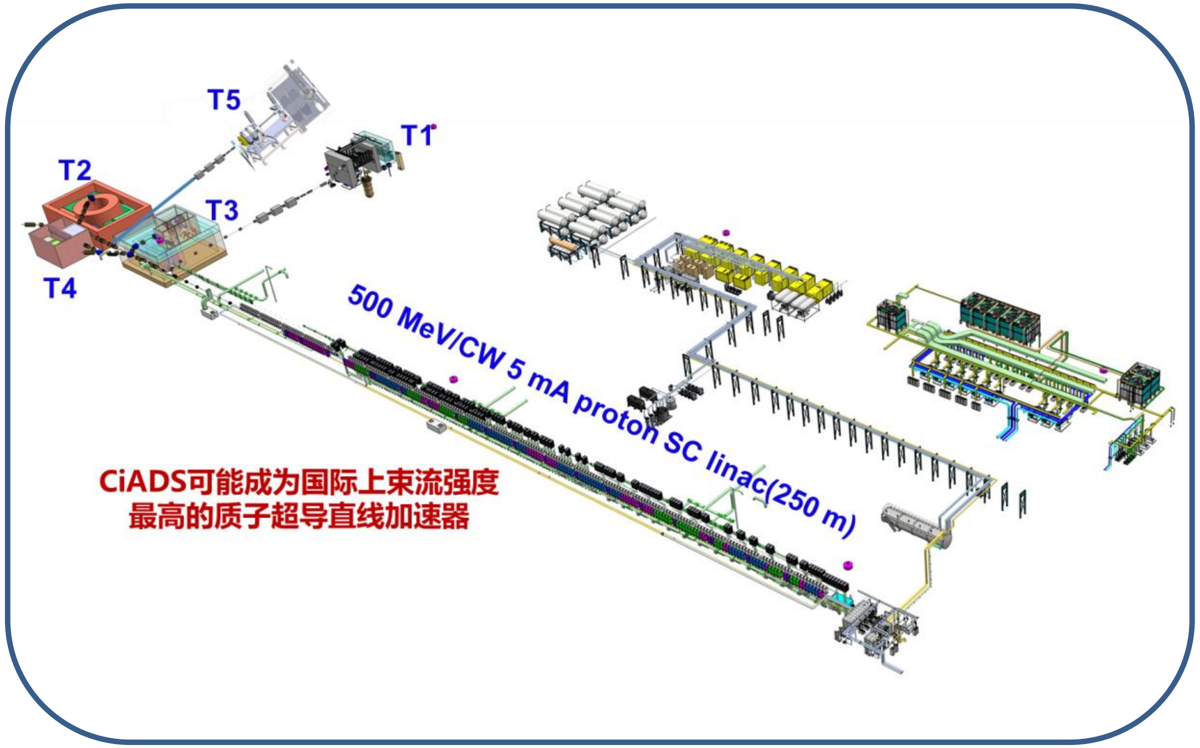
- **200 MeV/A—400 kW heavy ion beam， now 25 kW**
- **Designed U beam 8-10 pμA**
- **Started routine operation in 2022**

The world most powerful heavy ion accelerator!

HIAF



CiADS



HIAF & CiADS could be one of the world best-performance HIHP ion accelerators

Outline

High-Intensity High-Power (HIHP) Ion Accelerator Facility

1. Challenge and key technologies

2. World-wide HIHP ion accelerators

3. **HIAF&CiADS and key technology R&D**

4. Summary

Operational Accelerator Facility at IMP: HIRFL

SSC (K=450)

100 AMeV (H.I.), 110 MeV (p)

Heavy Ion Research Facility in Lanzhou (HIRFL)

SFC (K=69)

10 AMeV (H.I.), 17~35 MeV (p)

SECRAL II (28 GHz)

HIAF&CiADS brief introduction

- **HIAF: High Intensity heavy ion Accelerator Facility**
- **CiADS: China Initiative Accelerator Driven System**
- **Being built by IMP in Huizhou of Guangdong Prov.**

- **Two of 16 large-scale scientific infrastructure facilities approved by China Government during the 12^{th} 5-year-plan 2016-2020**

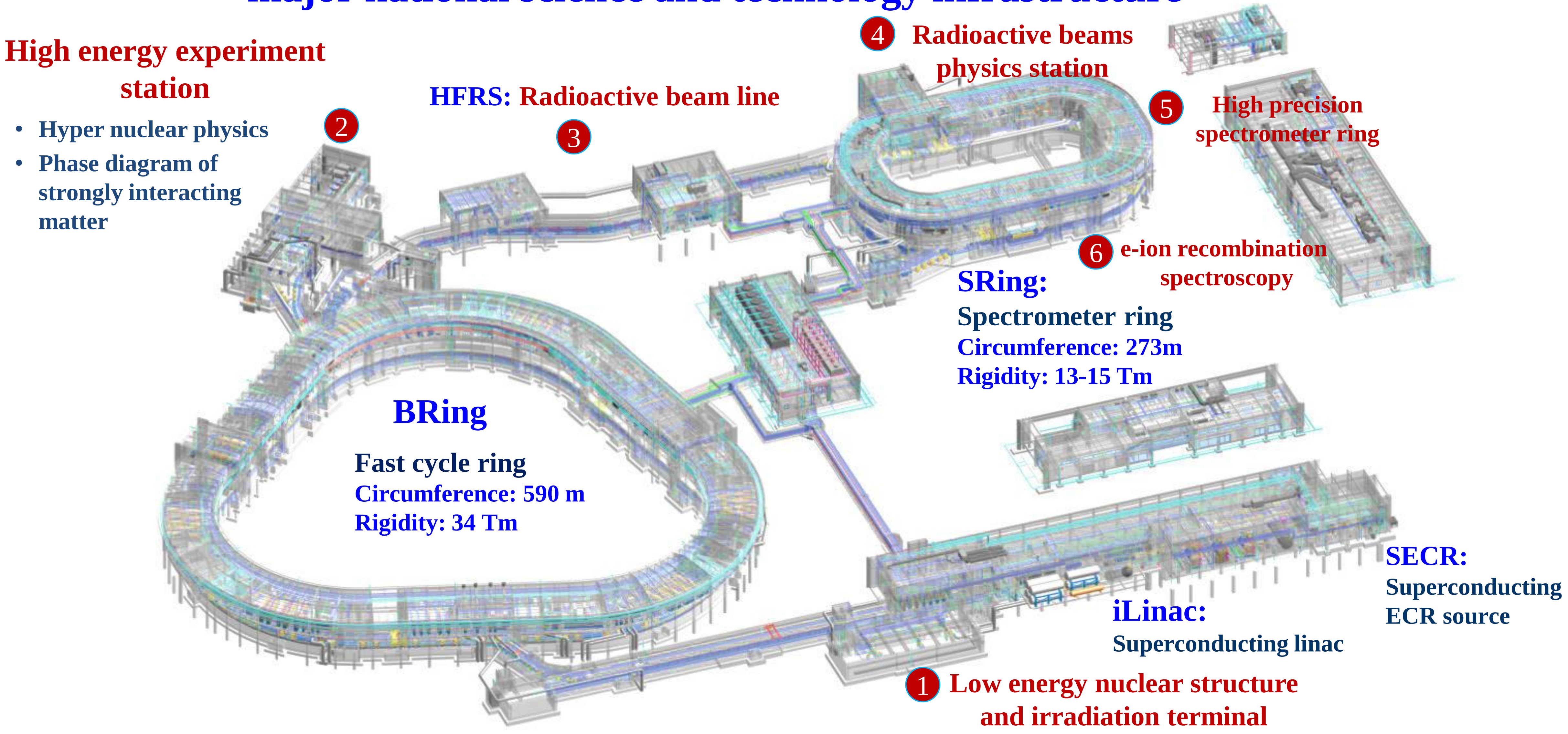
- **HIAF:** Nuclear physics research
- **Total budget:** 2.8 B CNY ¥ (424 M USD $)
- **Schedule:** 2018-2025
- Construction started officially Dec. 2018

- **CiADS:** Nuclear waste transmutation
- **Total budget:** 4.0 B CNY ¥ (606 M USD $)
- **Schedule:** 2021-2027
- Construction started officially July. 2021

HIAF&CiADS Construction Site

High-Intensity Heavy Ion Accelerator Facility-HIAF

major national science and technology infrastructure



BIM (Building information model) of HIAF facility construction started in 2018

Main parameters & science motivation

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+})**	835 (U^{92+})	**835 (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 (U^{35+}) 5×10^{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%	**30/30, 1.5% (normal mode)**

HIAF: for advances in nuclear physics and related research fields

- **Questions of nuclear physics:**
  - To explore the limit of nucleus existence
  - To study exotic nuclear structure
  - Understand the origin of the elements
- **High charge state ions for a series of atomic physics programs.**
- **Slow extraction beam with wide energy range for applied science,** phase diagram of strongly interacting matter, hyper nuclei physics
- **High energy and intensity ultra-short bunched ion beams for high energy and density matter research**

