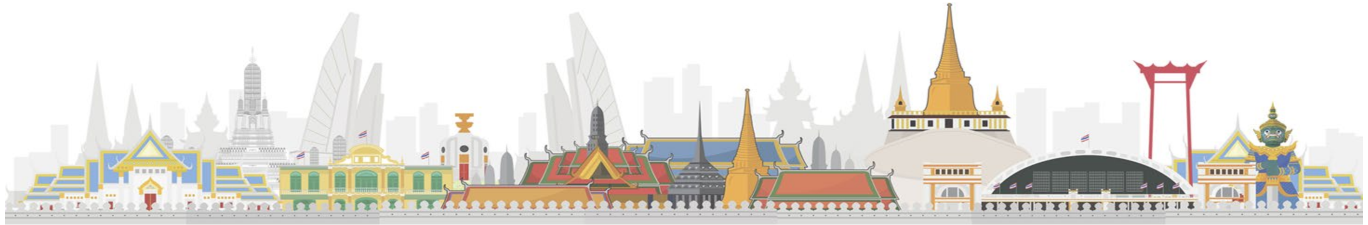


High intensity ion beam accelerator facilities HIAF and CiADS status and demonstration of key technologies

Hongwei Zhao

On behalf of HIAF&CiADS team

Institute of Modern Physics (IMP), Chinese Academy of Sciences, Lanzhou, China

OUTLINE

- Brief introduction and construction status of HIAF & CiADS
- Key technology R&D and demonstration

  1. High-intensity highly-charged heavy ion beam production
  2. Fast ramping power supply with full energy storage
  3. Magnetic alloy core loaded RF system

  (items 1–3: for HIAF)

  4. 17-20 MeV/CW 5-10 mA front-end demo-facility of proton SC linac for CiADS
- Summary and conclusion

HIAF&CiADS brief introduction

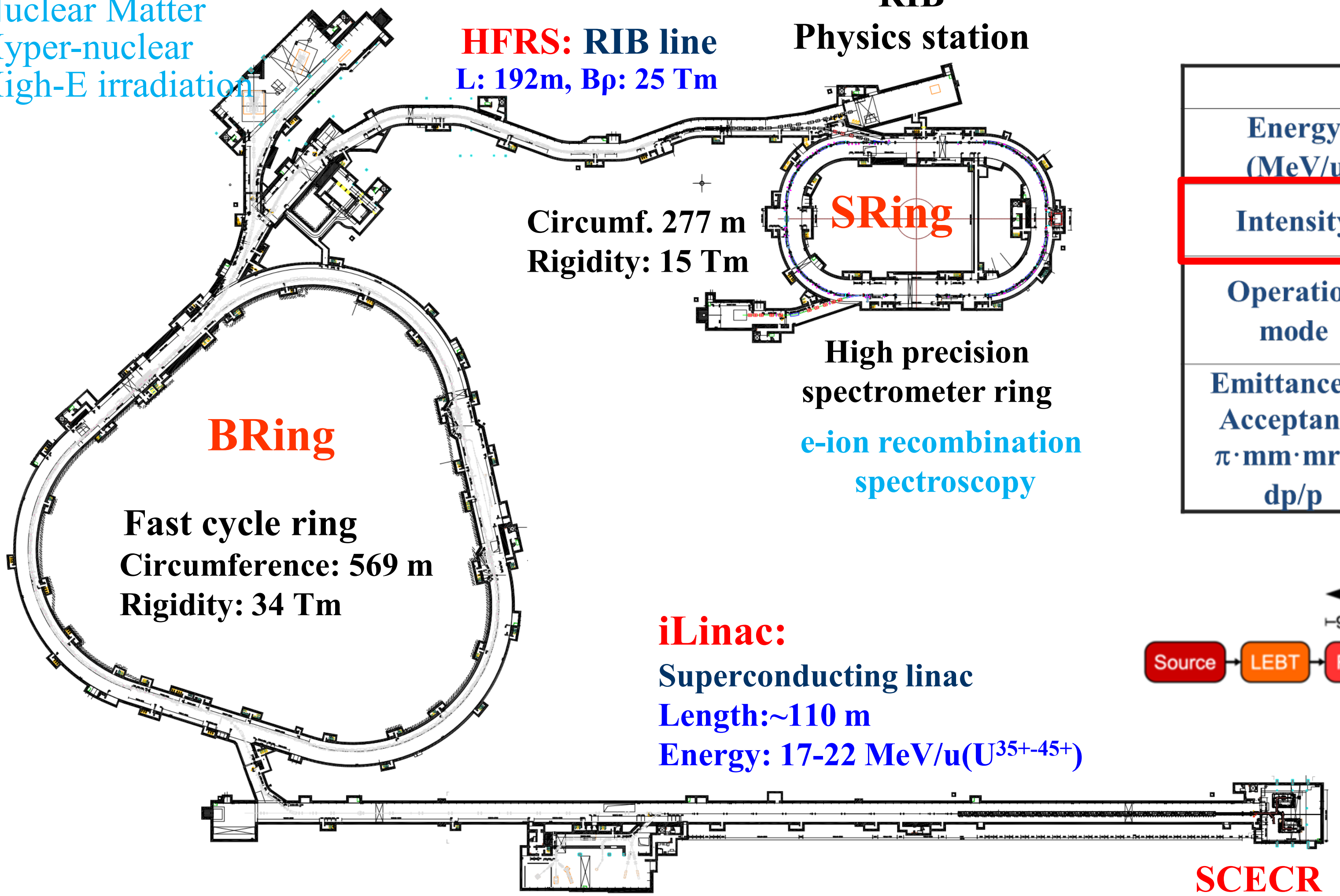
- **HIAF: High Intensity heavy ion Accelerator Facility**
- **CiADS: China Initiative Accelerator Driven System**
- **Being built by IMP in Huizhou of Guangdong Prov.**

- **Two of 16 large-scale scientific infrastructure facilities approved by China Government during the 12th 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

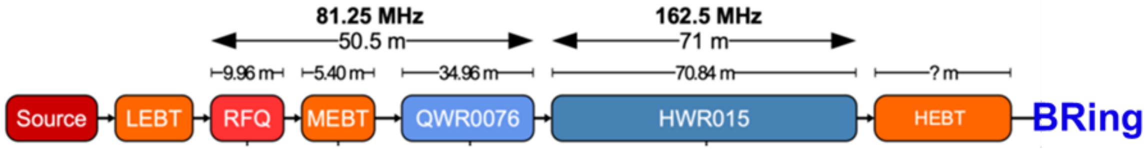
- **CiADS:** Nuclear waste transmutation
- **Total budget:** 4.0 B CNY ¥ (606 M USD $)
- **Schedule:** 2021-2027
- Construction started officially July. 2021

HIAF layout and parameters



HIAF key parameters

	SECR	iLinac	BRing	HFRS	SRing
Energy (MeV/u)	0.014 (U^{35+})	17 (U^{35+})	**835 (U^{35+})**	800 (U^{92+})	800 (U^{92+})
Intensity	**50 pμA (U^{35+})**	**28 pμA (U^{35+})**	**2×10^{11}ppp (U^{35+})**	-------	10^{10}ppp (U^{92+})
Operation mode	DC	CW or pulse	**fast ramping 12T/s 3Hz**	Momentum -resolution 1100	DC, deceleration
Emittance or Acceptance π·mm·mrad dp/p		5 / 5	**200/100 0.5%**	±30/±15 ±2%	40/40 1.5%



iLinac:

Superconducting linac injector

HIAF technical challenge

- High-intensity highly-charged heavy ion beam production and acceleration
- Two-phase painting injection to increase BRing injection efficiency and overcome space charge limit
- Fast ramping rate (12T/s) of BRing magnets to mitigate ionization beam loss and dynamic vacuum effect

Key technology R&D and Prototyping

- 28 GHz SECRAL-II and 45 GHz FECR ECR ion sources
- Fast ramping power supply with full energy-storage technology for BRing dipole magnet
- Magnetic alloy core loaded RF system