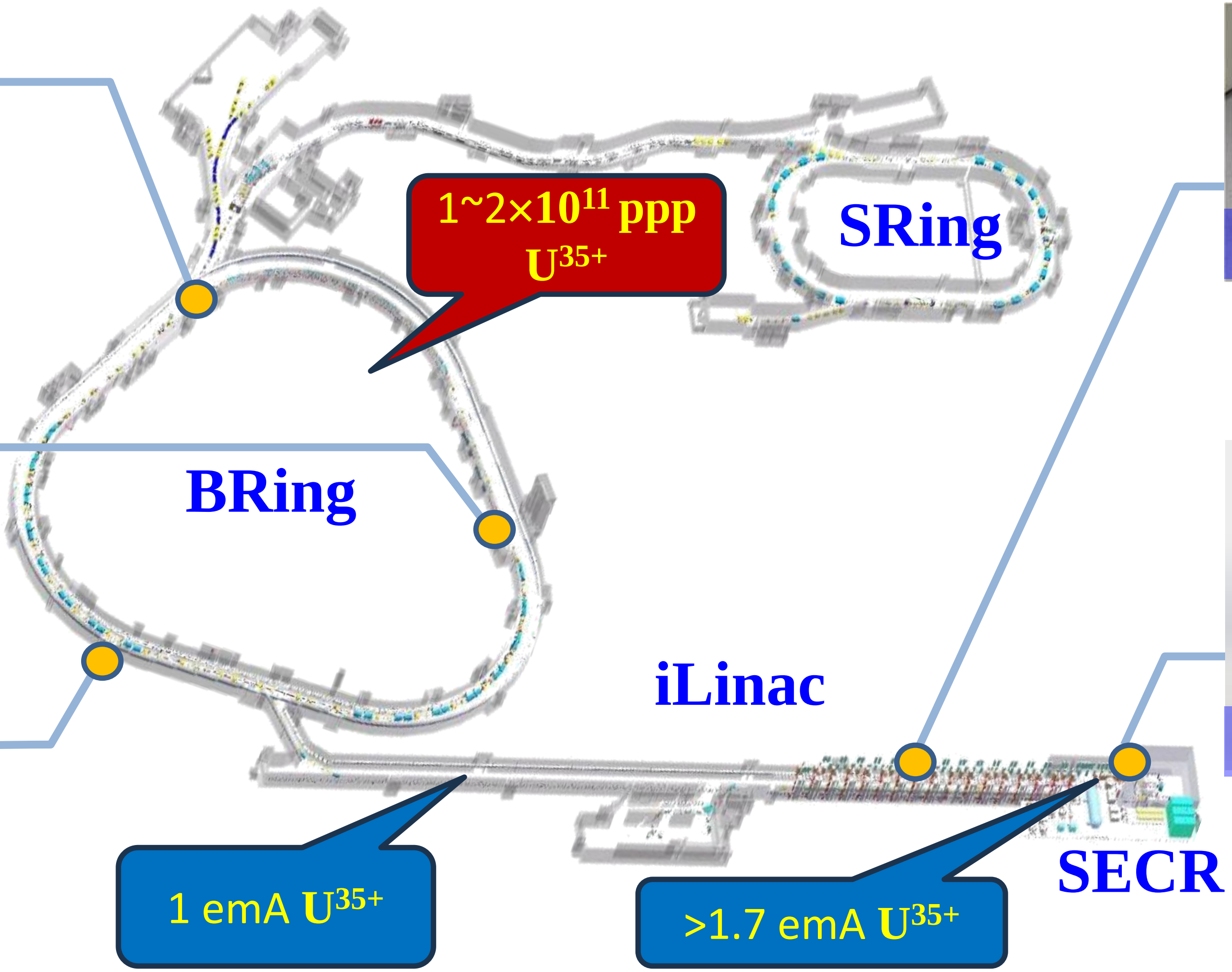
Challenges of HIAF accelerator complex

Provide the highest intensity heavy ion beams in the world

12T/s, 38kA/s, 3Hz

70kV, 35 kV/m

0.3 mm, $<7\times10^{-12}$ mbar

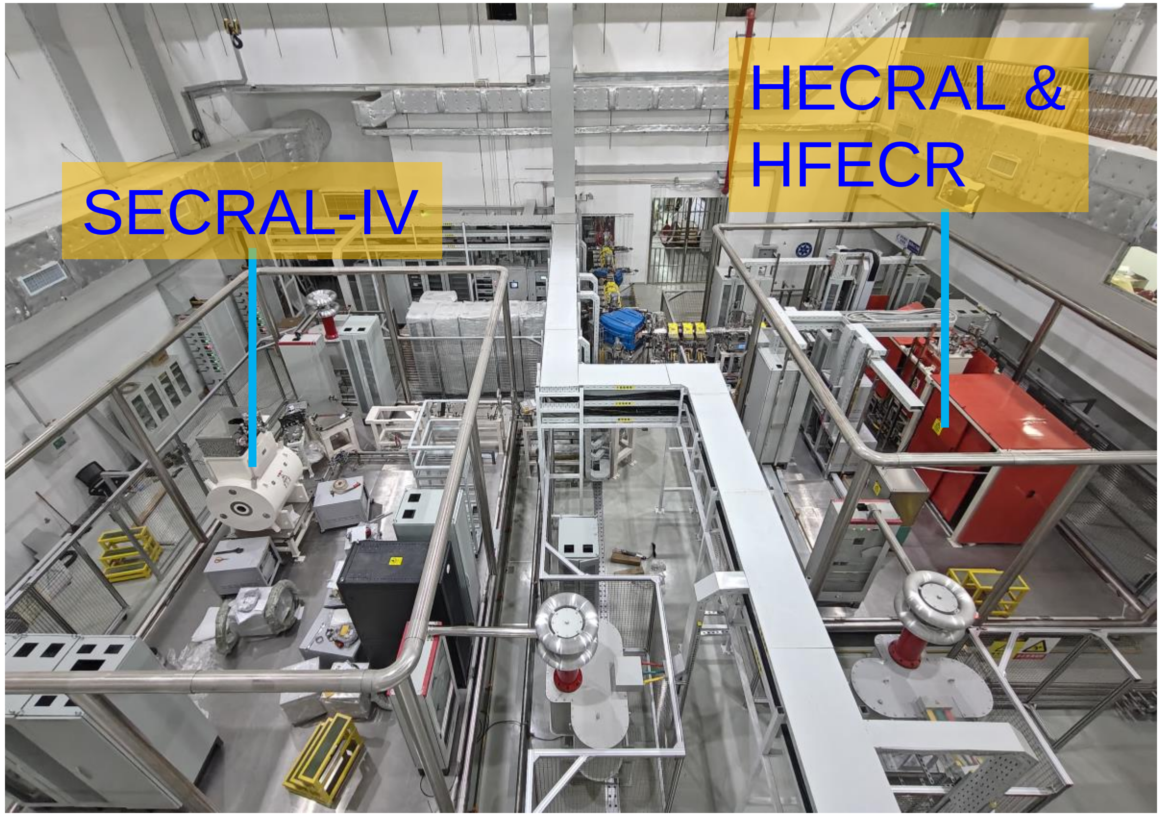


mA level heavy ion beam

Fourth generation high current ion source

Accelerator components: Warm Front-end

O^{6+}, Kr^{19+}, Bi^{31+}, U^{35+} have been successfully commissioned



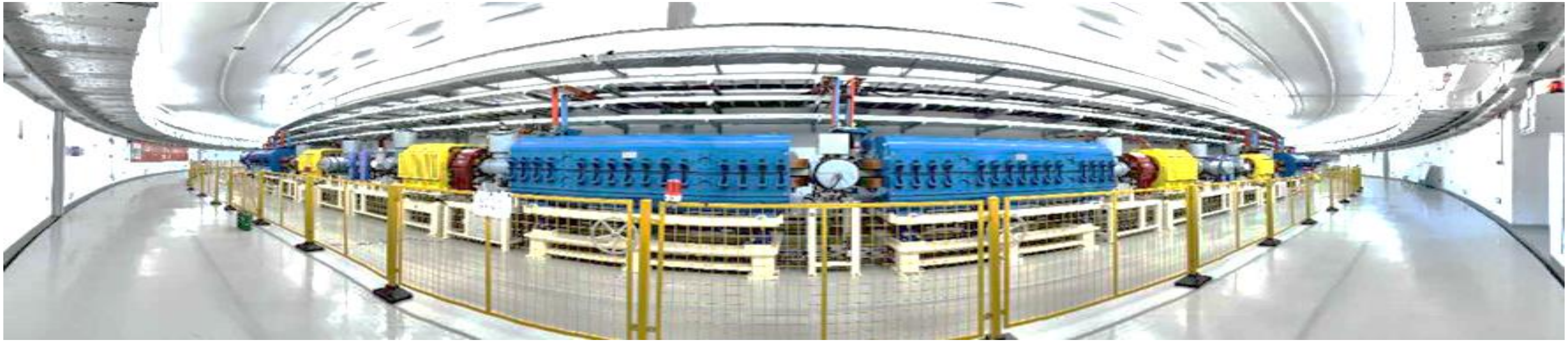
Ion Source Platform

RFQ and MEBT

Accelerator components: iLinac

Accelerator components: BRing

Full Commissioning without ion beam completed



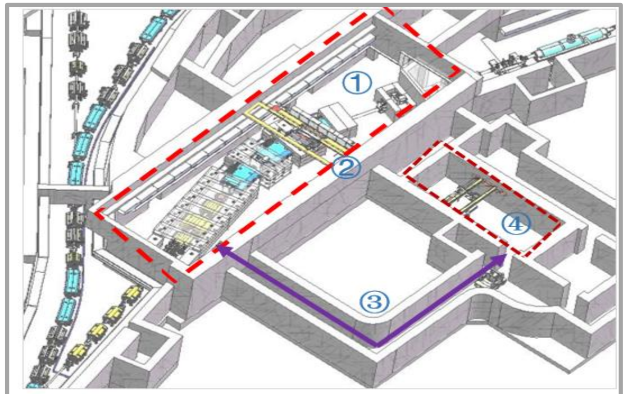
Full energy storage PS

Extraction Kicker PS

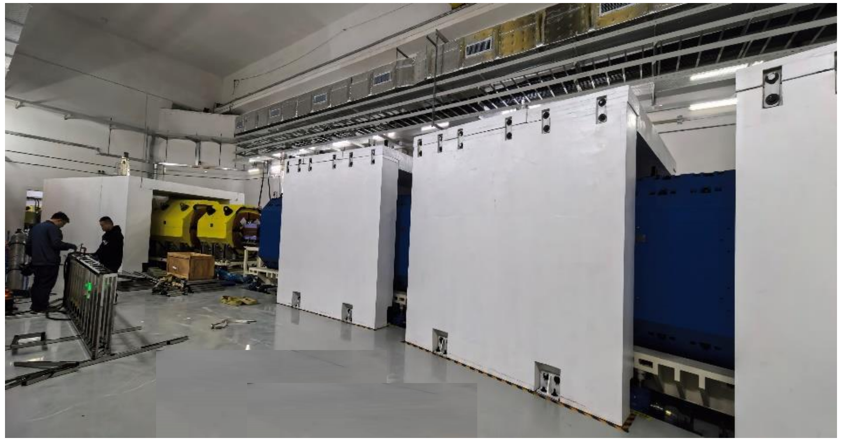
RF Power Station

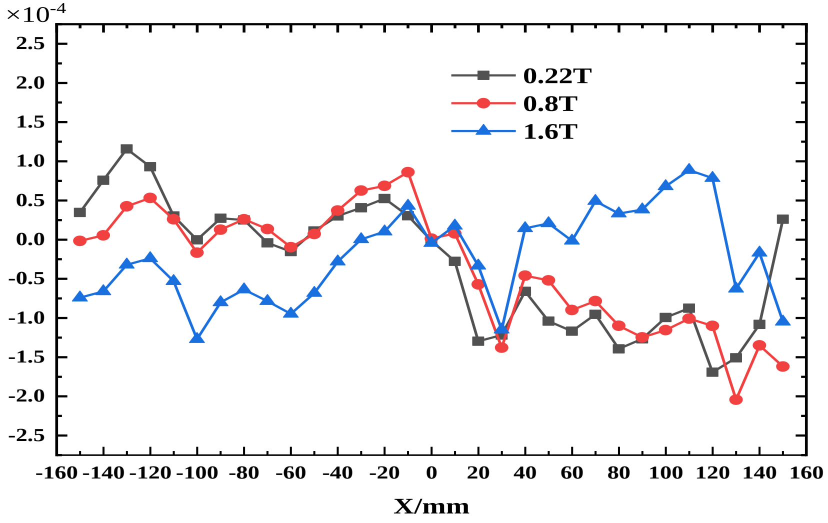
Controls and Electronics

Accelerator components: HFRS

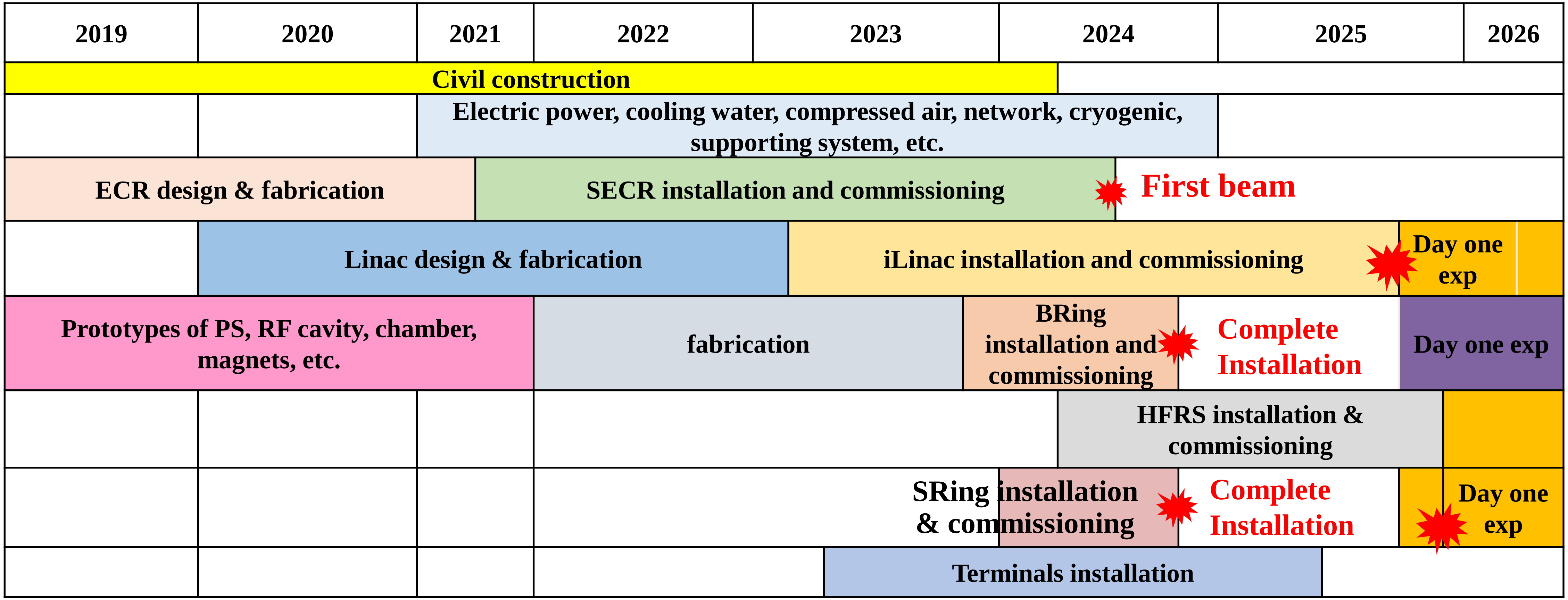


①PF0靶区②全自动行车③转运通道 ④热室





HIAF construction time schedule



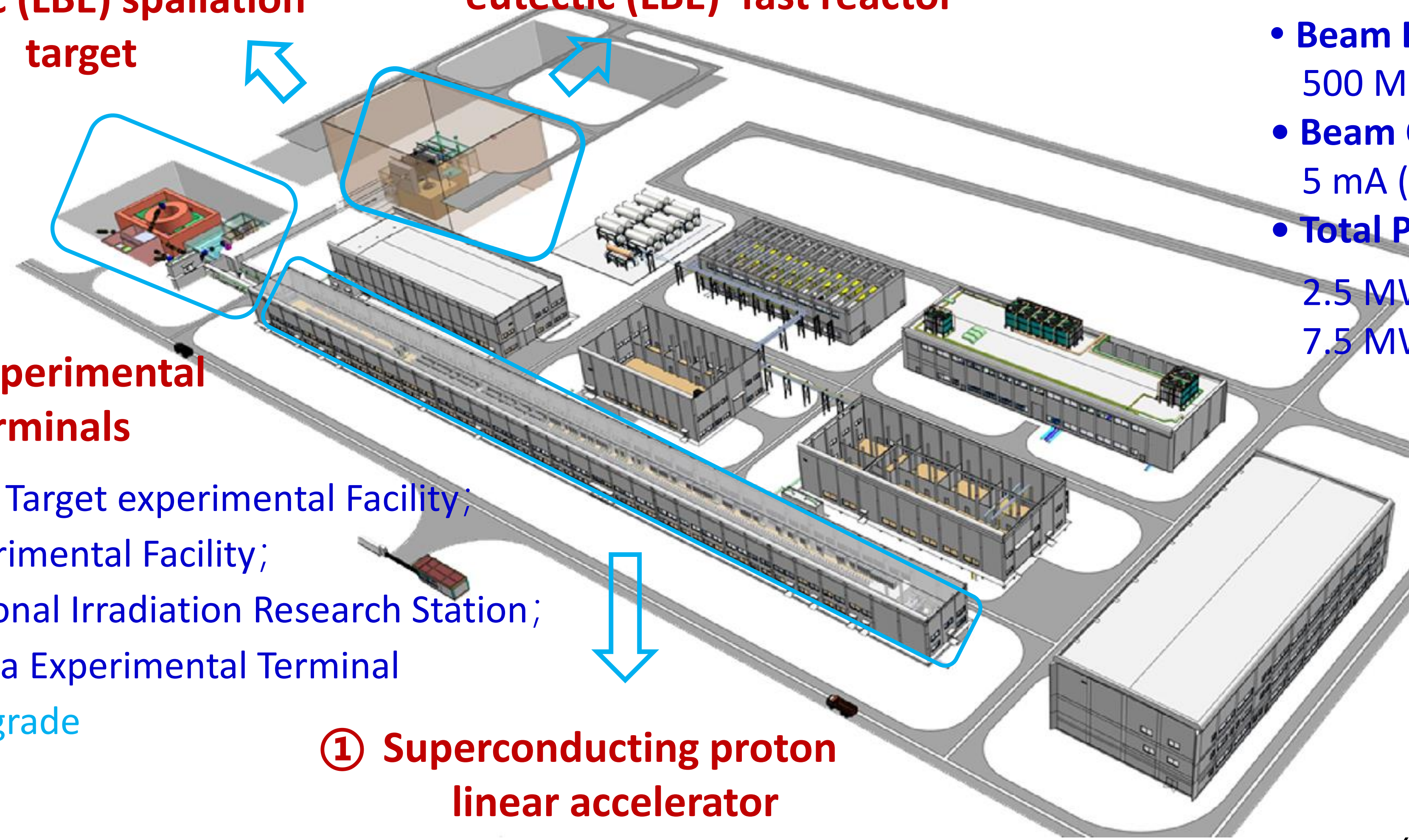
- The ion source **SECR** has provided first beam at the end of 2024
- First ion beam in **iLinac** is expected in Sept.2025
- Scheduled beam commissioning in **BRing** is in Oct. 2025

CiADS-China Initiative Accelerator Driven System

Accelerator-driven subcritical systems (ADS) is considered to be the most effective and promising method to solve the nuclear waste. CiADS will be the world's first prototype of ADS facility

Megawatt level to explore the safe and proper technology of nuclear waste disposal

- **Beam Energy:** 500 MeV (upgrade to 2.0 GeV)
- **Beam Current:** 5 mA (upgrade to 10 mA)
- **Total Power: <10 MW**
  2.5 MW beam power,
  7.5 MWth reactor power



- High power Target experimental Facility;
- Muon experimental Facility;
- Multifunctional Irradiation Research Station;
- Nuclear Data Experimental Terminal
- ISOL for upgrade

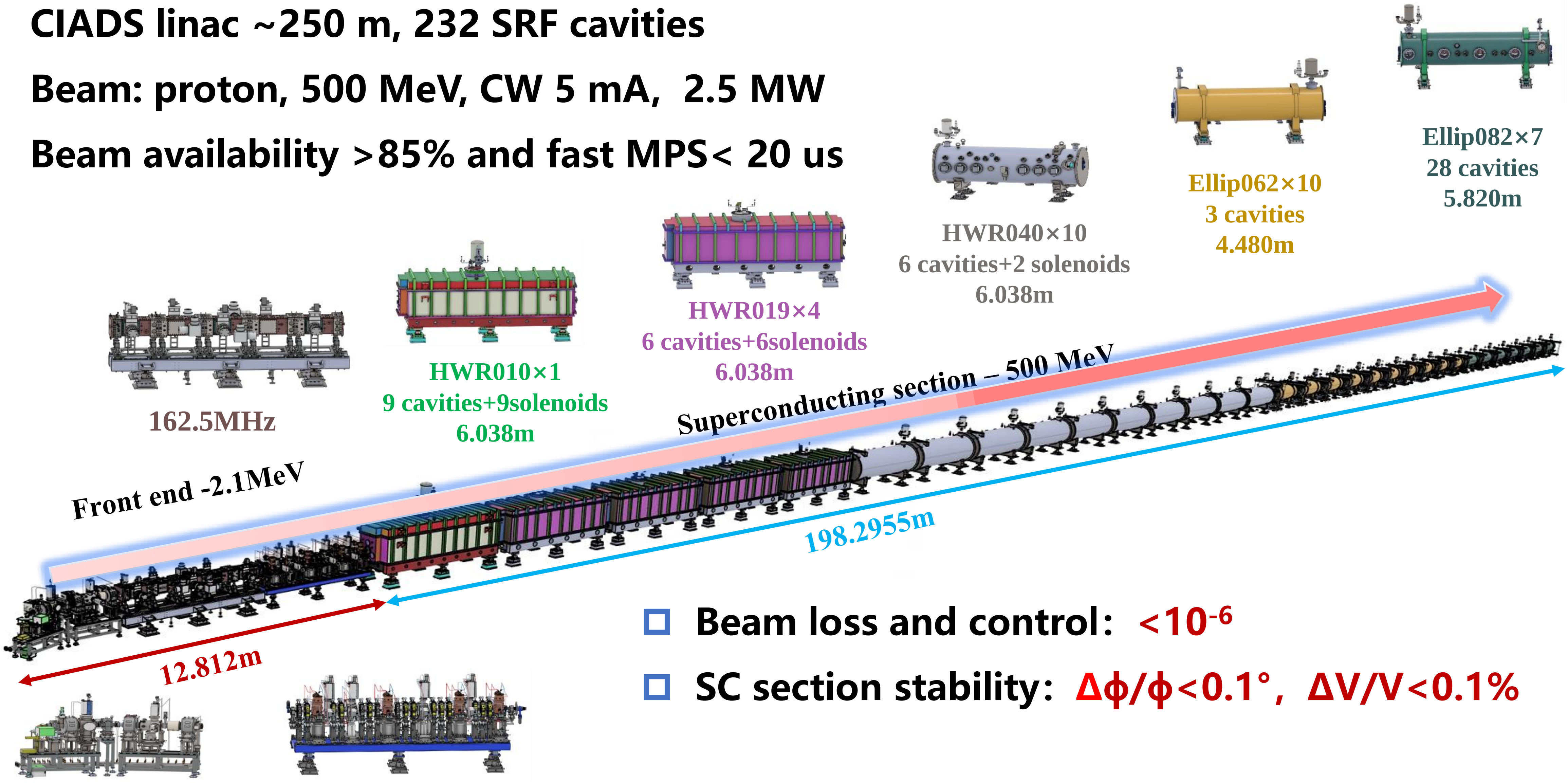
The total budget is 4.0 billion CNY

Construction period: 2021-2027, 6 years

The same campus with HIAF

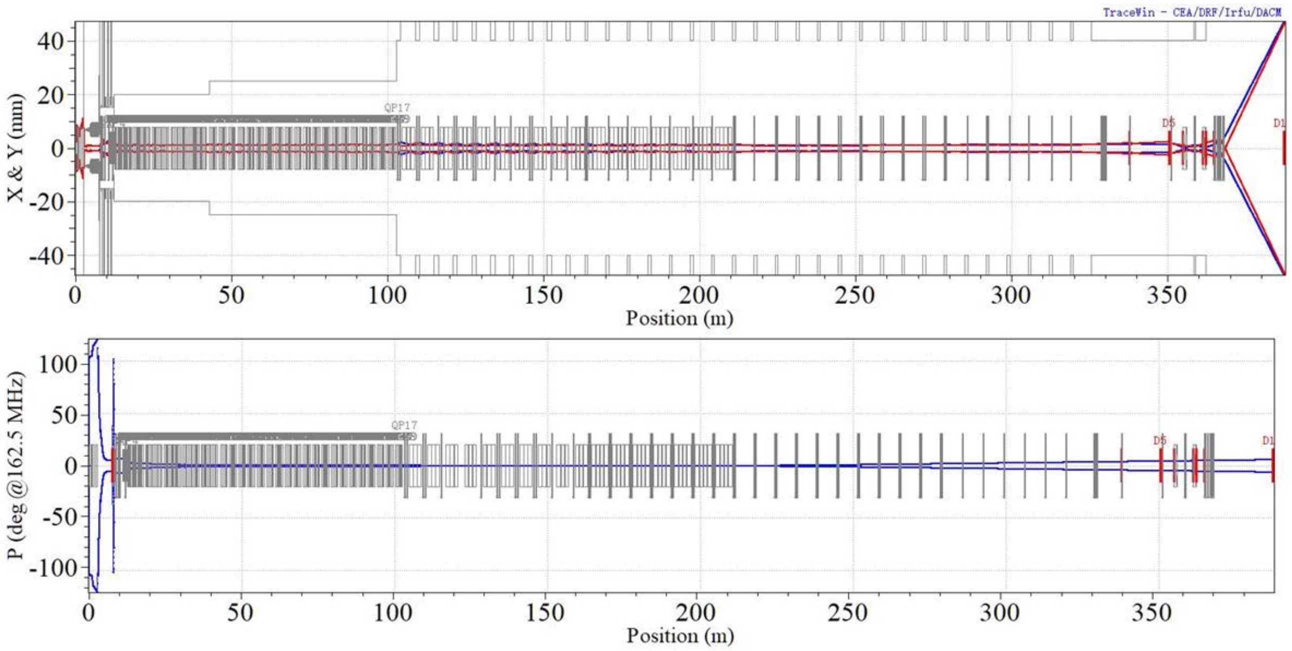
CiADS SC-linac and its challenge

- **CIADS linac ~250 m, 232 SRF cavities**
- **Beam: proton, 500 MeV, CW 5 mA, 2.5 MW**
- **Beam availability >85% and fast MPS< 20 us**



- ☐ **Beam loss and control: $<10^{-6}$**
- ☐ **SC section stability: $\Delta\phi/\phi<0.1°$, $\Delta V/V<0.1\%$**

Physics design of CiADS proton linac



Beam envelope along the linac

Parameters of the SRF cavities

	HWR010	HWR019	HWR040	Ellip062	Ellip082
Freq. (MHz)	162.5	162.5	325	650	650
Quantity	9	24	60	30	28
Dyna. load @ 2K	2.9	4.4	5.7	23	25
Ep @ op. (MV/m)	26	28	28	29	29
Ep @ cp. (MV/m)	31	32	31	31	32

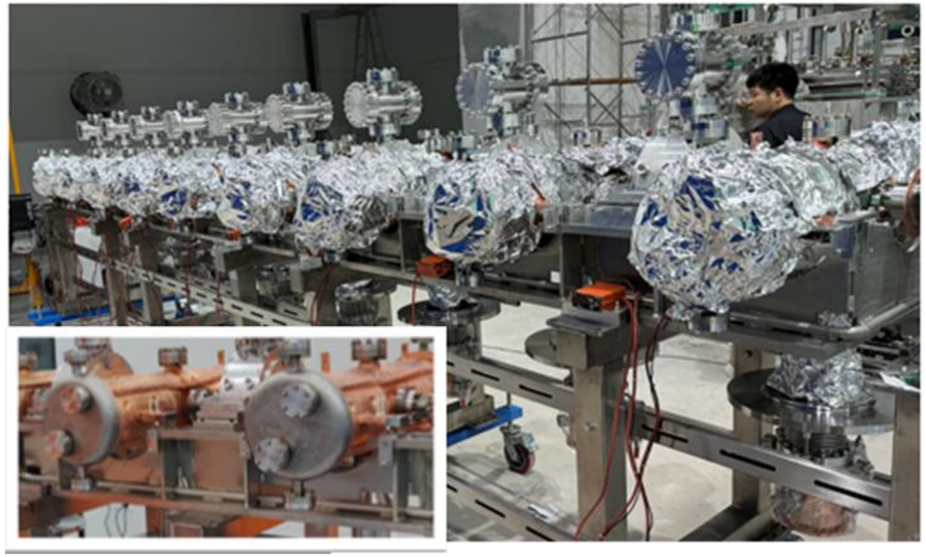
CiADS technical challenge

- **Minimize the beam loss and maintain a long-term high reliability and availability of the high power proton SC linac (500 MeV/5mA)**
- **High power spallation target (2.5 MW). Phase I: LBE target; Phase II: Granular flow target**
- **Coupling between the reactor, the target and the high power proton beam**

Key technology R&D and Prototyping

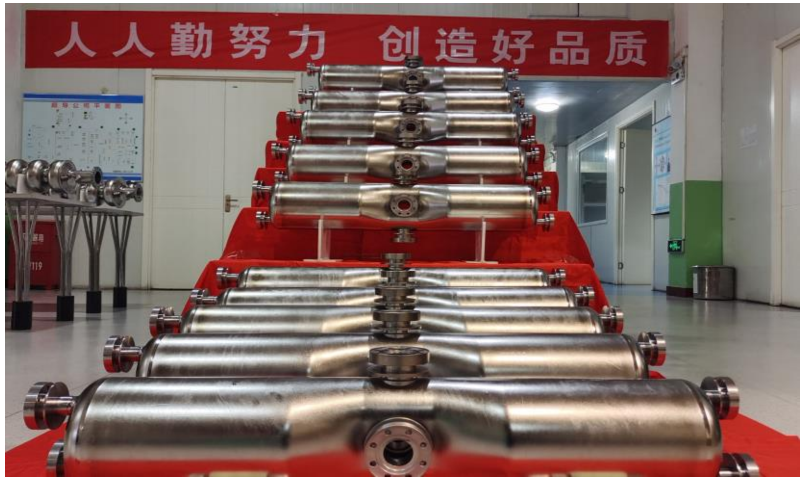
- **17-20 MeV/CW 5-10 mA ADS front-end demo-facility**
- Target prototype R&D (LBE target and granular flow target)
- Prototyping for fast subcritical reactor vessel, heat exchanger and LBE centrifugal Pump

CiADS SC-linac construction (1)



CiADS SC-linac construction (2)

■ CiADS components in mass-production

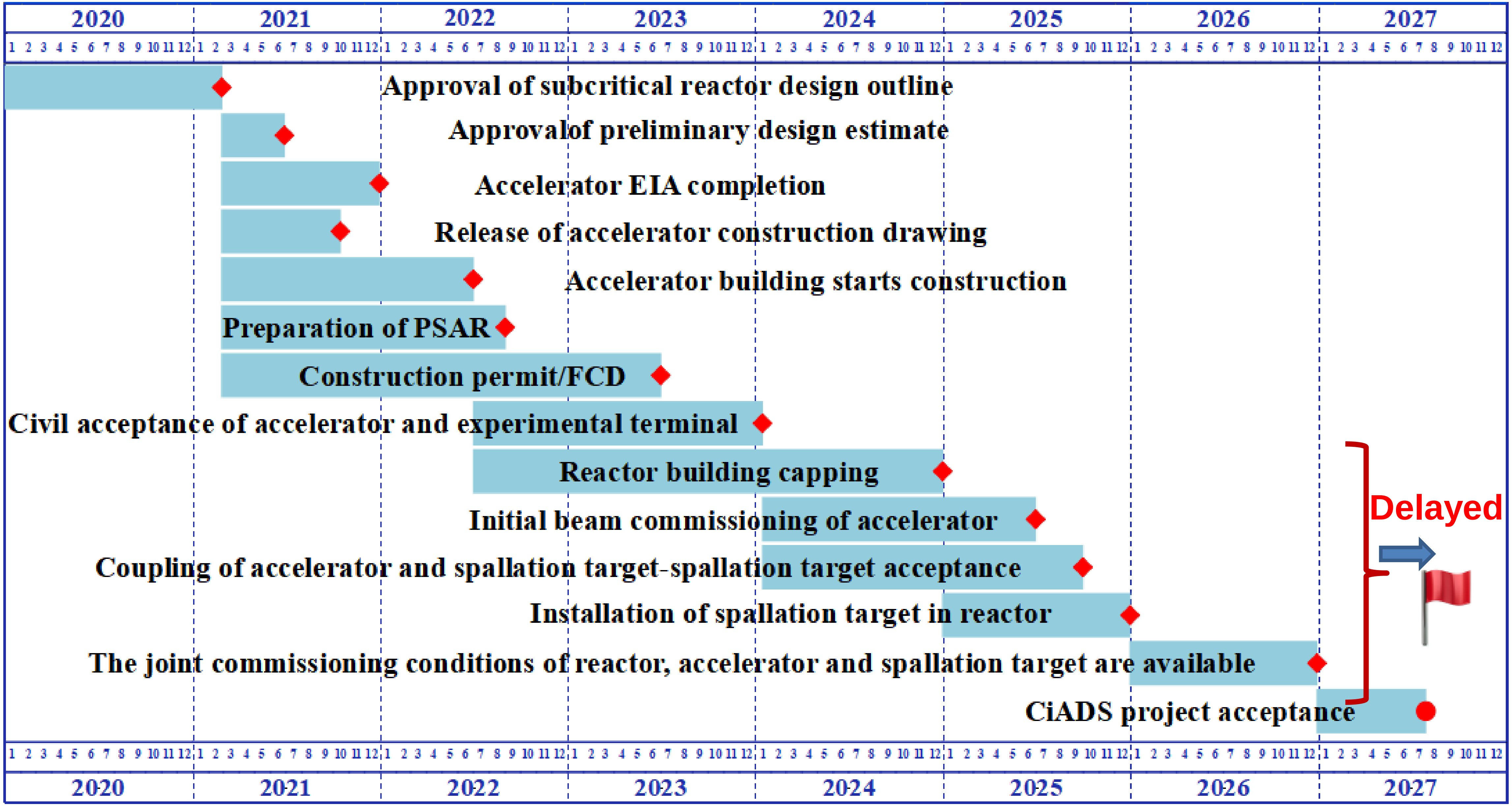


SRF cavities

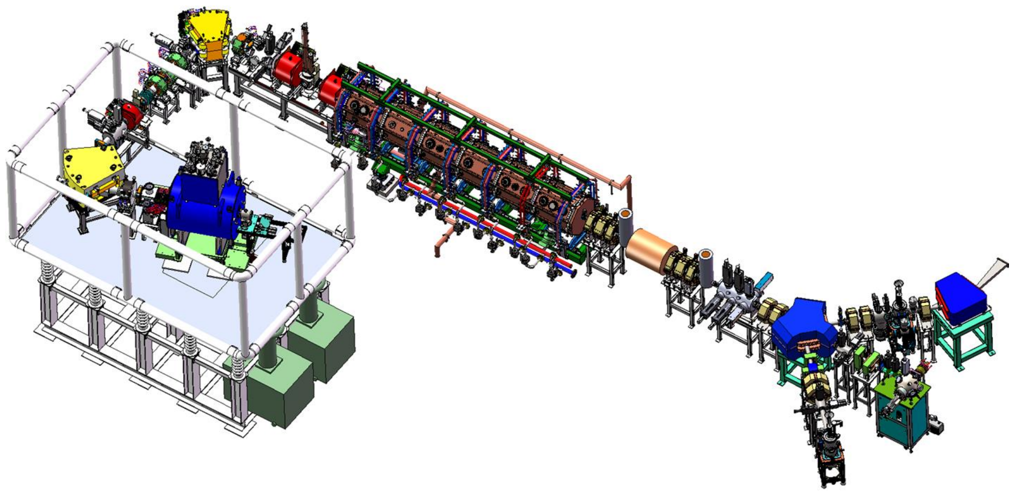
650 MHz @150 kW solid-state RF power source