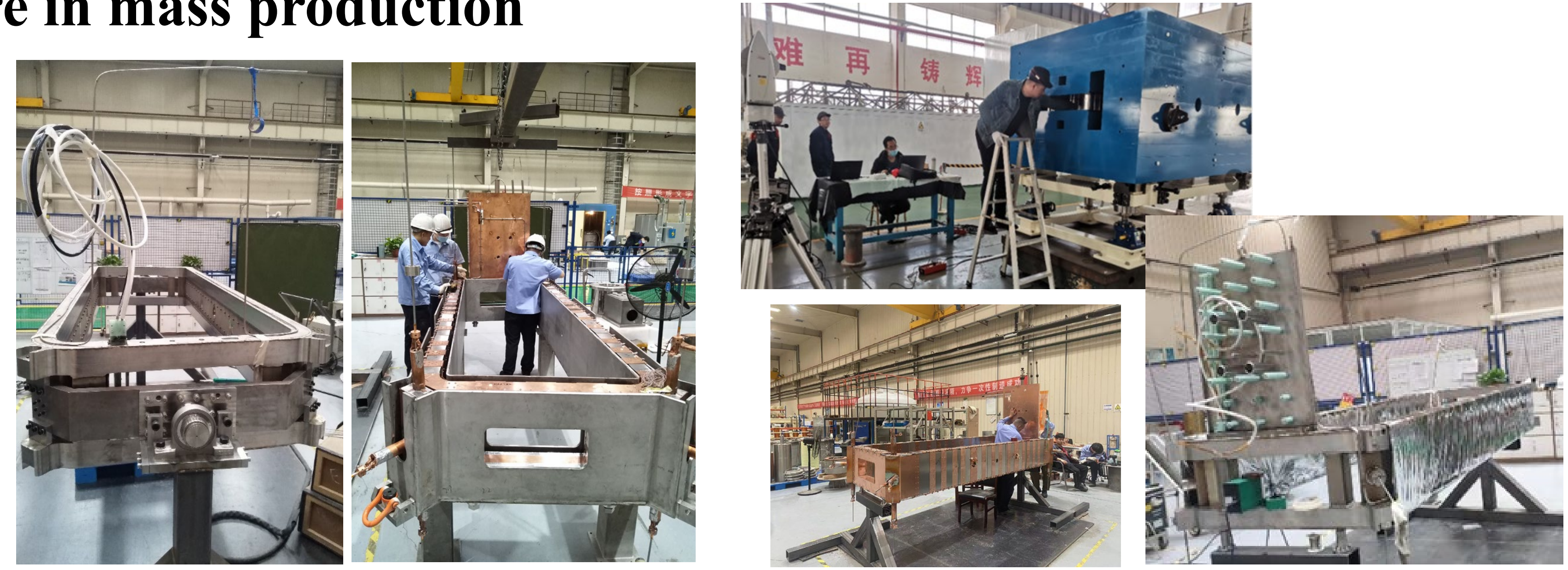
Civil construction site

HIAF civil construction status

HIAF components fabrication

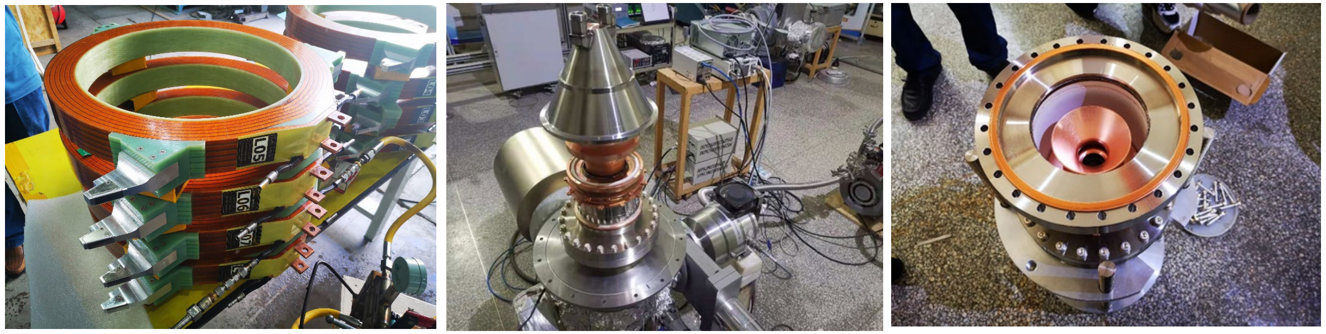
■ Most of the components are in mass production

BRing dipole magnets

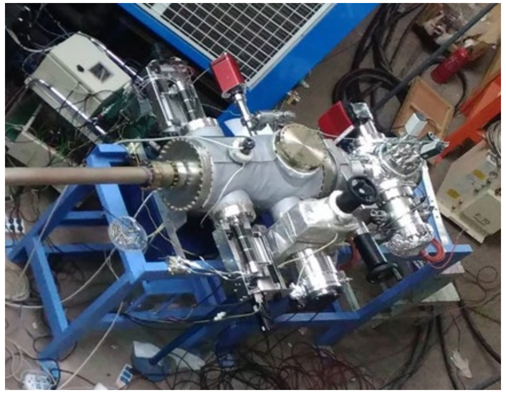


Components of HFRS superconducting magnets

iLinac HWR015 cavities

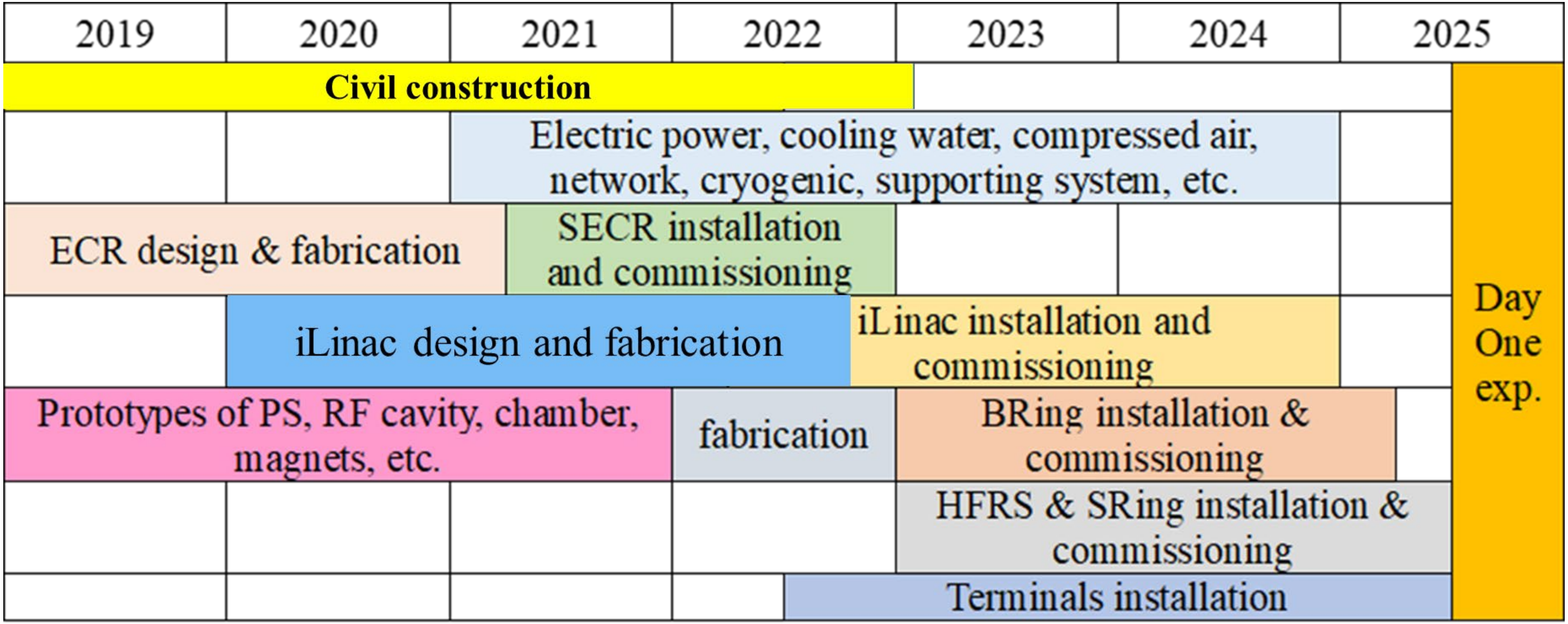


Components of SRing electron cooler



BRing collimator

HIAF planed milestones and time schedule

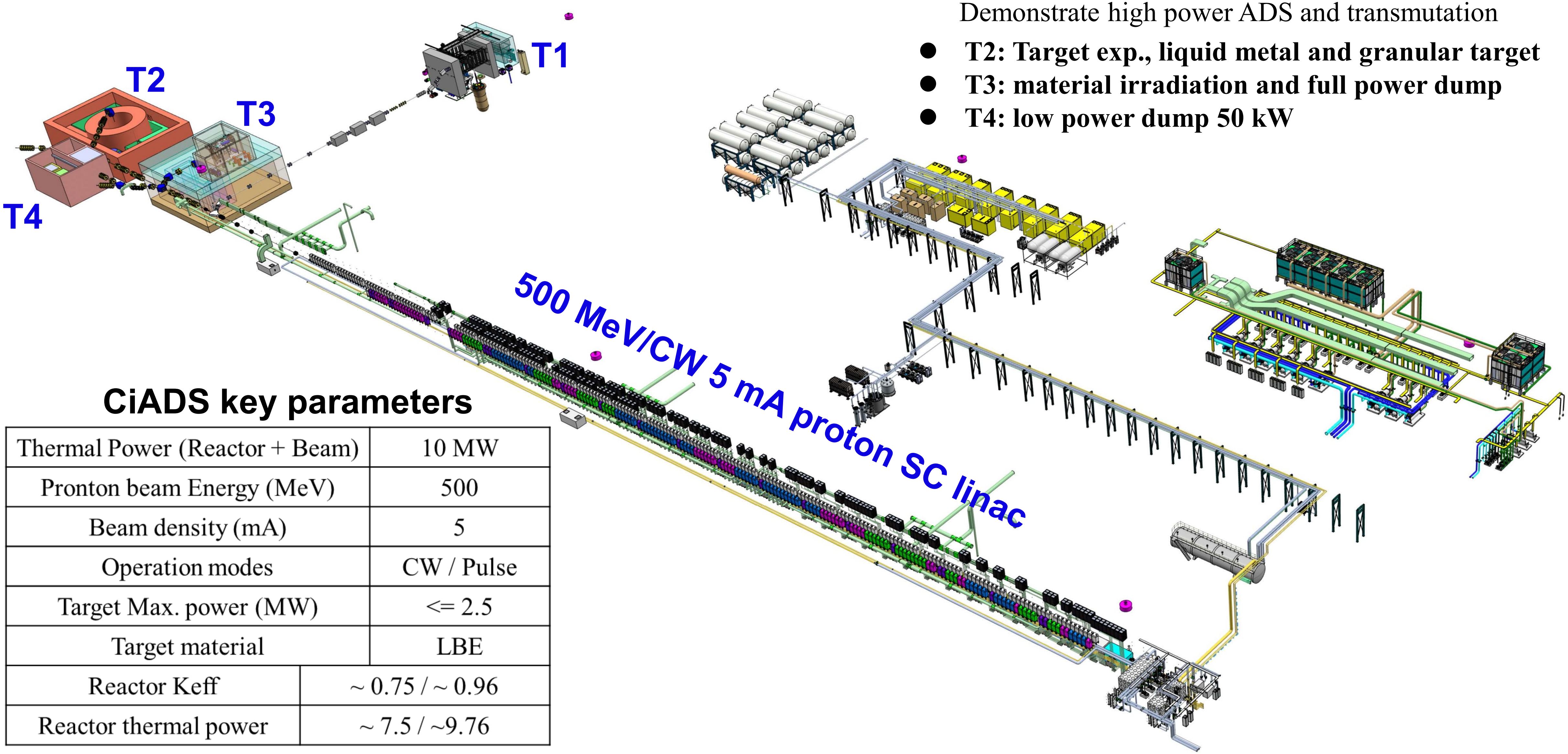


- **The first ion beam provided by SECR in the end of 2022;**
- **The first ion beam from iLinac in the end of 2024;**
- **The first ion beam injected, accelerated and extracted from BRing in May 2025**

CiADS layout and parameters

CiADS could be the world first MW-level ADS facility

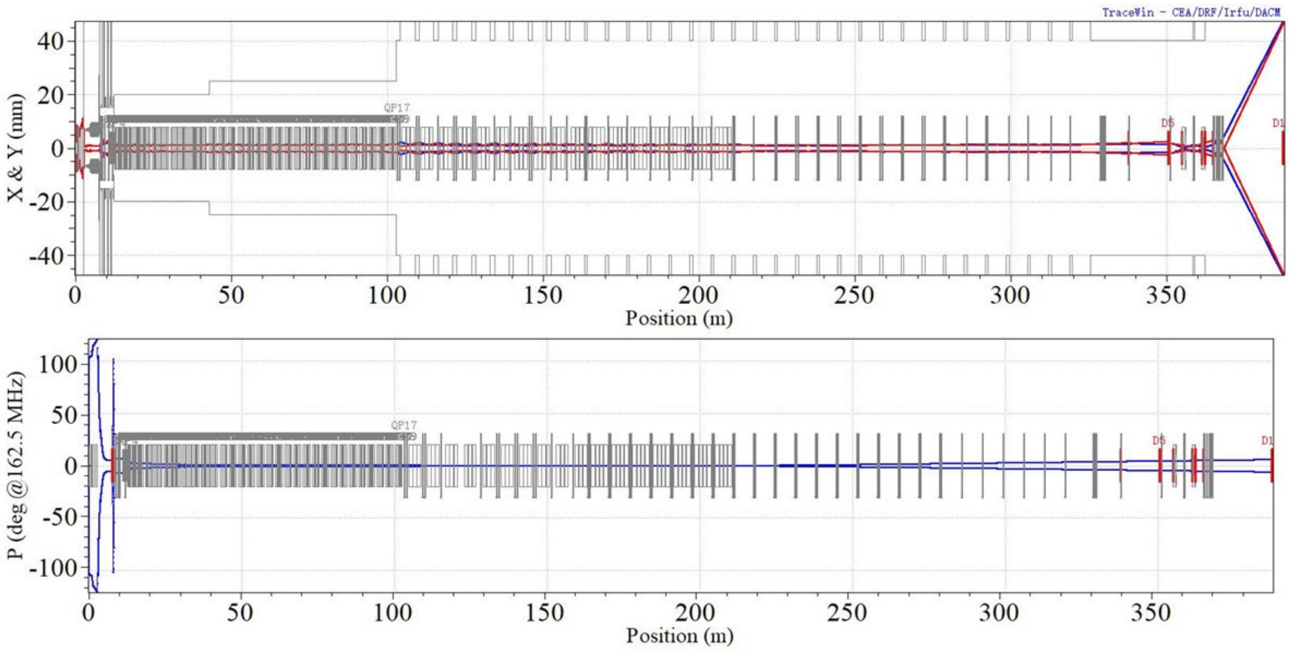
- **T1: Fast reactor, LBE target**
  Demonstrate high power ADS and transmutation
- **T2: Target exp., liquid metal and granular target**
- **T3: material irradiation and full power dump**
- **T4: low power dump 50 kW**



CiADS key parameters

Thermal Power (Reactor + Beam)	10 MW
Pronton beam Energy (MeV)	500
Beam density (mA)	5
Operation modes	CW / Pulse
Target Max. power (MW)	<= 2.5
Target material	LBE
Reactor Keff	~ 0.75 / ~ 0.96
Reactor thermal power	~ 7.5 / ~9.76

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

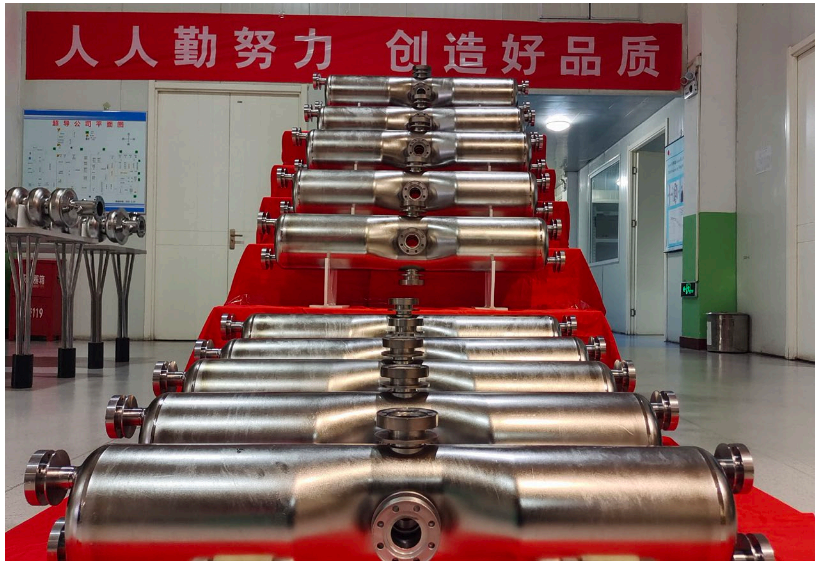
- **Minimize the beam loss and maintain a long-term high reliability and availability of the high power proton SC linac (500 MeV/5mA)**
- **High power spallation target (2.5 MW). Phase I: LBE target; Phase II: Granular flow target**
- **Coupling between the reactor, the target and the high power proton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

Key technology R&D and Prototyping

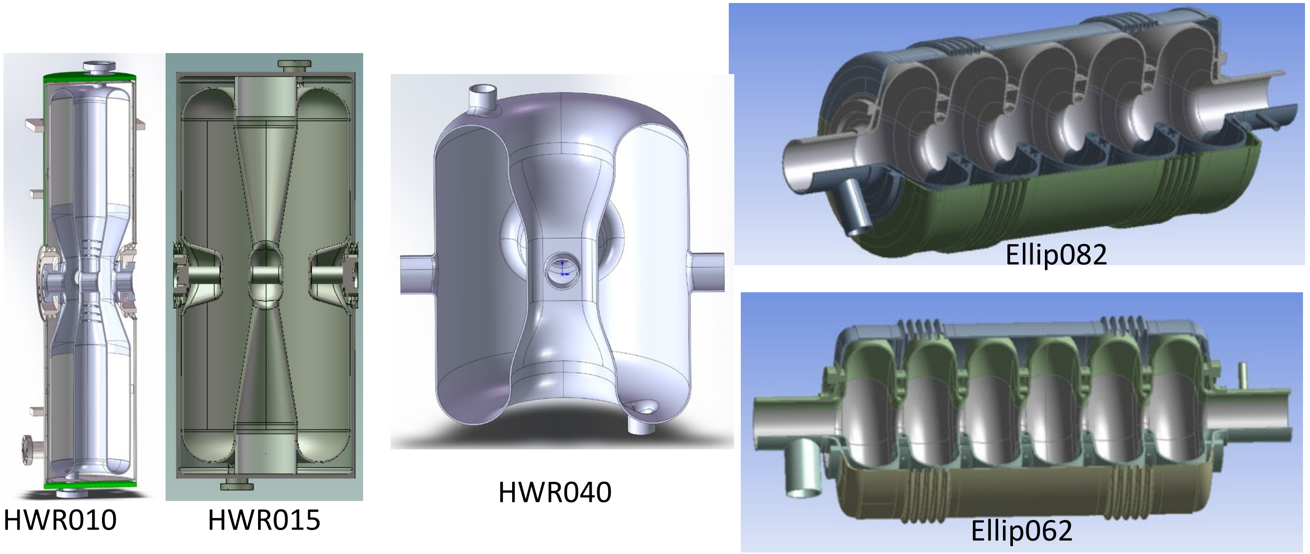
- **17-20 MeV/CW 5-10 mA front-end demo-facility of CiADS linac for reliability demo.**
- Target prototype R&D (LBE target and granular flow target)
- Prototyping for fast subcritical reactor vessel, heat exchanger and LBE centrifugal Pump

CiADS civil construction status

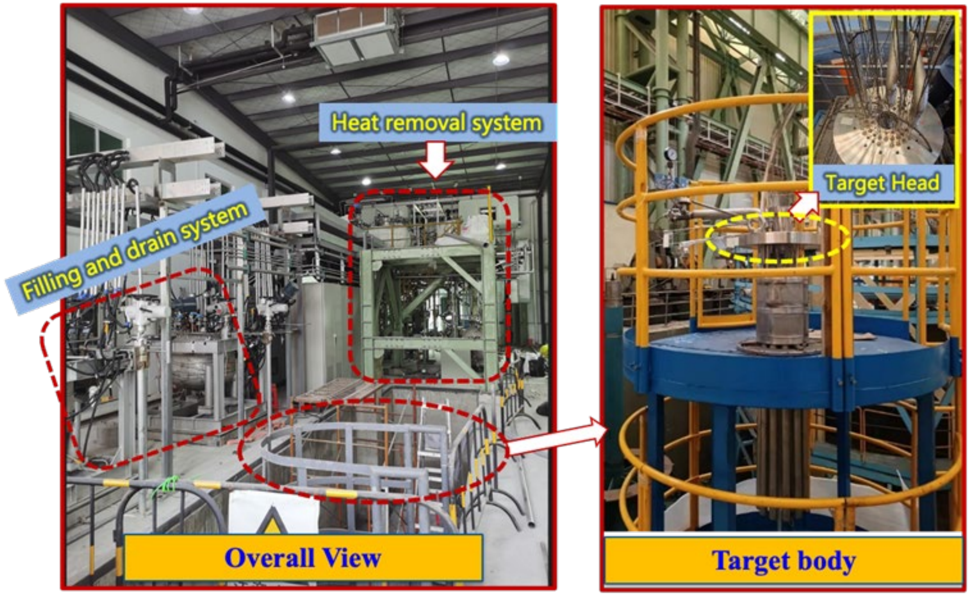
CiADS facility in prototyping and engineering design