Proton source and RFQ

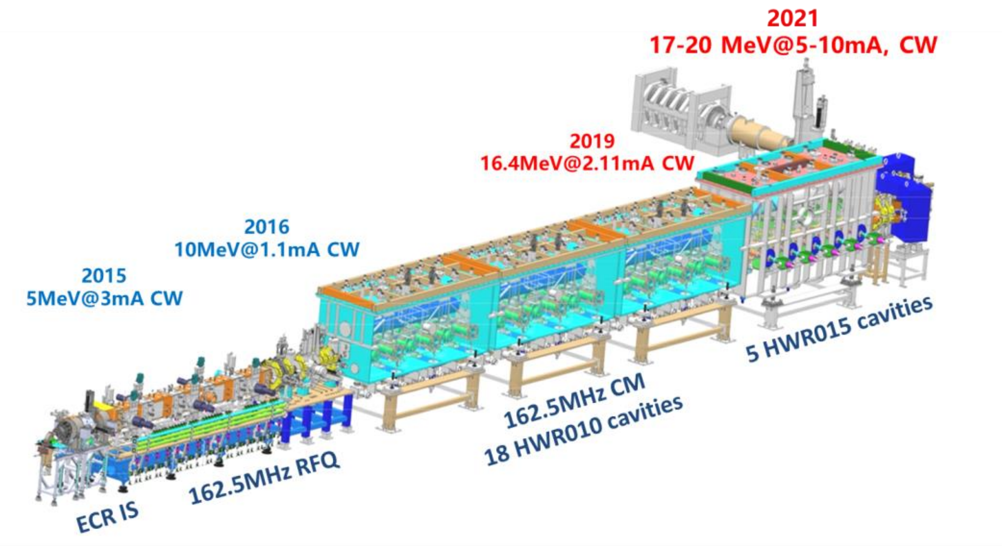
CiADS planed milestones and time schedule



Key technology R&D for HIAF and CiADS

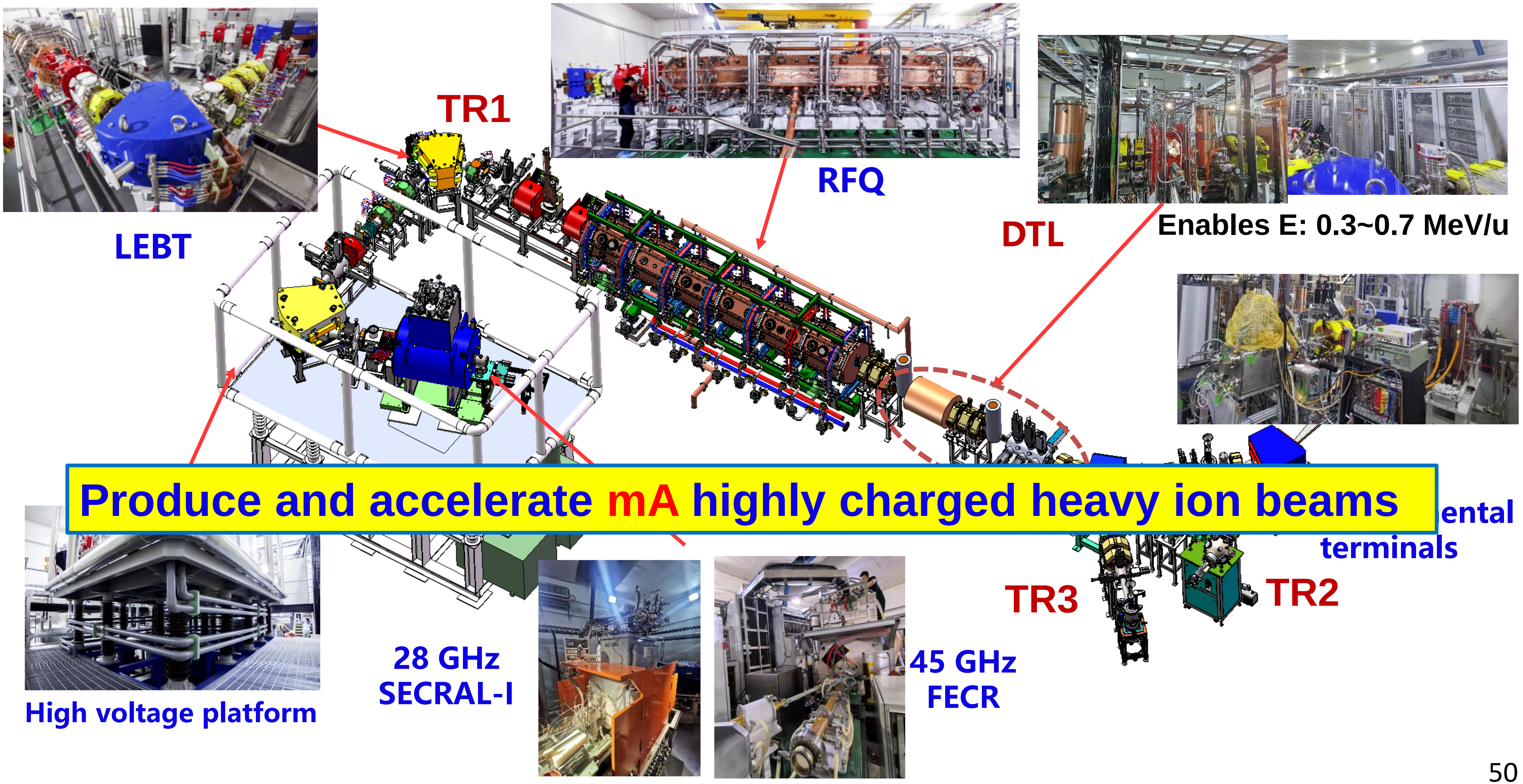


LEAF – FECR+RFQ， 0.5 MeV/A
Front-end demo for HIAF



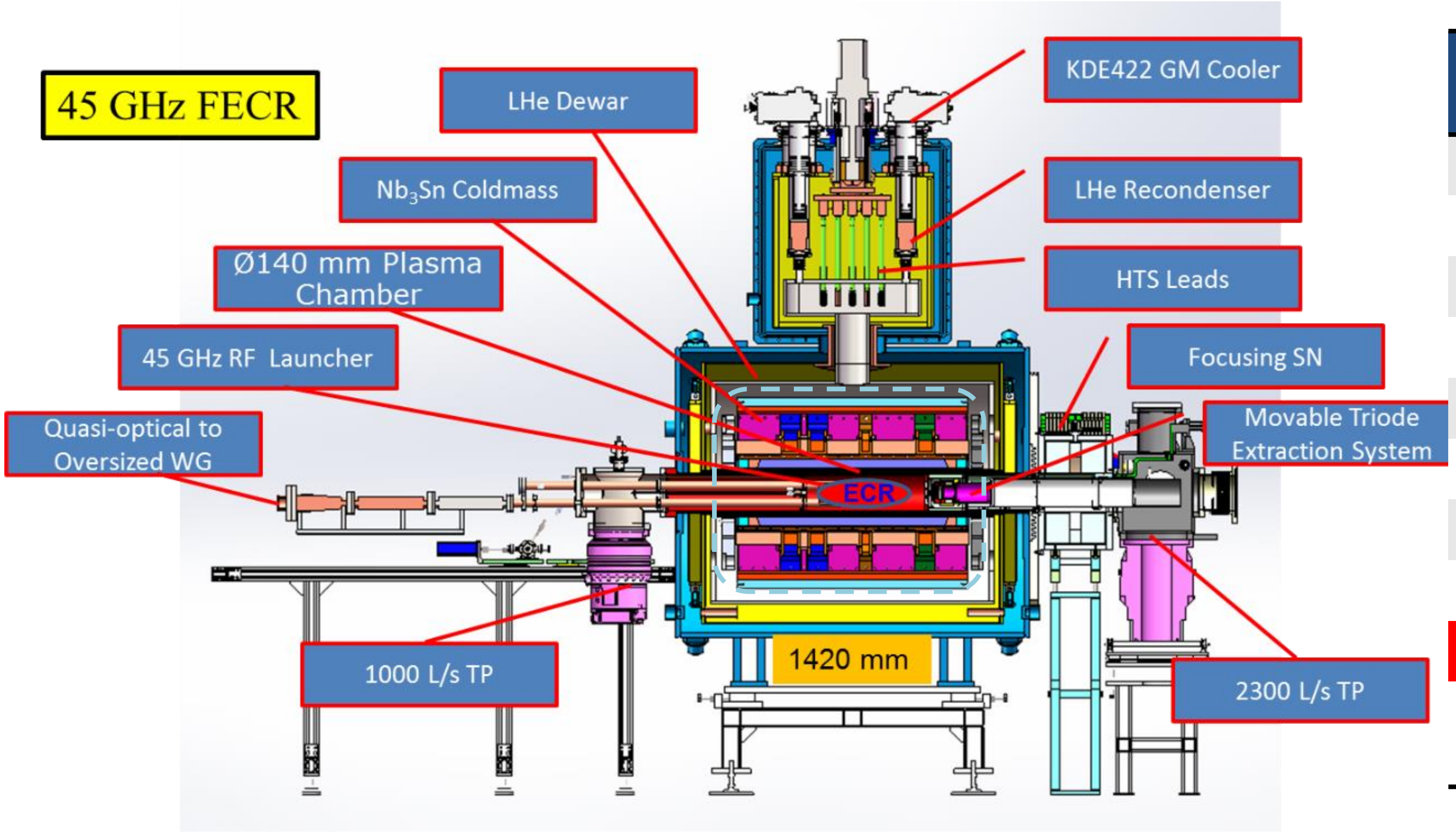
SC proton linac – 20 MeV/10 mA
Front-end demo for CiADS linac

Low energy accelerator for high intensity heavy ion beams: LEAF



Produce and accelerate mA highly charged heavy ion beams

The world first 45 GHz ECRIS --- FECR



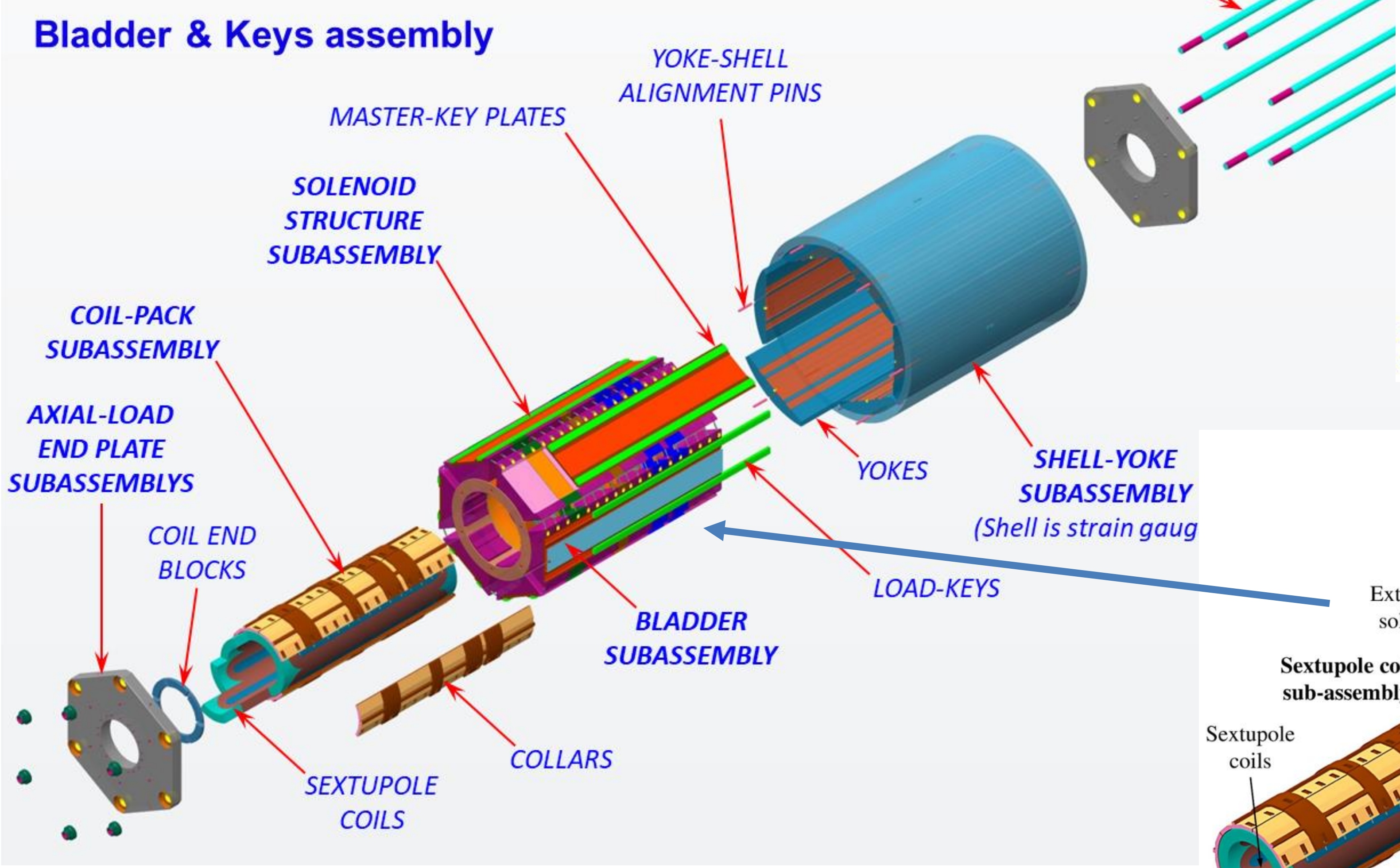
FECR Parameters

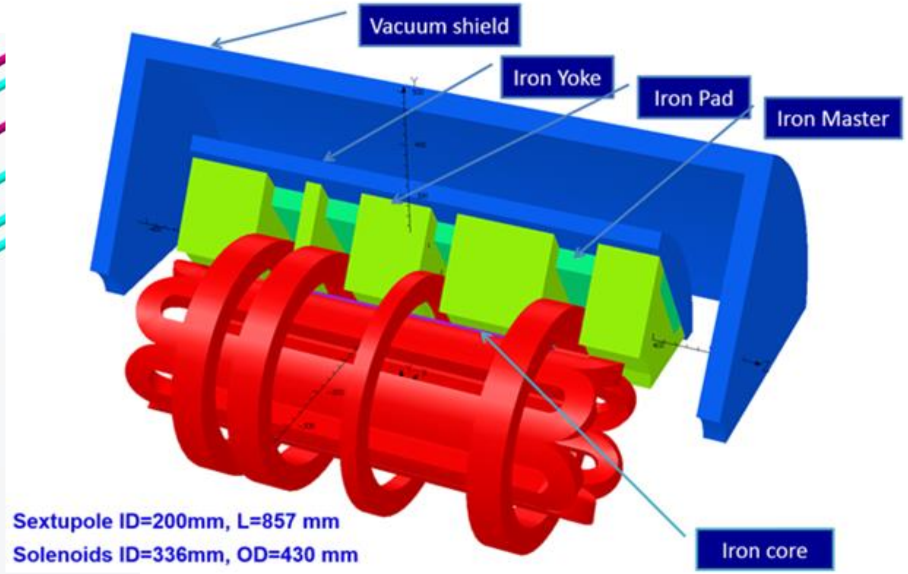
Specs.	Unit	45 GHz ECRIS
Frequency	GHz	45
RF Power	kW	20
Chamber ID	mm	>Ø140
Mirror Fields	T	≥6.4/3.2
B_{rad}	T	≥3.2
Mirror Length	mm	~500
B_{max} in conductor	**T**	**~11.8**
Magnet coils	/	Nb_3Sn
Nb_3Sn	J_c>1500 A/mm²@12T	
Cooling Capacity@4.2 K	W	>10.0