650 MHz SSAMP @ 150 kW

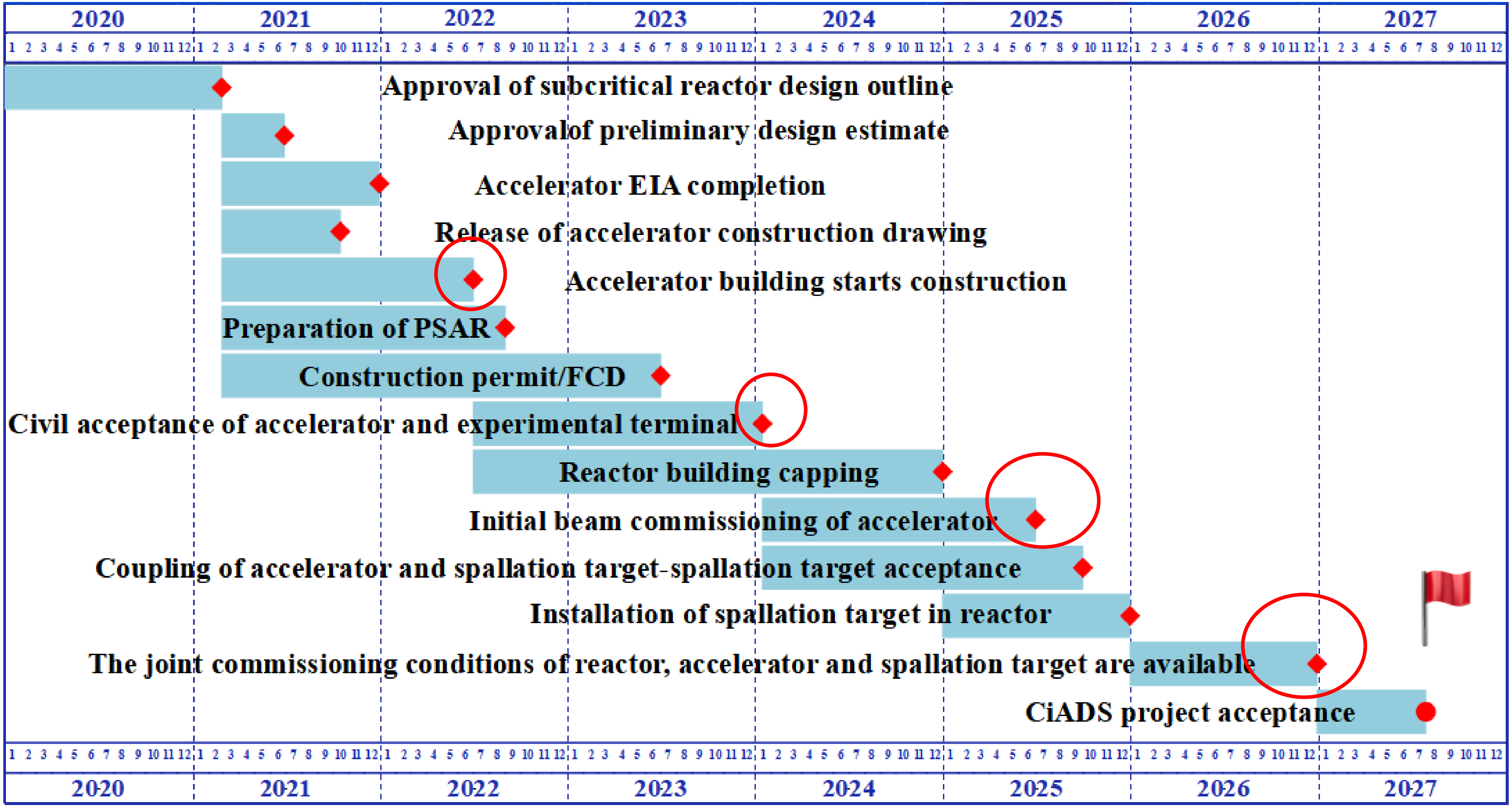


SRF cavities



Target Prototype

CiADS planed milestones and time schedule



OUTLINE

- HIAF & CIADS brief introduction and construction status
- **Key technology R&D and demonstration**

  1. High-intensity highly-charged heavy ion beam production

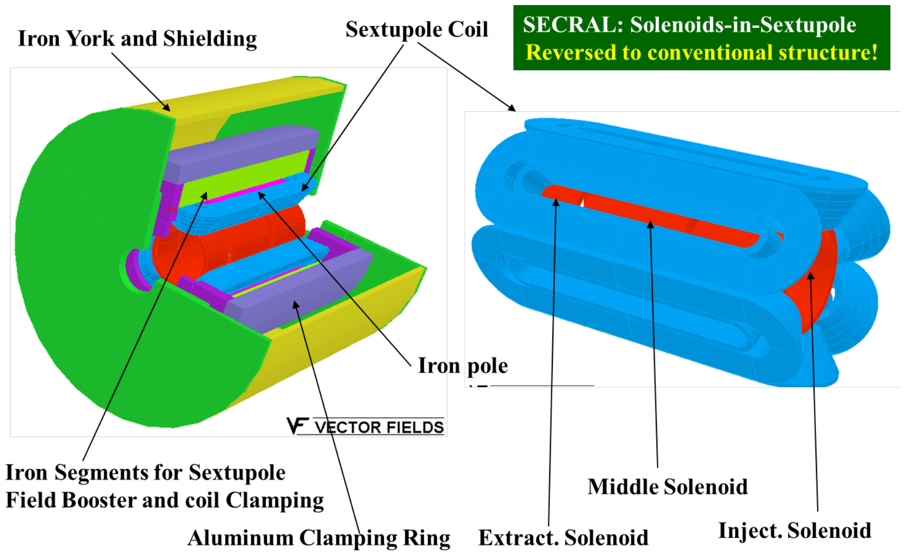
  2. Fast ramping power supply with full energy storage

  3. Magnetic alloy core loaded RF system

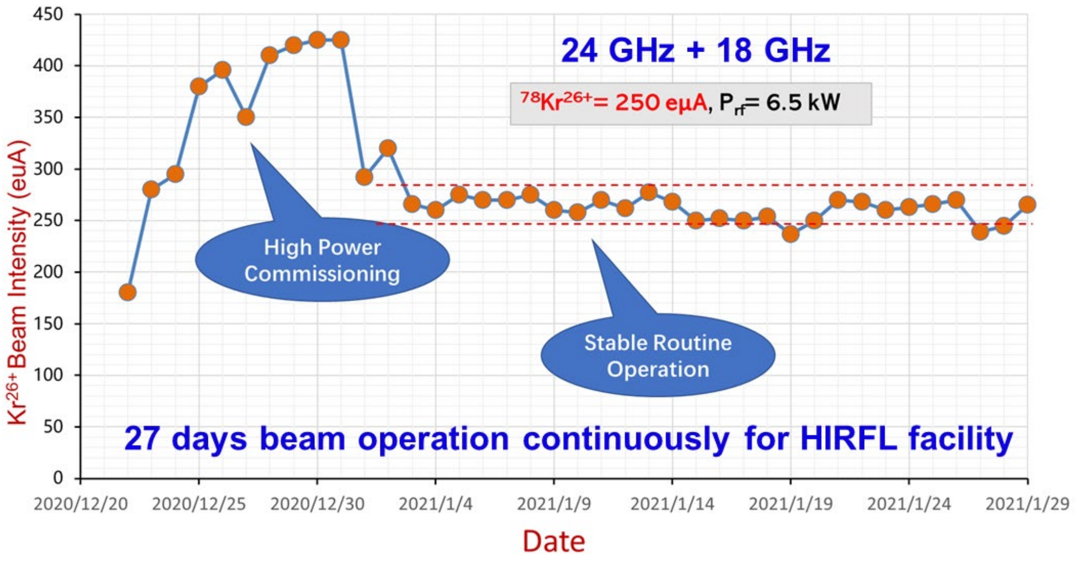
  4. 17-20 MeV/CW 5-10 mA front-end demo-facility of proton SC linac

- Summary and conclusion

High-intensity highly-charged heavy ion beam production by SECRAL II



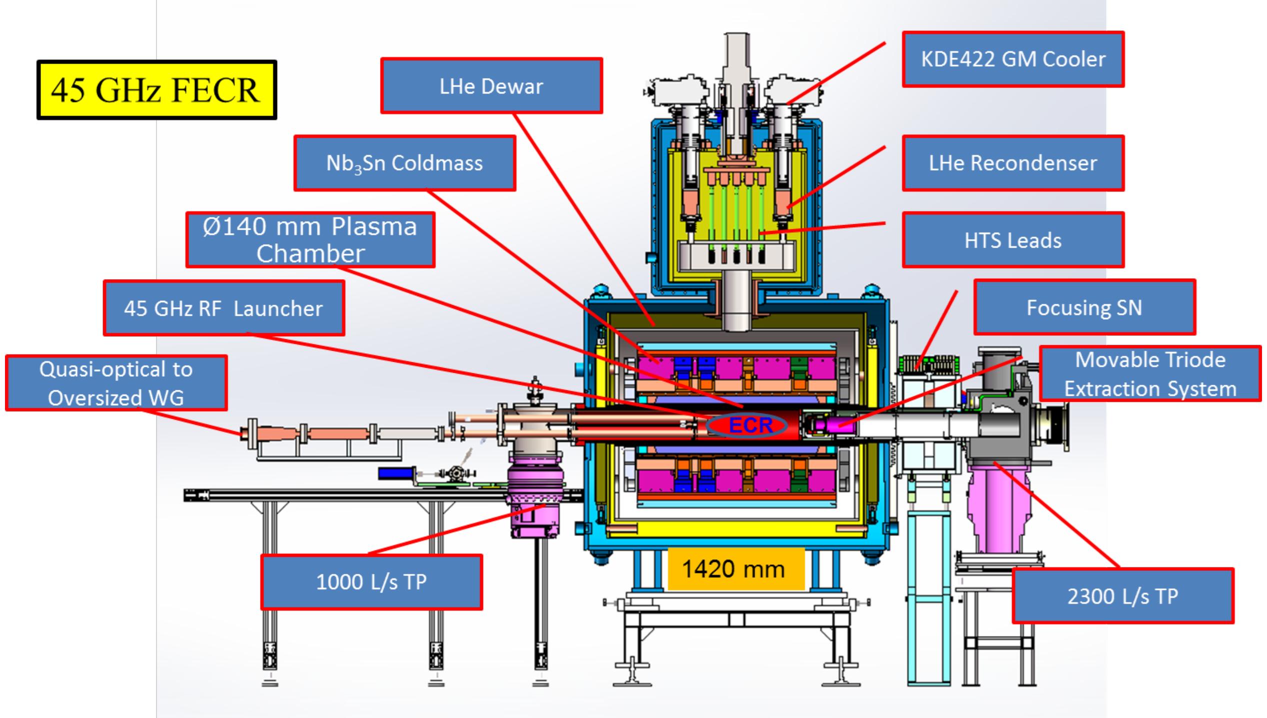
Ion Beam	SECRAL (eμA) (2015-2019)
$^{16}O^{6+}$	6700
$^{40}Ar^{12+}$	1420
$^{40}Ar^{16+}$	620
$^{40}Ar^{18+}$	15
$^{40}Ca^{11+}$	710
$^{78}Kr^{18+}$	1030
$^{78}Kr^{28+}$	146
Xe^{26+}	1100
Xe^{30+}	365
Xe^{42+}	16
$^{209}Bi^{31+}$	680
$^{209}Bi^{41+}$	100
$^{209}Bi^{50+}$	10
$^{238}U^{33+}$	450
$^{238}U^{35+}$	315