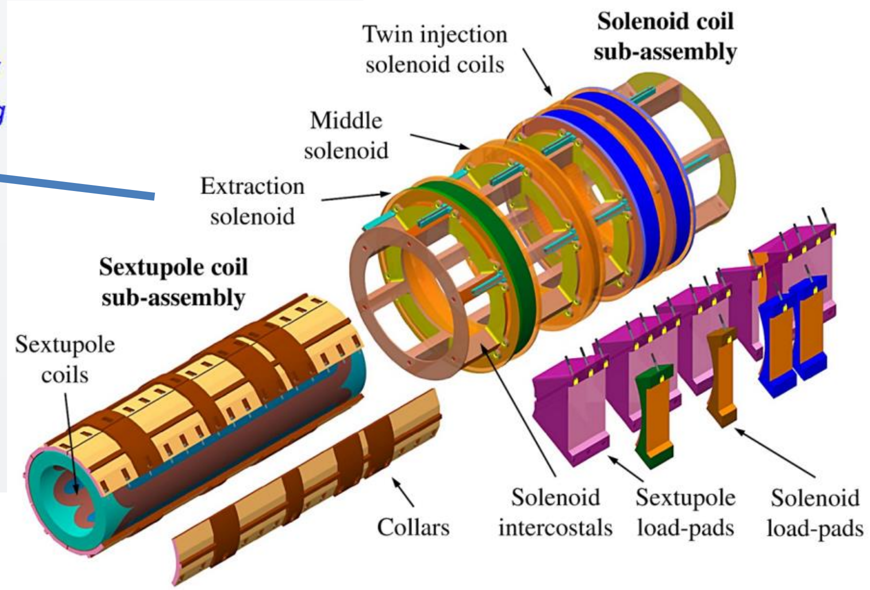
- ***H. W. Zhao***, *Review of Scientific Instruments* ***89***, *052301 (2018)*
- ***L. Sun***, *Journal of Physics: Conference Series* ***2244(1)***, *012021(2022).*

FECR Nb_3Sn magnet

The magnet mechanical structure was designed by collaboration with ATAP magnet group at LBNL



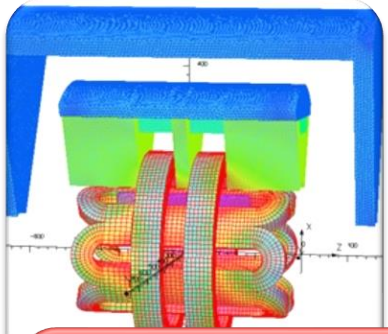




FECR Nb_3Sn magnet development

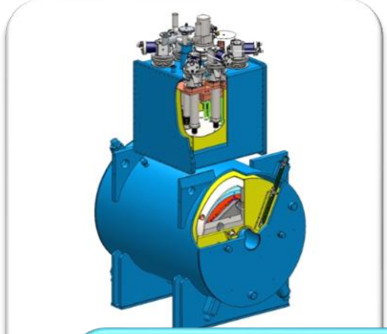
From prototyping to operational machine (2015-2023)

Key technologies
- Coils fabrication
- Keys & Bladder
- Quench protection
- Know-how of Nb_3Sn coil



½ Prototype Coldmass
- Quality control and analysis
- SG assisted mechanical assembly
- Quench protection
- Reliability

Full Sized coldmass
- Quality control of mass production
- Quench protection
- Reliability
- System integration



FECR Magnet
- System integration
- Coldmass alignment
- Reliable operation

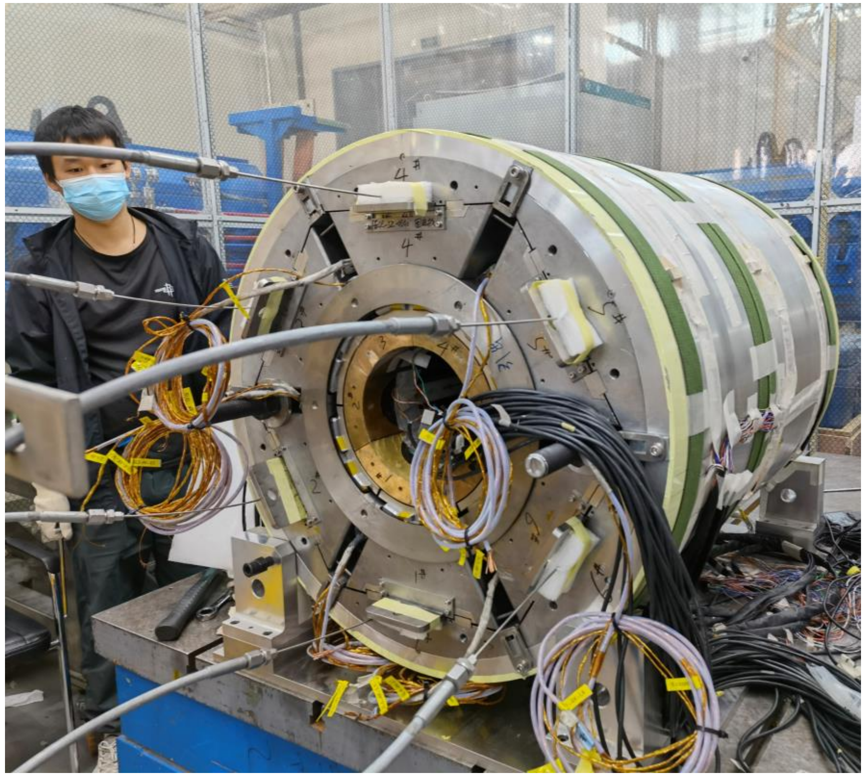
To demonstrate 80~85% of FECR coldmass performance

Operational FECR Nb_3Sn magnet

8 years R&D for FECR magnet

FECR full-scale Nb_3Sn magnet status

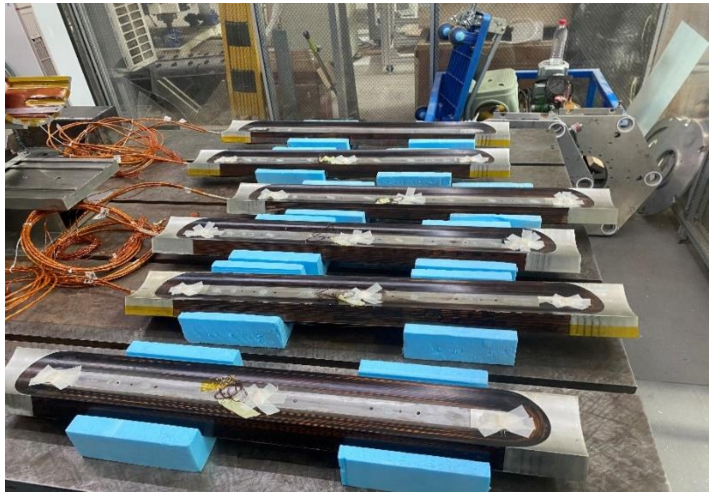
But need to verify the quench protection system, one sextupole coil in the cold-mass insulation problem!