- Demonstrated a good long-term stability

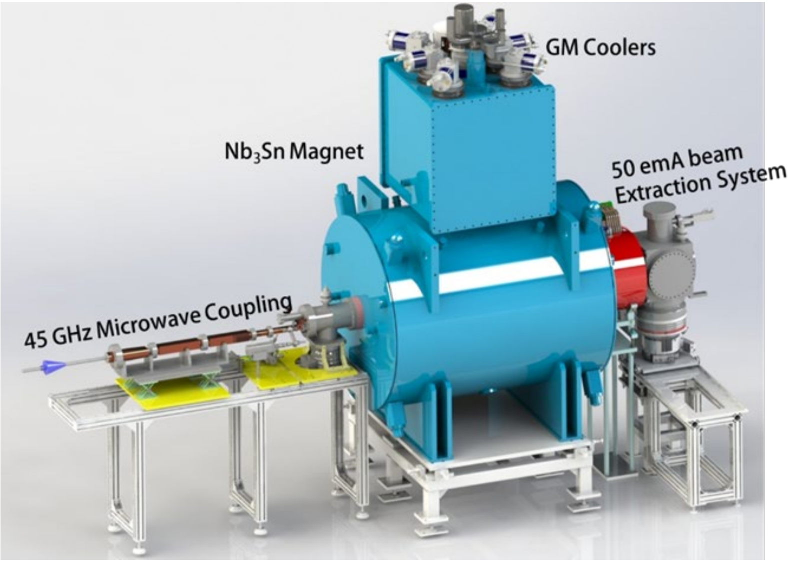
Record beam intensities (red numbers) produced by IMP SECRAL I &II

The world first 4th generation ECR ion source FECR



FECR key parameters

Microwave	45 GHz/20 kW
Magnet conductor	Nb_3Sn
Axial fields (T)	6.5/1.0/3.5
Sextupole field (T)	3.8@r=75 mm
Maximum field (T)	11.8 T
Maximum stress (MPa)	150
Magnet bore (mm)	>Ø160
Stored energy (MJ)	1.6
Extraction (kV)	50
Typical beam	1.0 emA U^{35+}

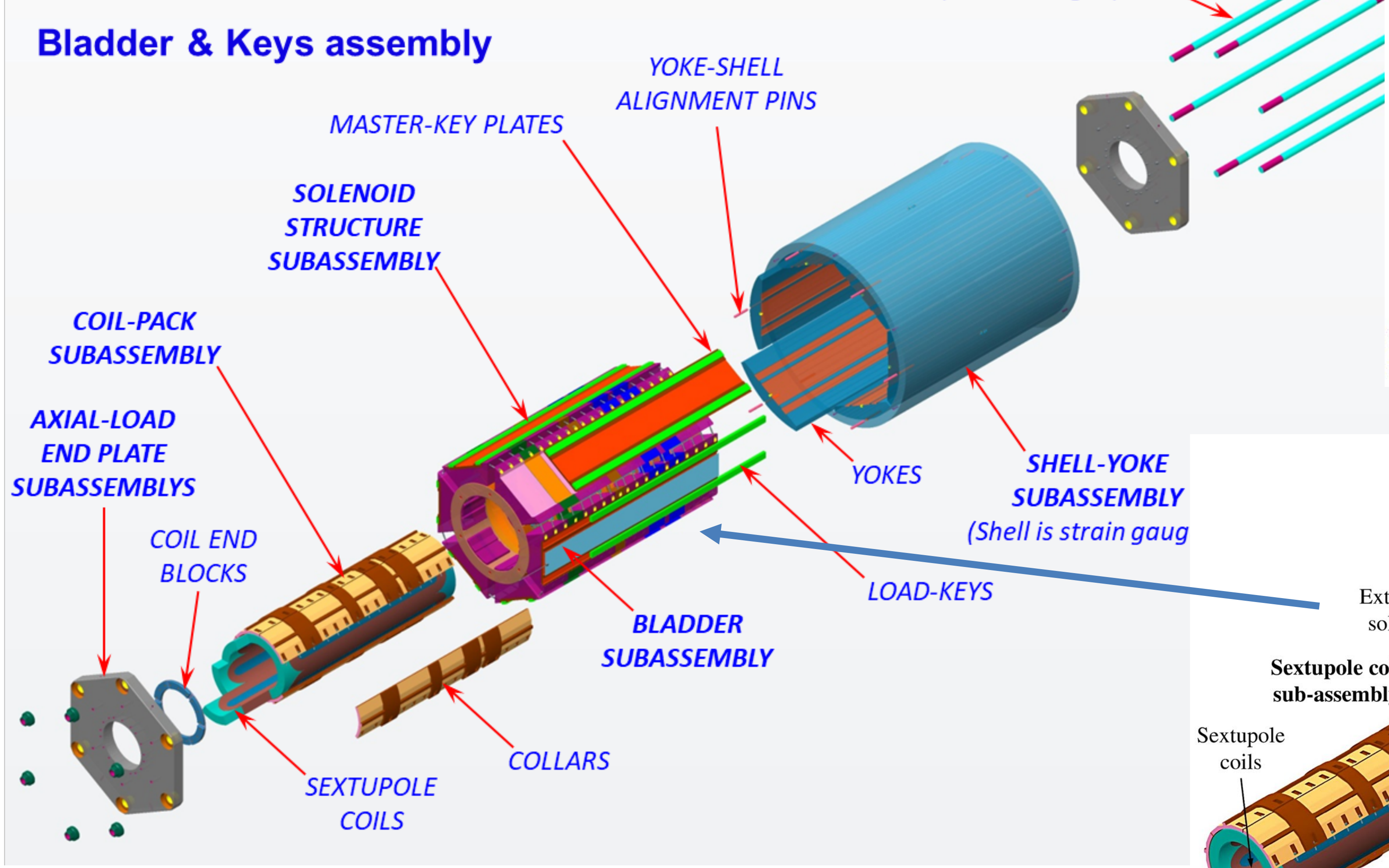


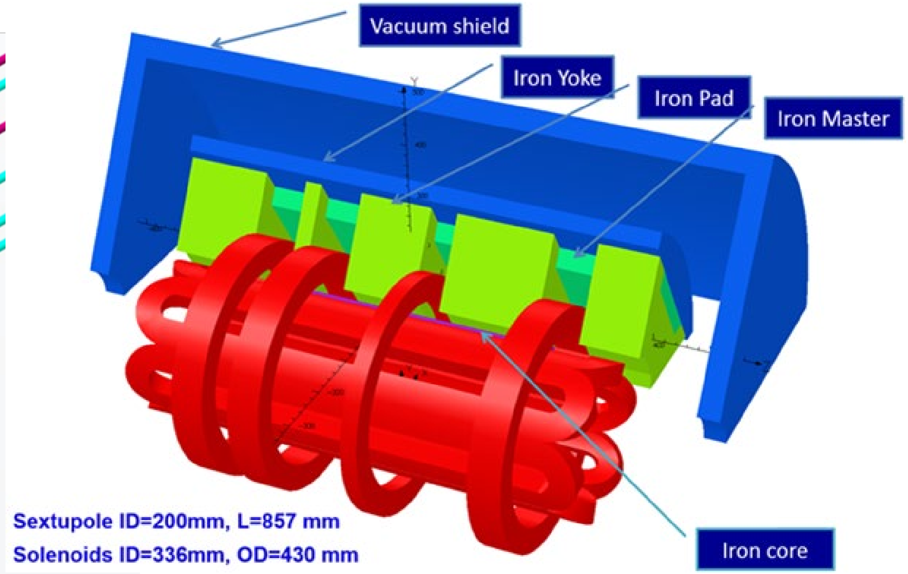
- Beams and intensities expected from FECR
- 3-5 times higher than the existing record beam intensities

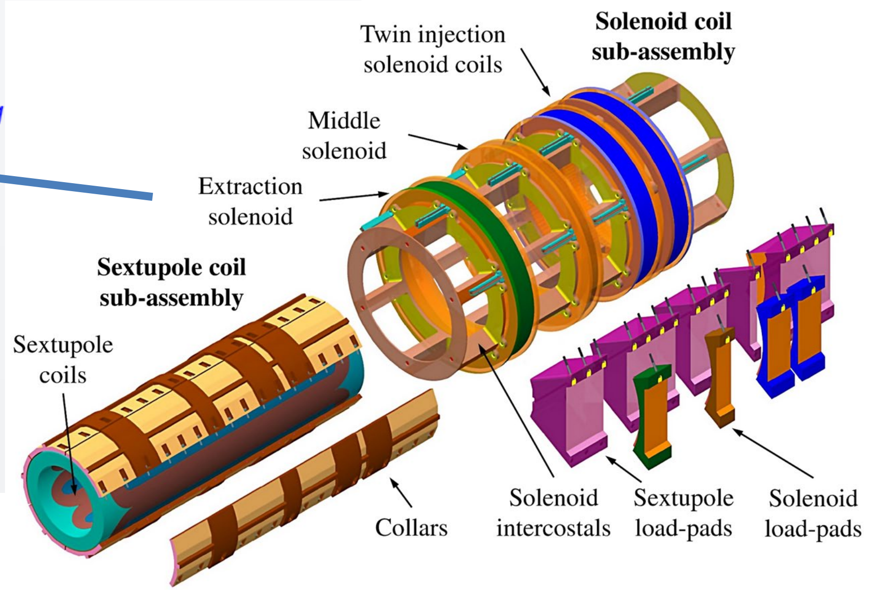
$^{129}Xe^{30+}$	>1000 μA
$^{129}Xe^{45+}$	> 50 μA
$^{209}Bi^{31+}$	>1000 μA
$^{209}Bi^{55+}$	> 50 μA
$^{238}U^{35+}$	>1000 μA
$^{238}U^{41+}$	> 200 μA
$^{238}U^{56+}$	> 30 μA

FECR Nb_3Sn magnet

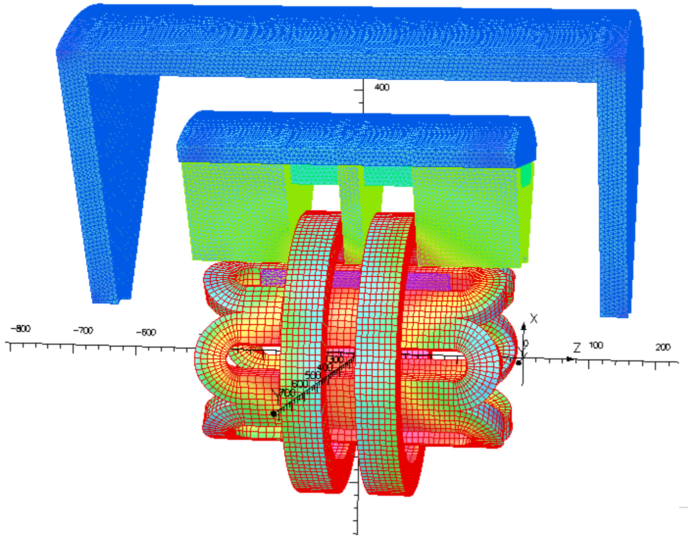
The magnet mechanical structure was designed by collaboration with ATAP magnet group at LBNL

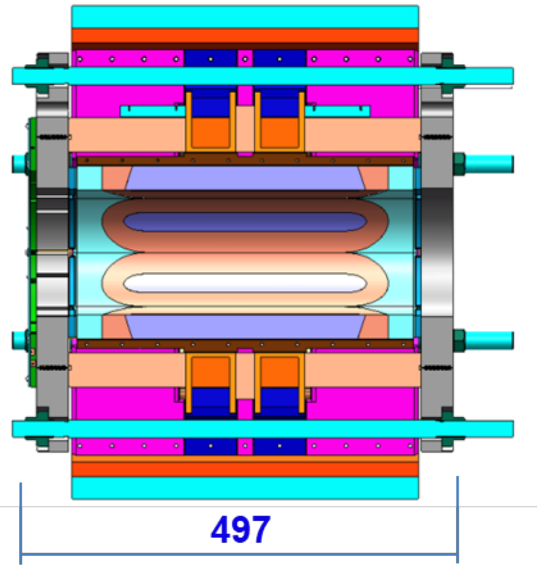


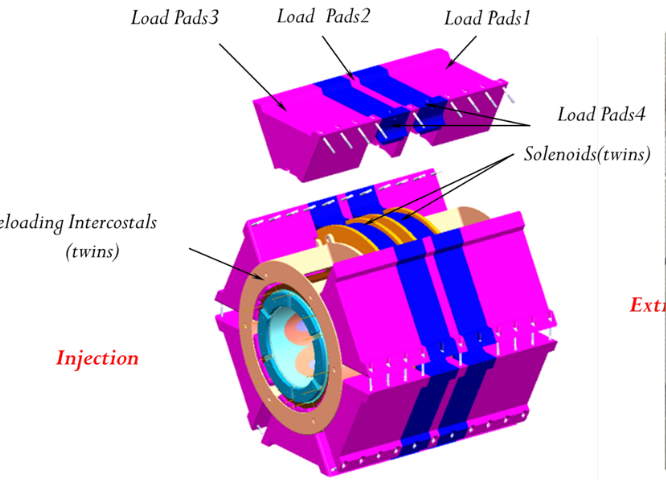




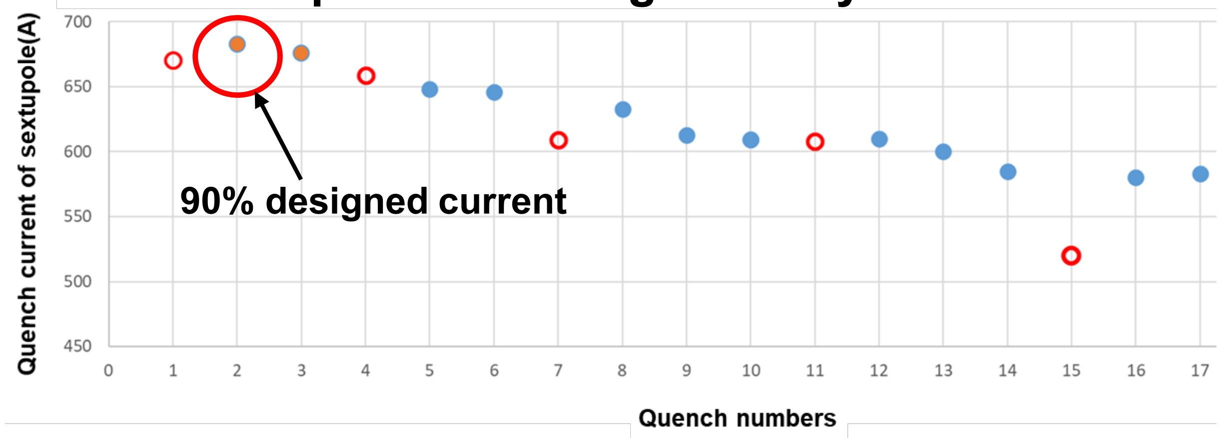
½ Prototype of FECR Nb_3Sn magnet



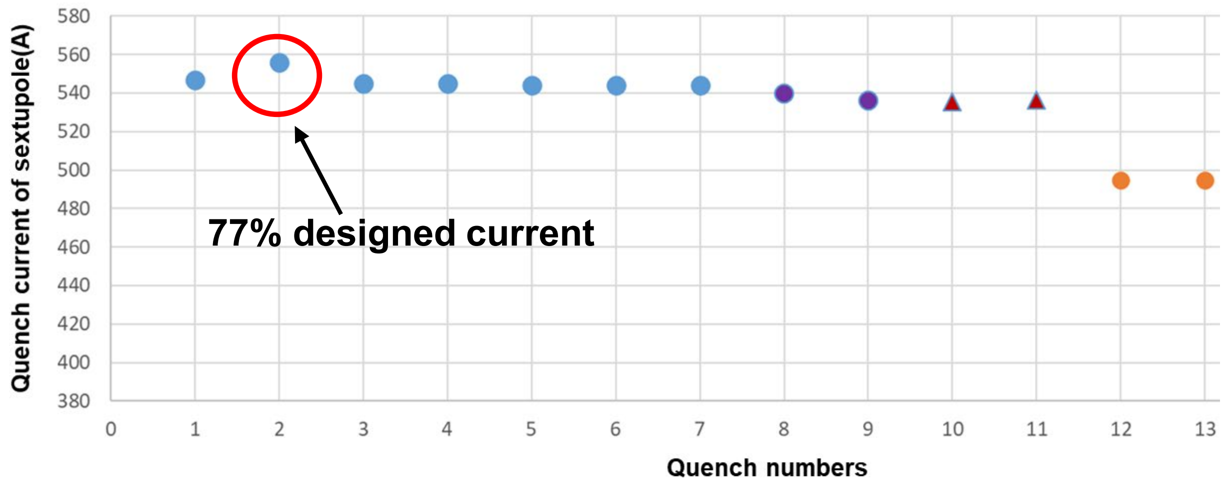




■ Sextupole was energized only



■ Sextupole and one solenoid were energized

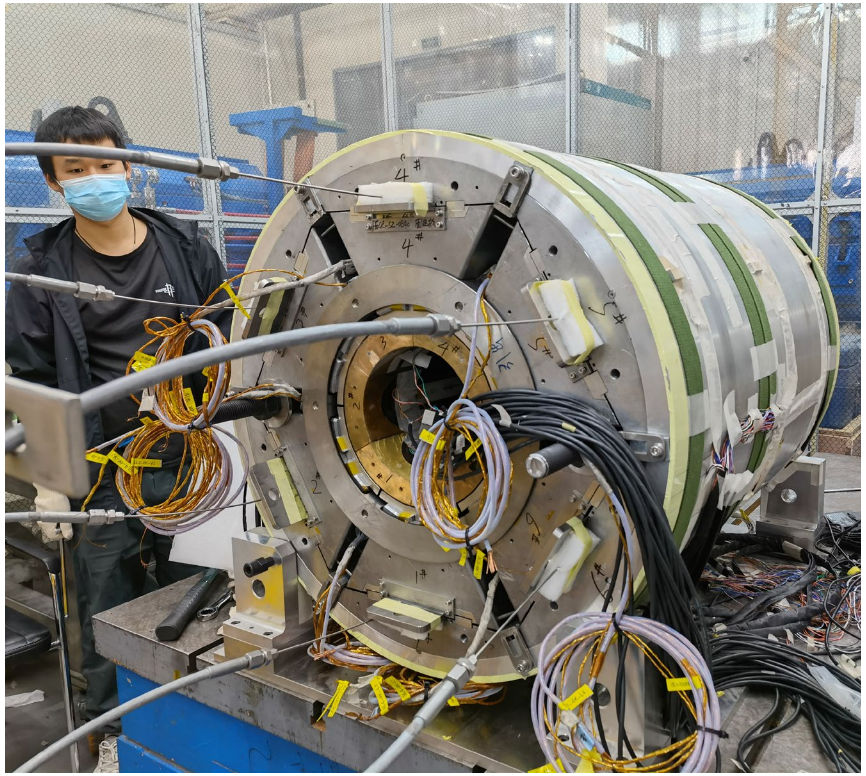


- Manufacturing and 8 times energizing tests of the ½ prototype Nb_3Sn magnet took more than 5 years
- The sextupole quenched at 70%-90%, sextupole+one solenoid reached 77% design current
- 2 of the 6 sextupole coils turned out to have performance degradation or minor damage
- Learned a lot of lessons and experiences, manufacturing, assembling, quench protection, flux jump, ….

FECR full-scale Nb_3Sn magnet status

Almost ready for cooling down and energizing

But need to verify the quench protection system carefully

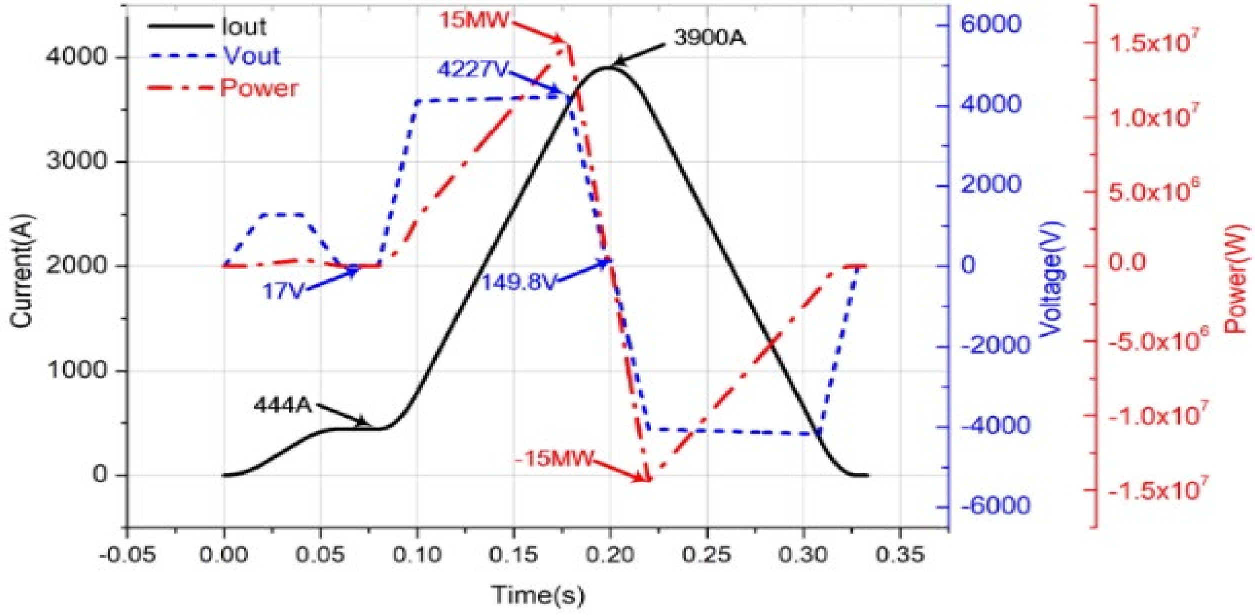


The magnet was manufactured and assembled by collaboration with XSMT company in Xi-an