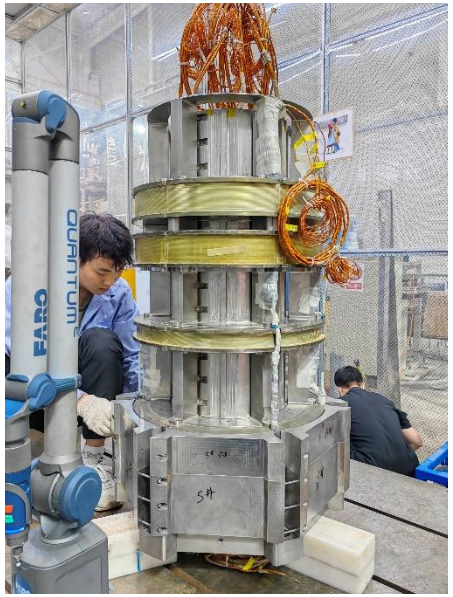


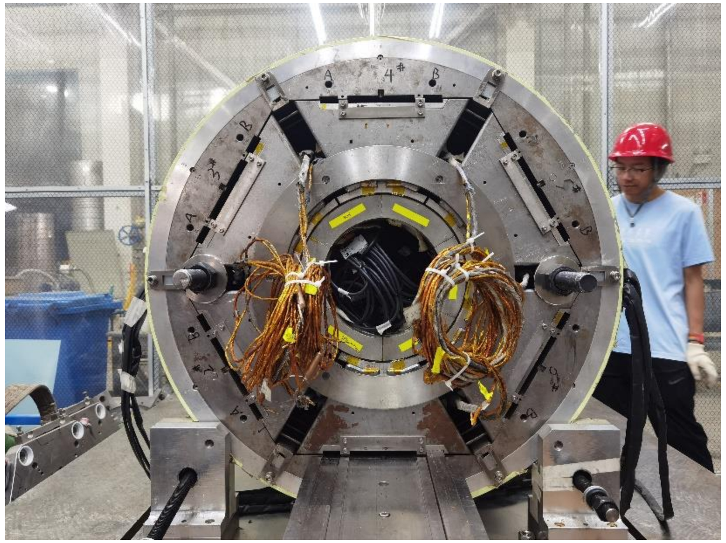
Continue and not give up

FECR Nb_3Sn+NbTi hybrid magnet

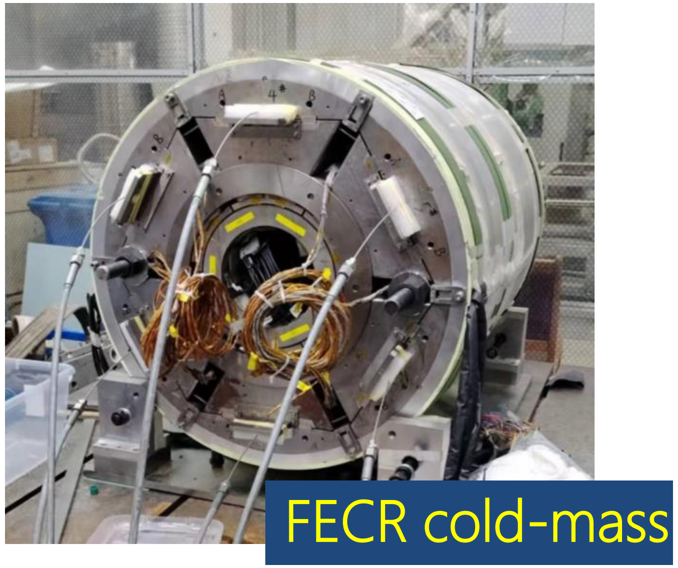
NbTi Sextupole+Nb_3Sn Solenoids

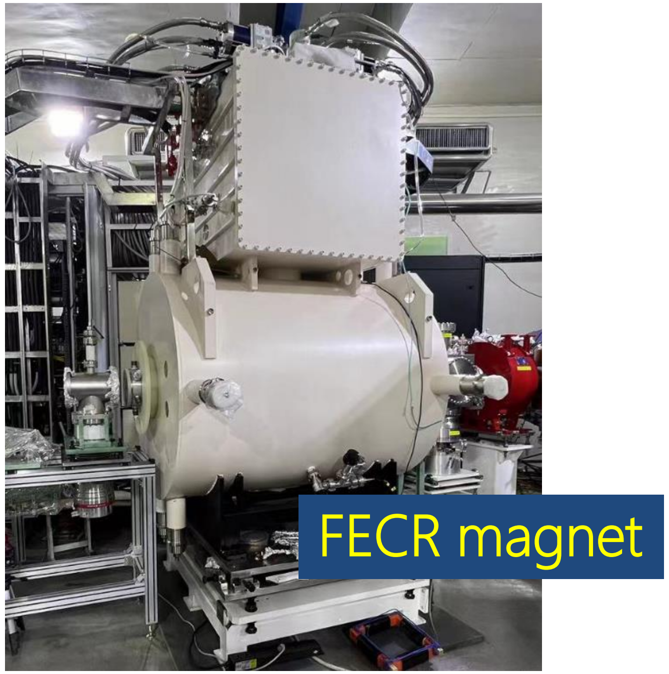


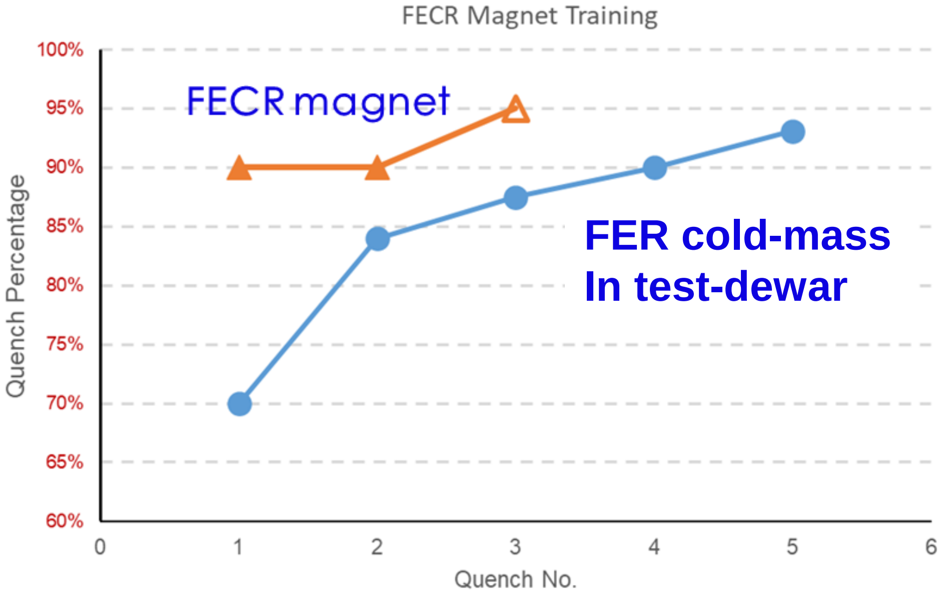


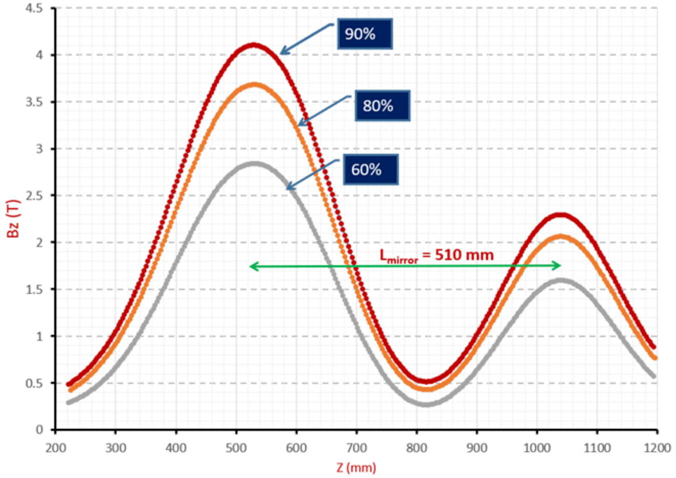


Magnetic field measurements of FECR hybrid magnet

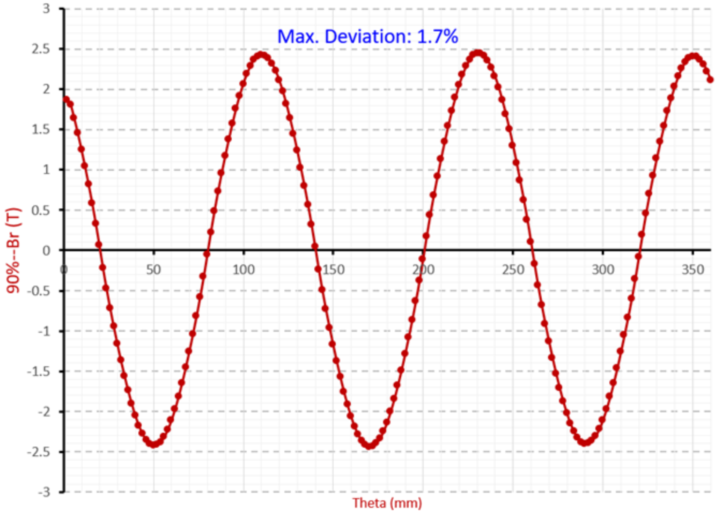








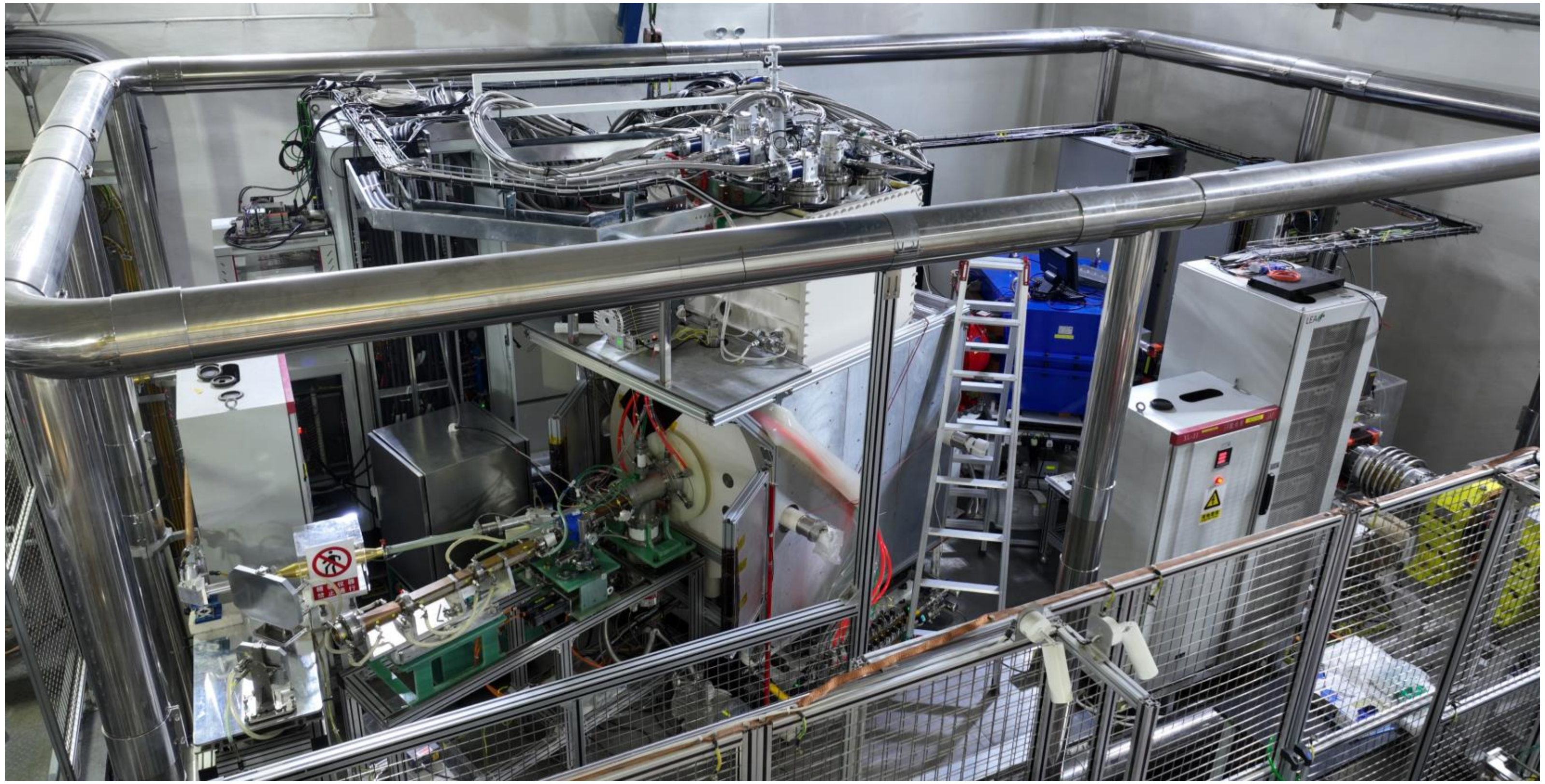
Axial mirror field at measured the axis



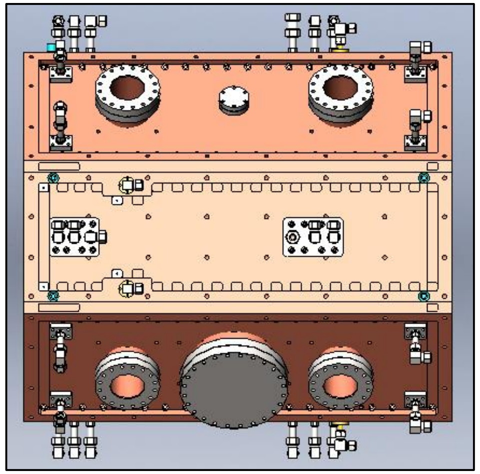
Sextupole field measured at r=65 mm

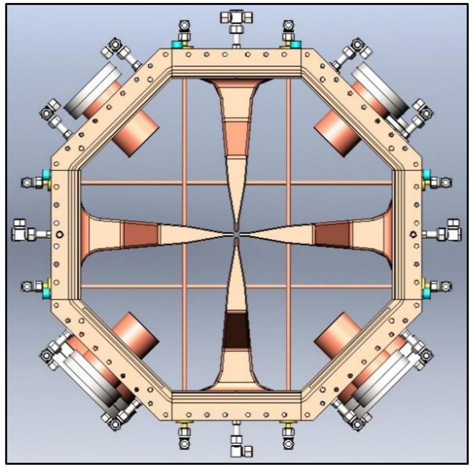
LEAF- 45 GHz FECR

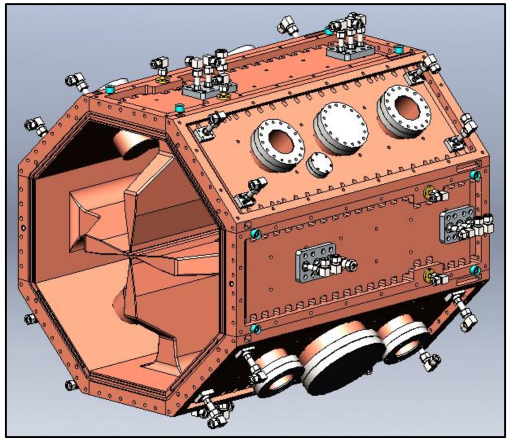
FECR with hybrid magnet

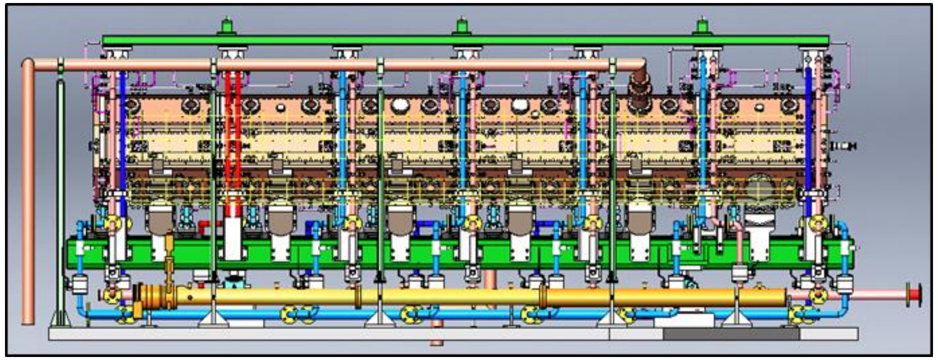


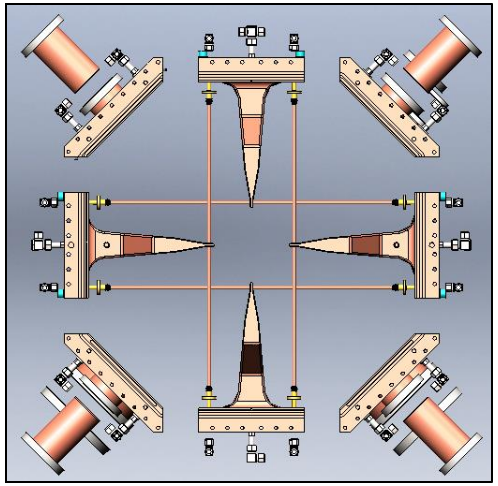
LEAF- RFQ (1)