Fast ramping power supply with full energy storage for dipole magnets

- **To reduce beam loss , 12 T/s ramping rate is required for the HIAF BRing dipole magnets.**
- **Challenge for the dipole power supply: High peak power, very fast ramping rate (38000 A/s), high tracking precision, very low current ripple and voltage fluctuation.**

Excitation current/voltage	3900A/3600 V 3 Hz
load inductance	**116 mH**
Load Resistance	**36.4 mΩ**
Current changing rate	**±38000 A/s**
Flat top/bottom error	**≤±0.2 A** **≤ 5.1x10^{-5}**
tracking error	**≤±0.2 A** **≤ 5.1x10^{-5}**

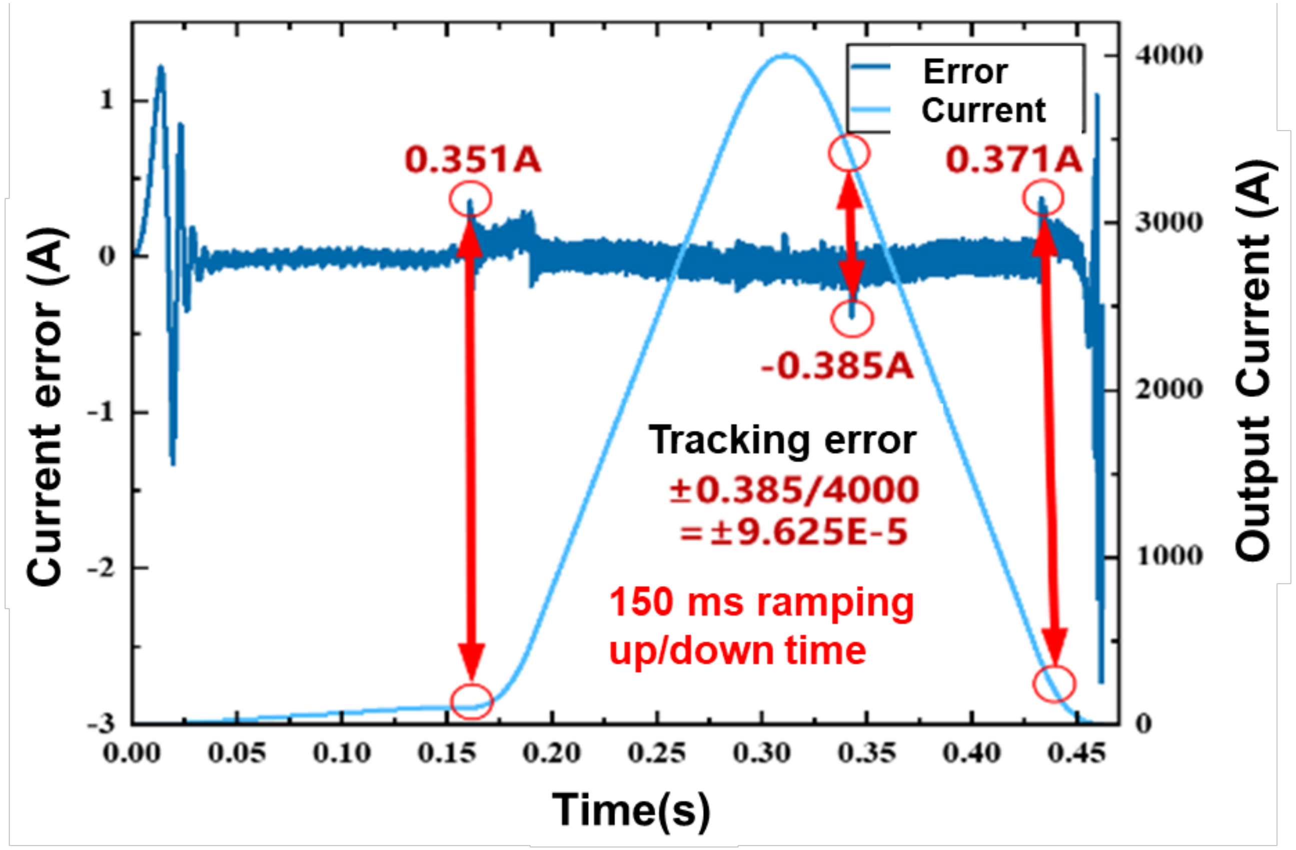


- **A innovative power supply topology and technology proposed for HIAF BRing dipole magnets**

Variable forward excitation; full energy storage technology; high-power-pulse technology with FPGA-based full-digital controllers.

Prototype of fast ramping power supply with full energy storage

- A prototype power supply with full current and power has been developed. The key technologies and the innovative design with variable forward excitation and full energy storage technology at high-power pulse have been verified.

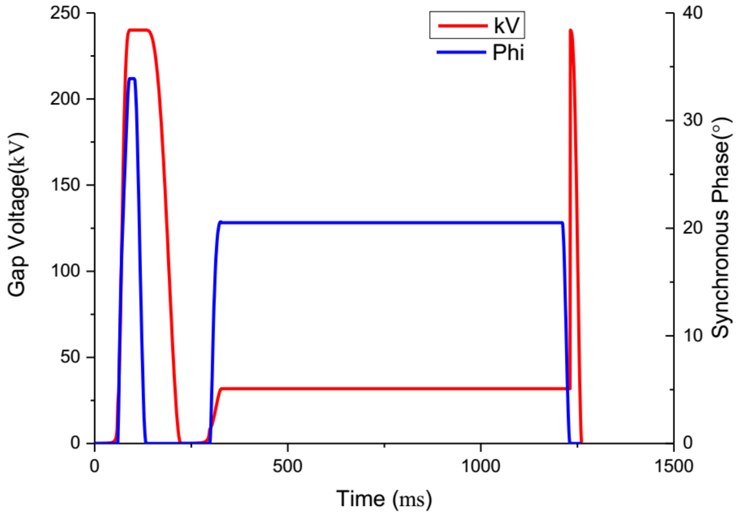


The prototype power supply was tested successfully with 4 real BRing dipole magnets connected in series

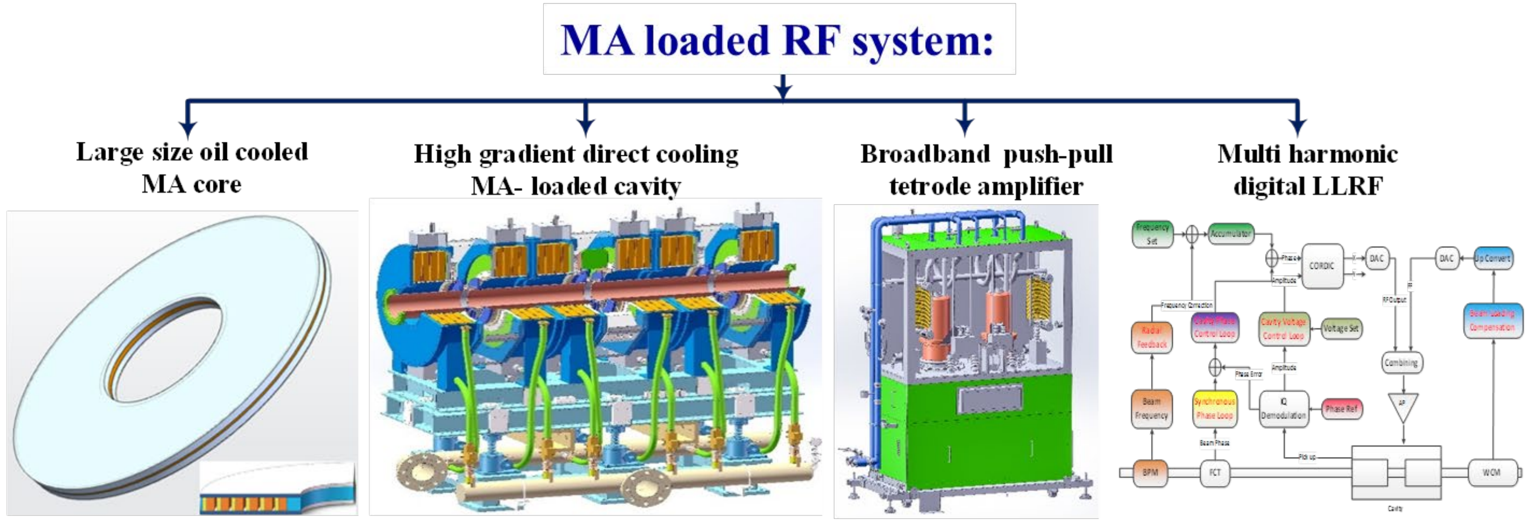
Achieved results: maximum current 4000 A/3600 V, ramping rate 38000 A/s
repetition rate 3 Hz, tracking error $\pm 9.62\times10^{-5}$

Magnetic alloy core loaded RF system for HIAF BRing

- **RF system of HIAF BRing: high RF voltage 240 kV and short rise time ≤10μs for beam compression**



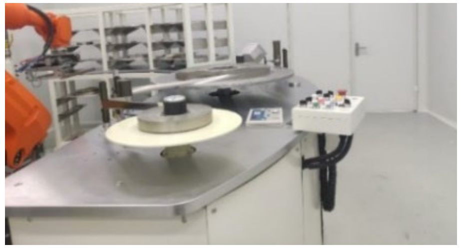
Voltage and phase waveform



- **MA core production line was built through collaboration between IMP and a domestic company**
- **Key technology:** 14μm ribbon production, ribbon shearing， 1~2μm insulation silica coating, constant tension horizontal winding, atmosphere annealing and water proof coating