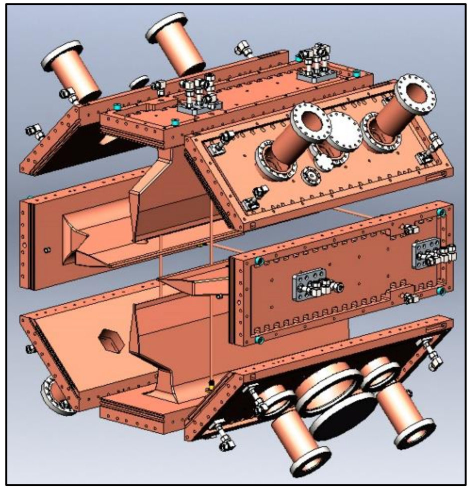


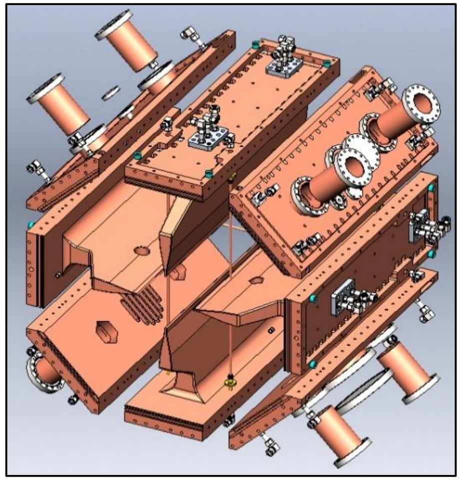


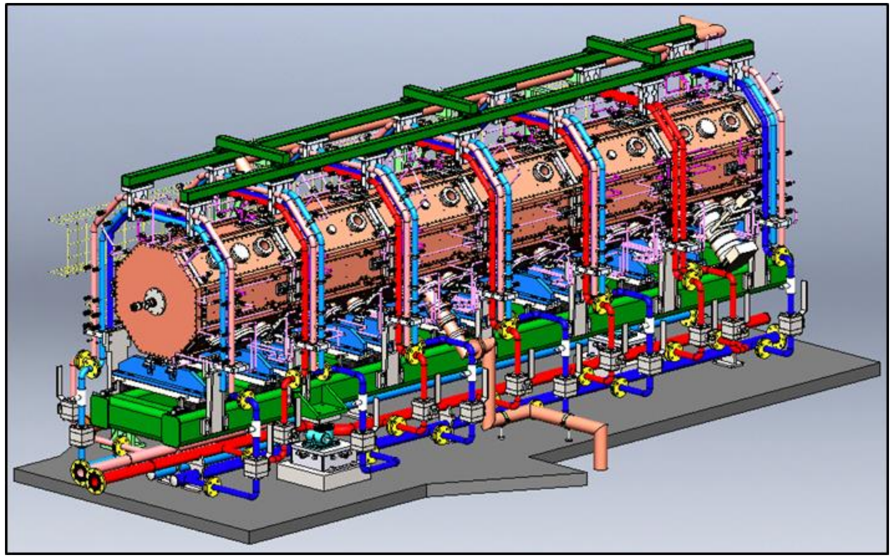




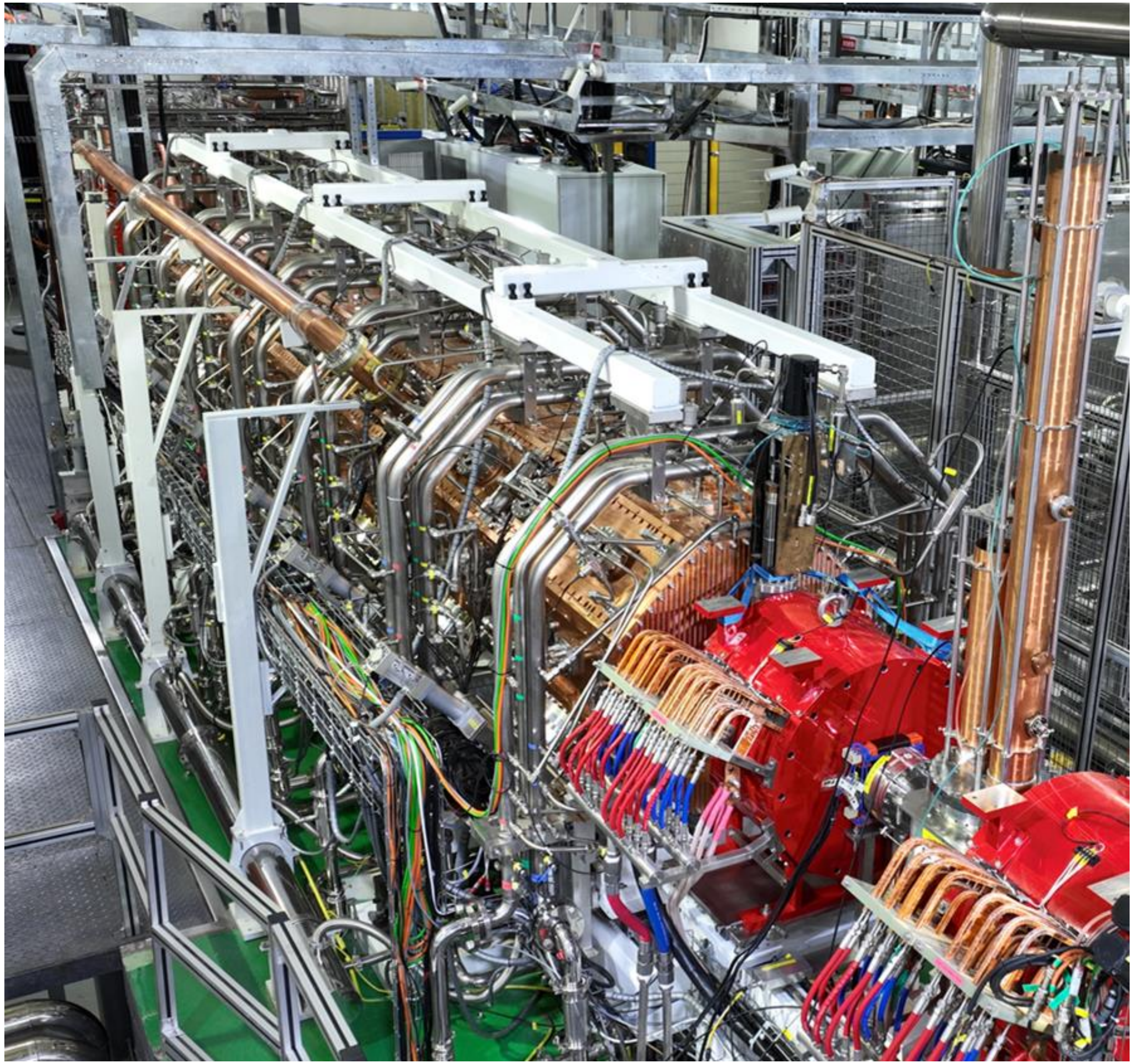


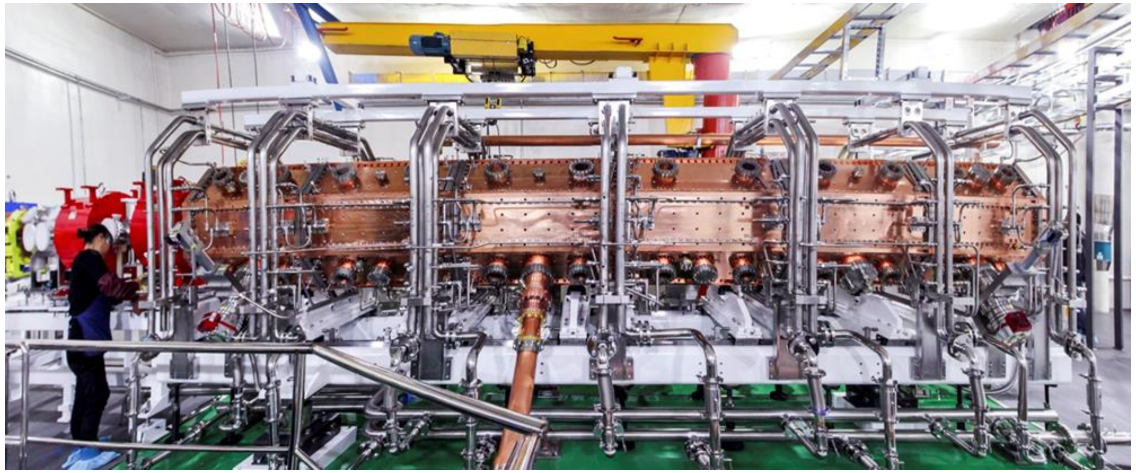




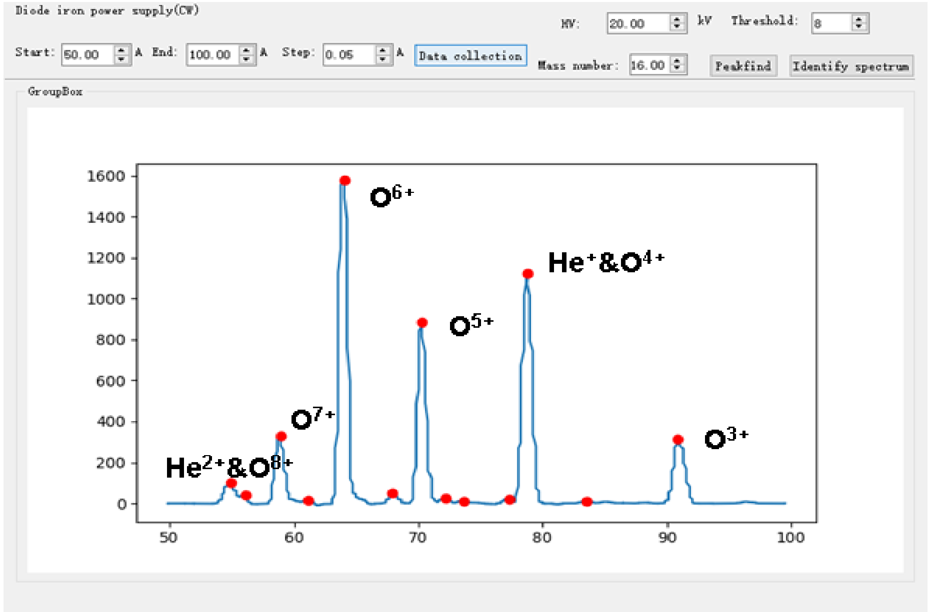


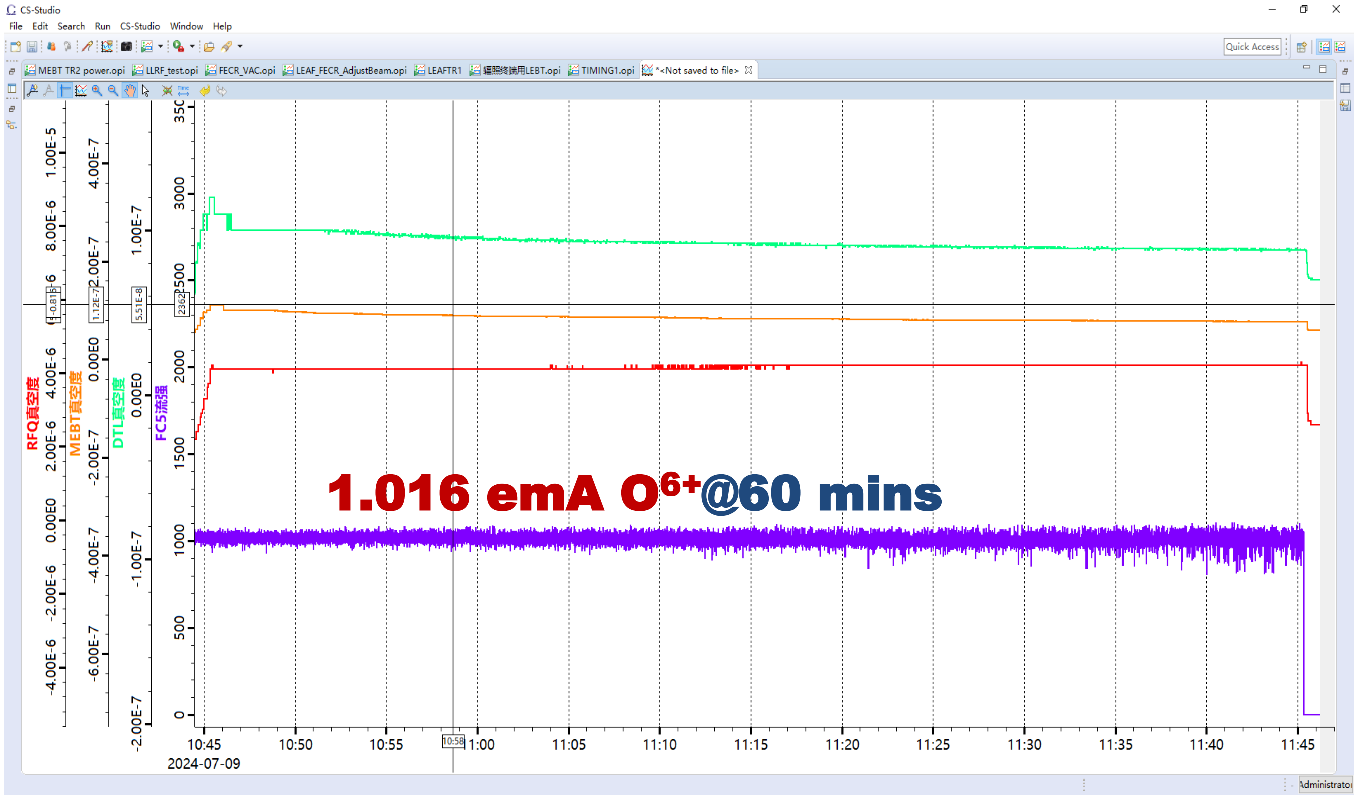
LEAF-RFQ (2)





1 emA $^{16}O^{6+}$ CW beam acceleration by LEAF-RFQ





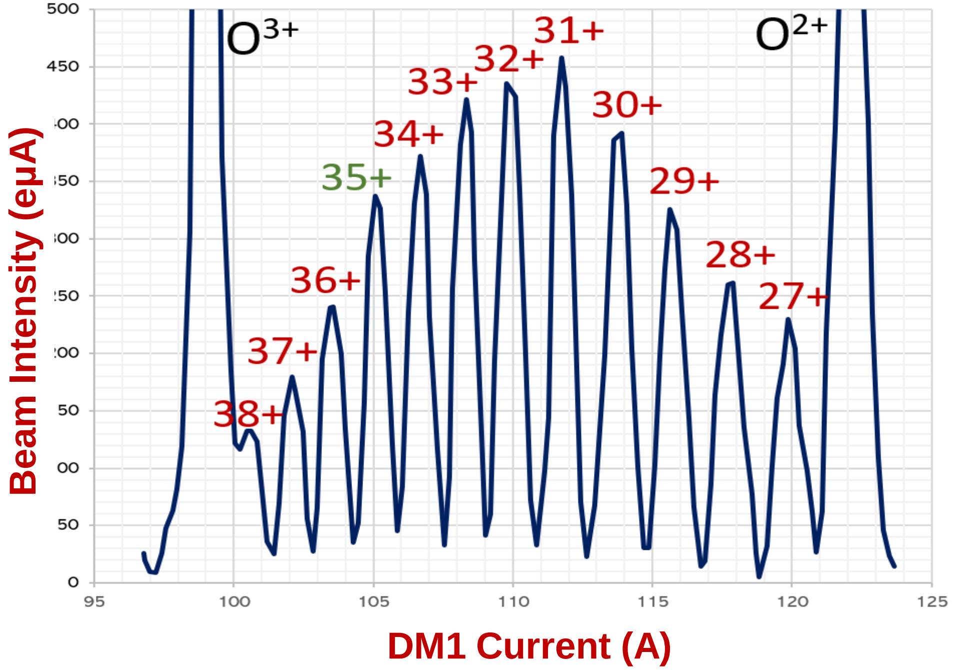
FECR: 1.6 emA O^{6+}

CW beam acceleration of 1.0 emA $^{16}O^{6+}$

- **RFQ transmission efficiency ~90%**

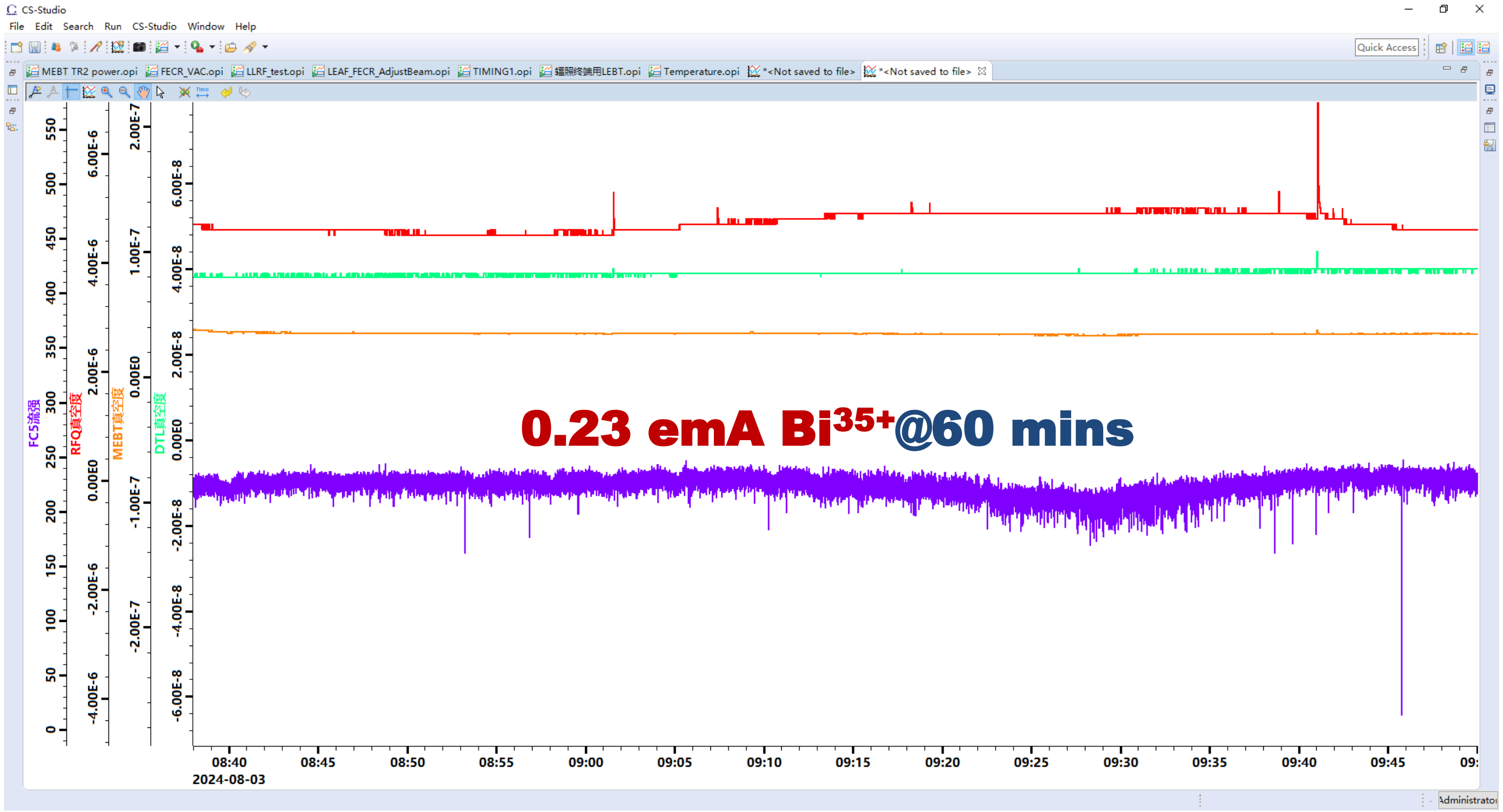
The world first demonstration

0.23 emA $^{209}Bi^{35+}$ CW beam acceleration by LEAF-RFQ



FECR: 330-350 eμA $^{209}Bi^{35+}$

6.5 kW 45GHz+5.5 kW 28GHz



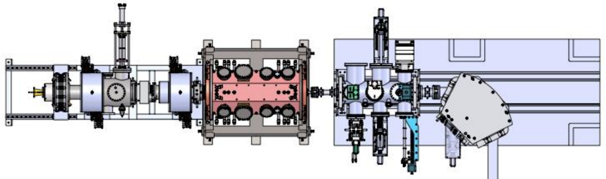
1 hour stability demonstration of CW 230 eμA Bi^{35+} beam accelerated by the LEAF-RFQ

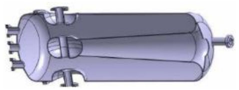
- **RFQ transmission efficiency ~90%**

The world first demonstration

Milestone of CW proton SC linac as R&D for CiADS

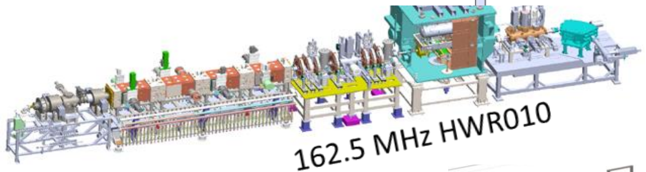
1





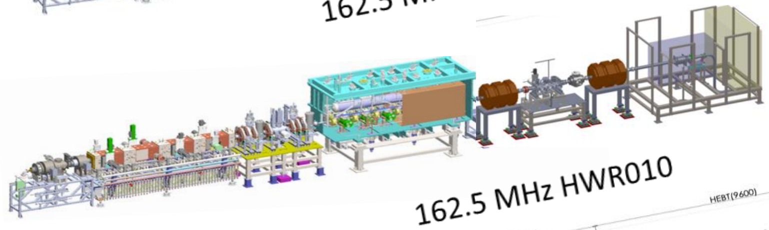
- 2009-2012, SRF and RFQ design, prototyping

2



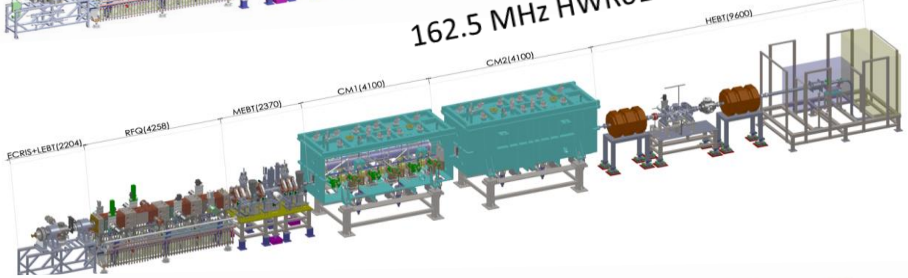
- 2014， 2.1 MeV RFQ+single HWR cavity
- CW 2.5 MeV/10 mA

3



- 2014-2015，RFQ+6 HWR cavity
- CW 4-5 MeV/4 mA

4



- 2016，RFQ+12 HWR cavity
- CW 10 MeV/2 mA

5

- 2017-2019，RFQ+23 HWR cavity
- CW 15-25 MeV/2 mA

6

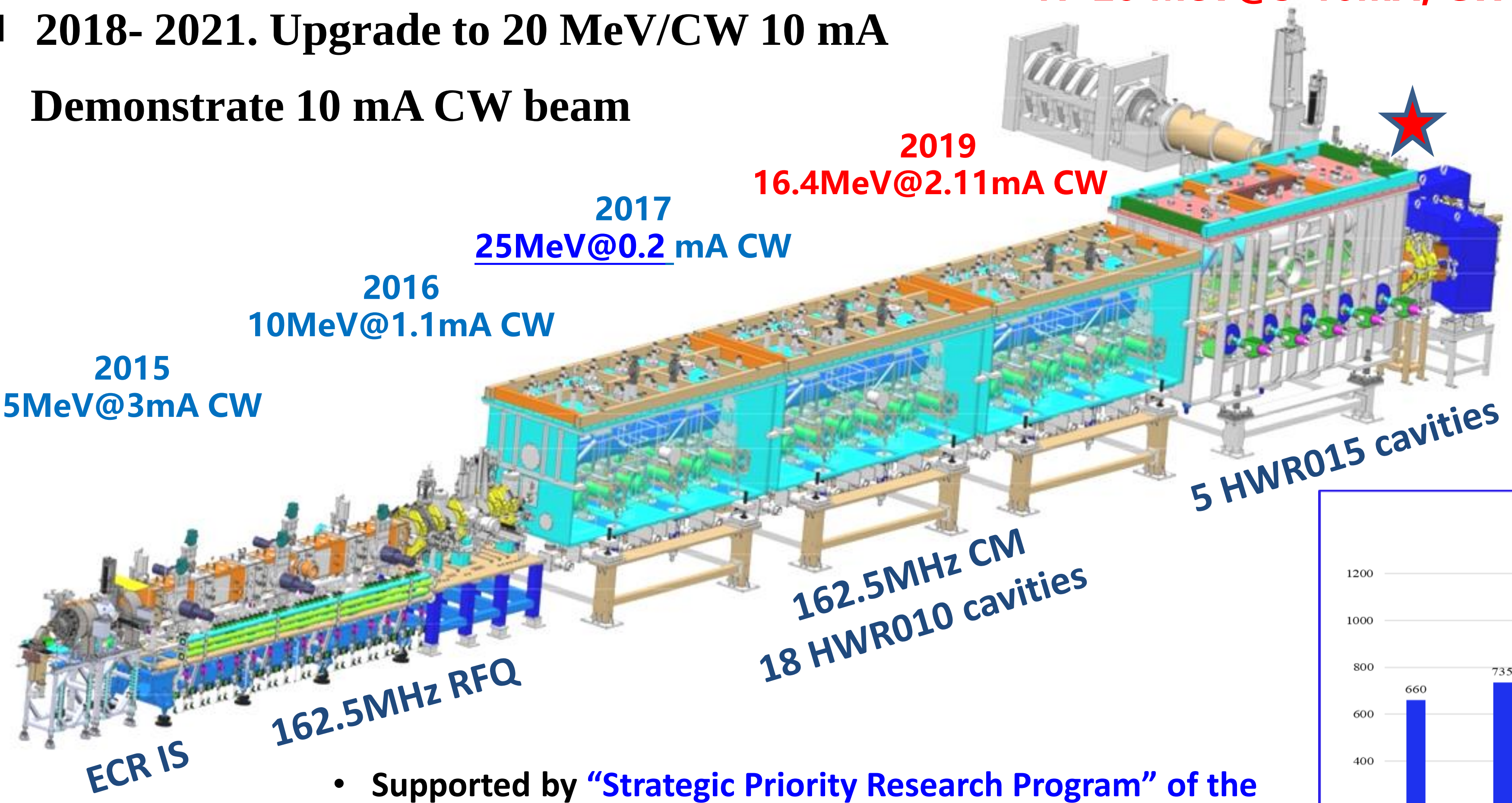
- 2019-2021，RFQ+23 HWR cavity
- CW 20 MeV/10 mA
- 7.3 mA@126 kW，108 hours

The world first demonstration for CW proton linac

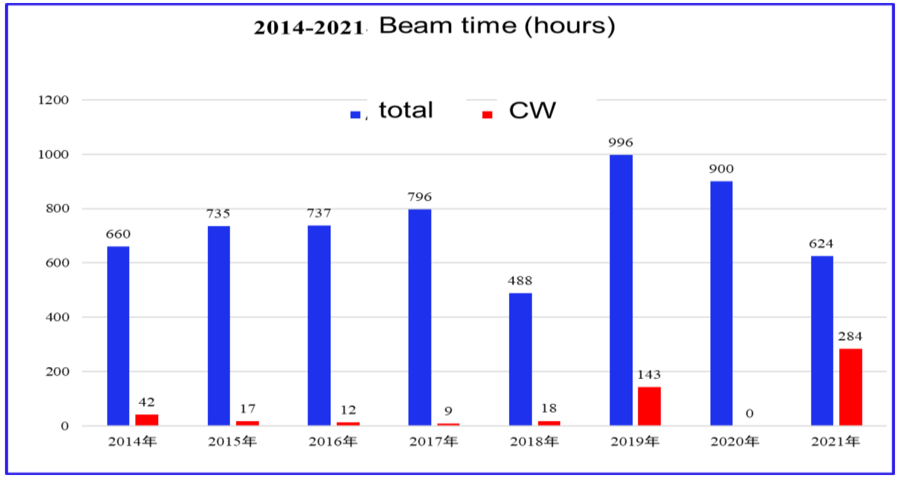
17-20 MeV/5-10 mA front-end demo facility for CiADS linac

- 2011-2017. SC linac 10-25 MeV/ CW 0.2-1.1 mA IMP collaborated with IHEP.
- 2018- 2021. Upgrade to 20 MeV/CW 10 mA

Demonstrate 10 mA CW beam



ions	P, H_2^+, α
Frequency	162.5 MHz
Current	10 mA
E_{in} RFQ	40 keV
E_{out} RFQ	3.1 MeV
E_{out} SC linac	20/30/40MeV
Cryo. Temp.	4.5 K

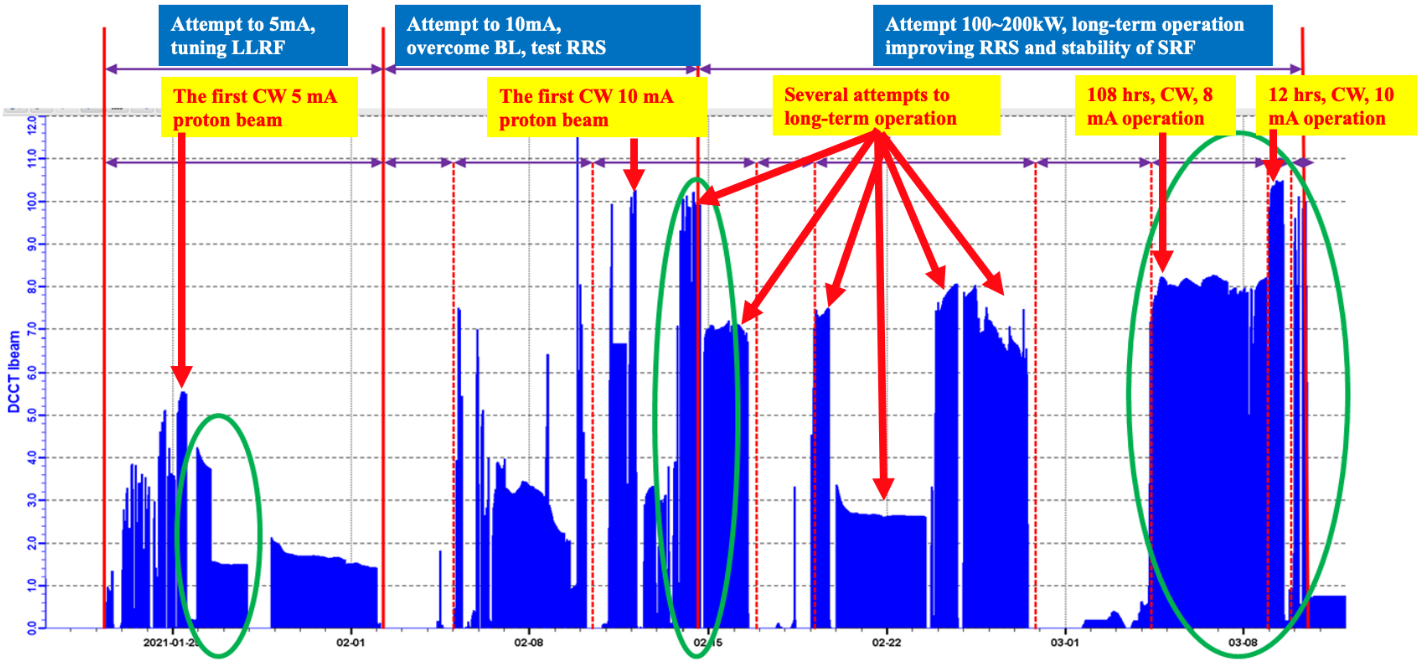


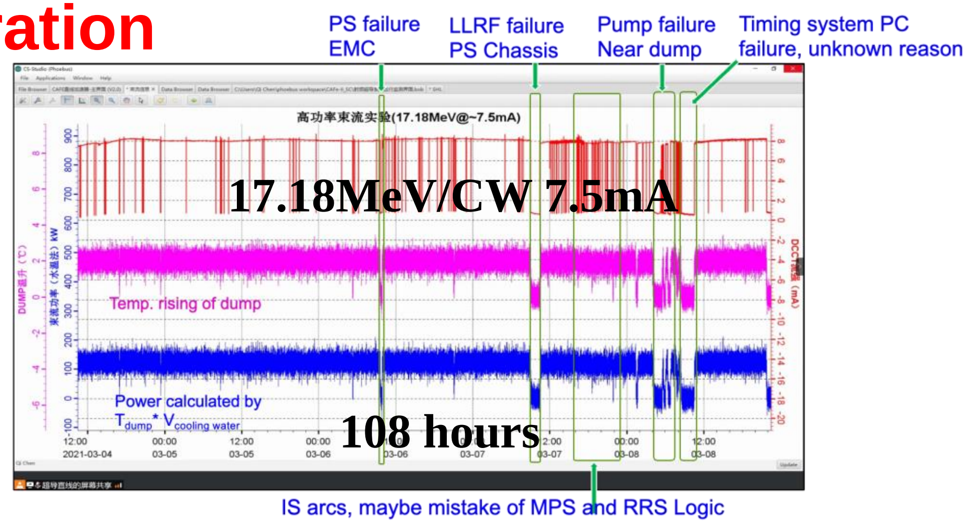
- Supported by "Strategic Priority Research Program" of the Chinese Academy of Sciences.

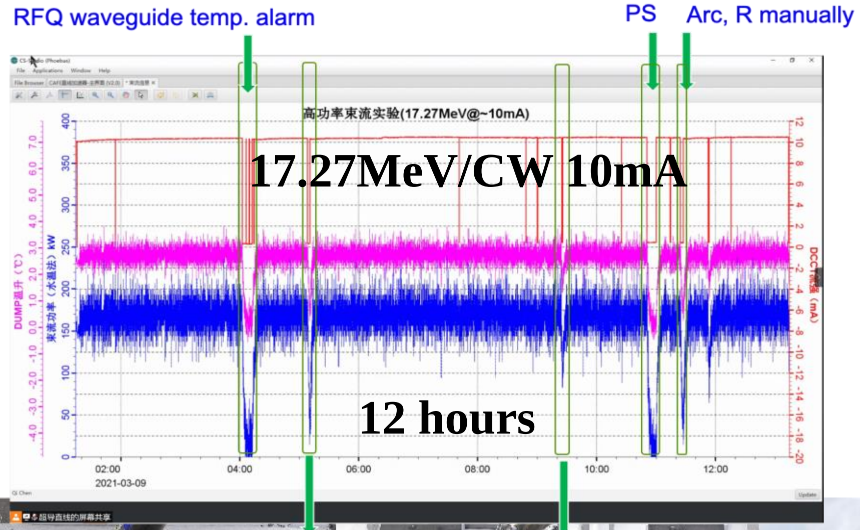
High power CW SC proton linac reliability demonstration

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

The world first demonstration







Availability: 126.1 kW, op. time 108 hs, availability 93.6%

Beam current: 174.4 kW、10.08 mA, op. time 12 hs

High power: 20.18 MeV、10.18 mA、beam power 205.5 kW

Summary

- Many applications for HIHP ion accelerator in scientific research and national demands

- Technically challenging for HIHP ion accelerator, key technologies need R&D, such as
  high intensity ion sources, high performance SRF cavities, high field SC magnets,
  high power targets, diagnostics, LLRF, MPS, AI&ML..

- Many HIHP ion accelerators being operated and planed, globle collaboration necessary.

- HIAF&CiADS being built after many years R&D. Expected to reach the designed performance and could be one of the world best-performance HIHP ion accelerators

Thank you for your attention !