Ribbon shearing


1~2μm silica coating


Constant tension horizontal winding


Atmosphere annealing


Water proof coating

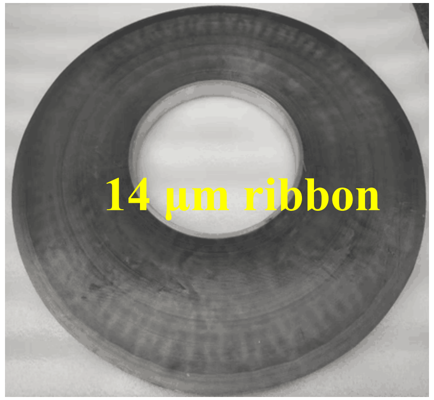
Performance of the magnetic alloy core produced

■ Independent development of MA core

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

95×65×25mm

460×230×25mm

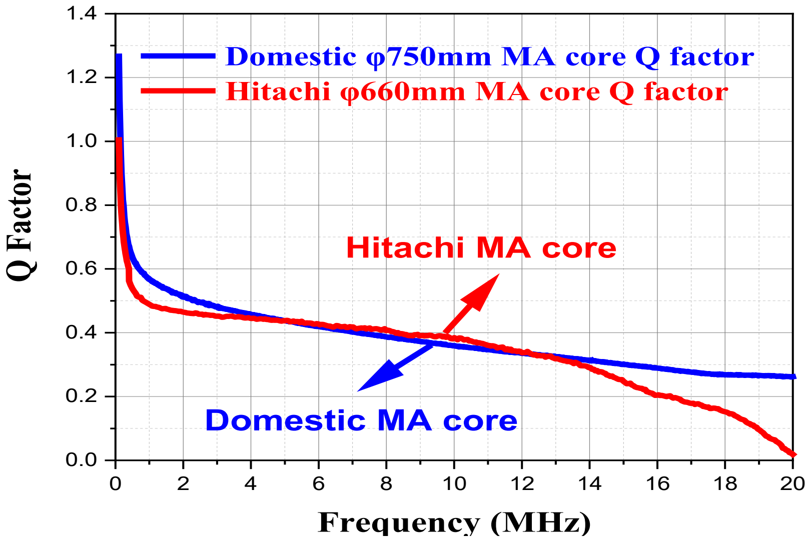


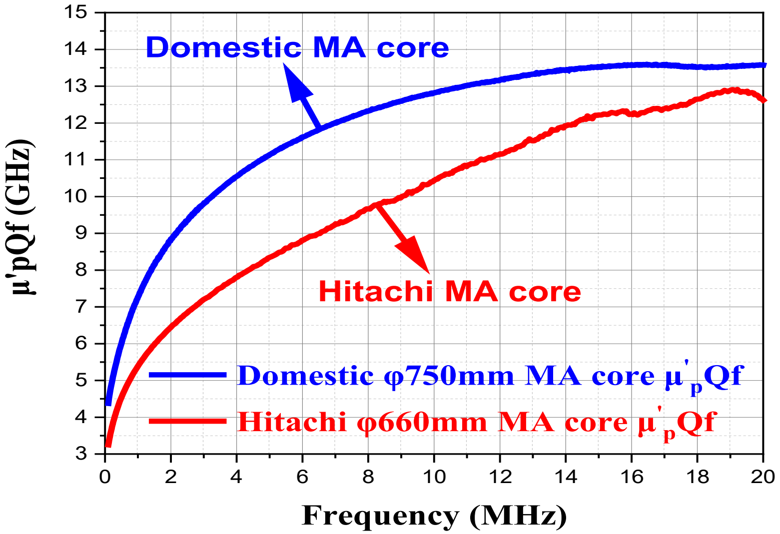
750×345×35mm

780×360×35mm

■ Breakthrough in MA core manufacturing

Q value: (0.65~0.3) @ (0.1~20MHz) **μ'pQf : 5.3GHz @ 0.3MHz**





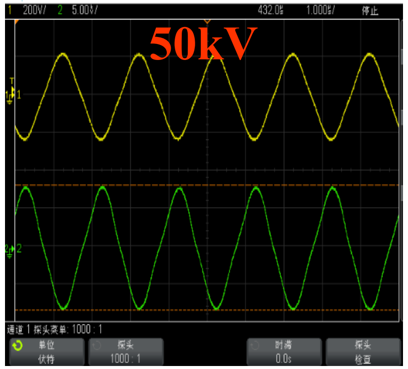
Oil-cooling MA core loaded cavity and RF system manufactured

MA RF system

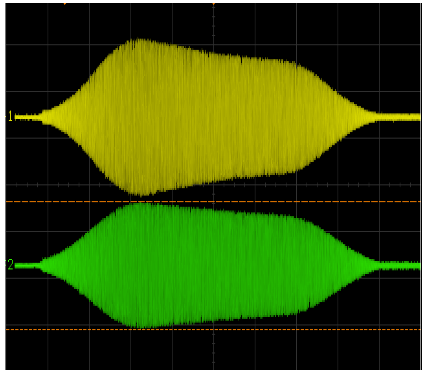
Two-TH558-tube amplifier cabinet

- **RF power test was carried out:** Gap voltage/one cavity 50kV@0.3~2.1MHz

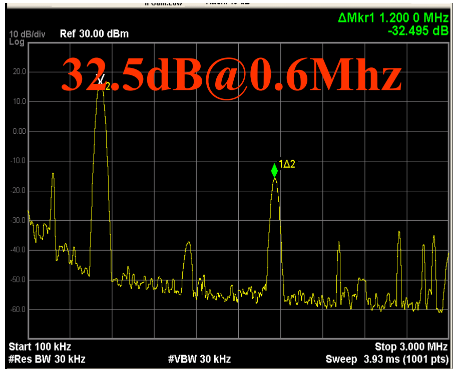
  The third harmonic suppression better than 25 dB



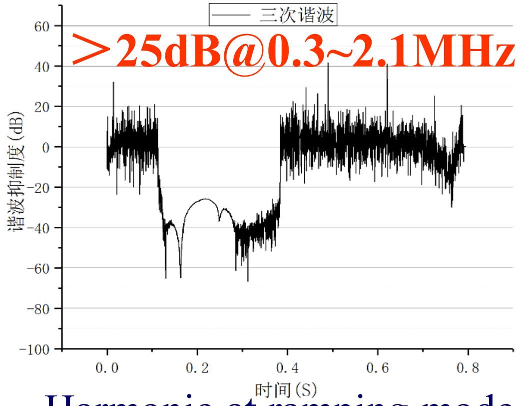
Cavity pick-up voltage



Voltage of ramping mode



Harmonic suppression

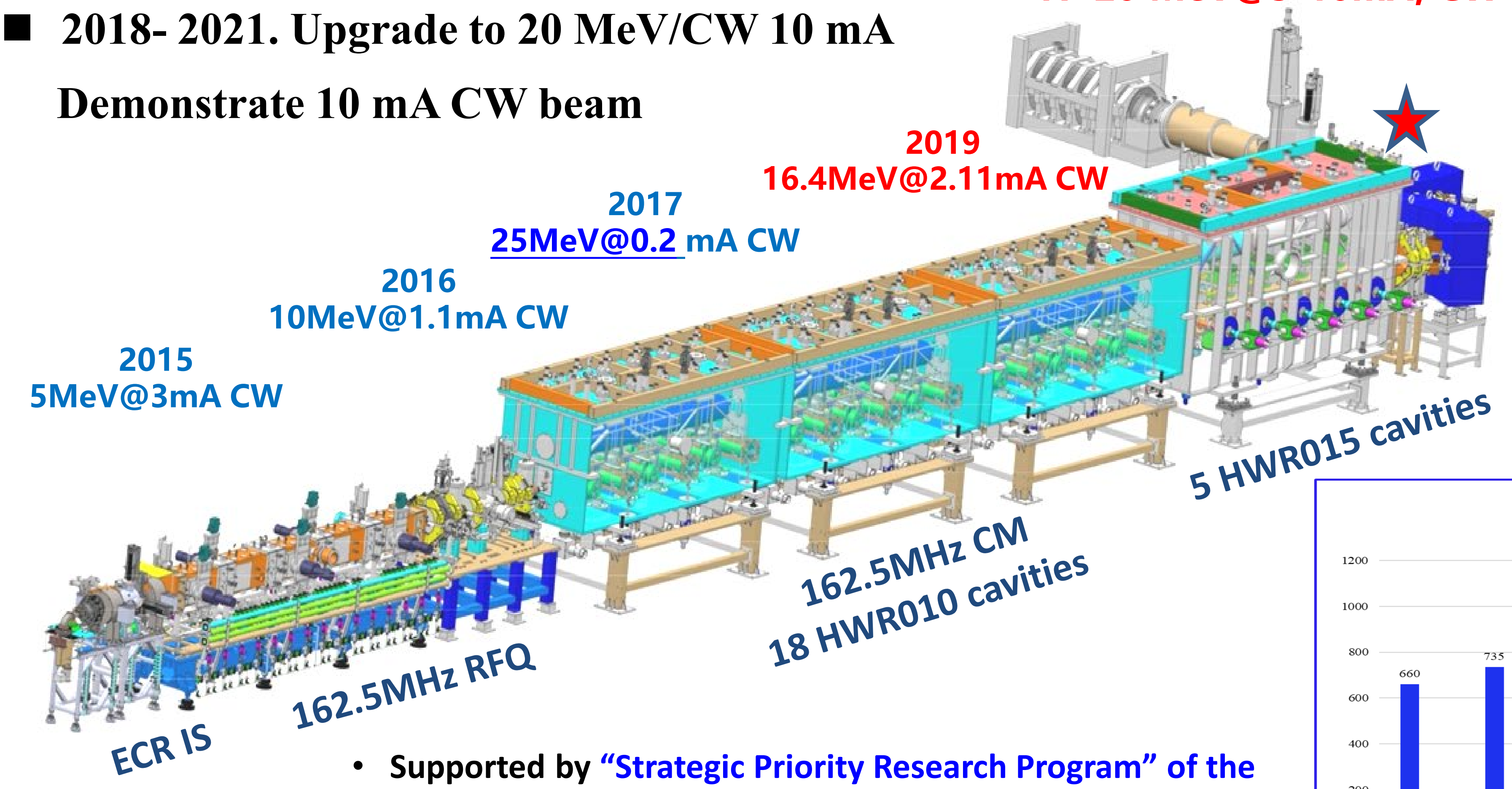


Harmonic at ramping mode

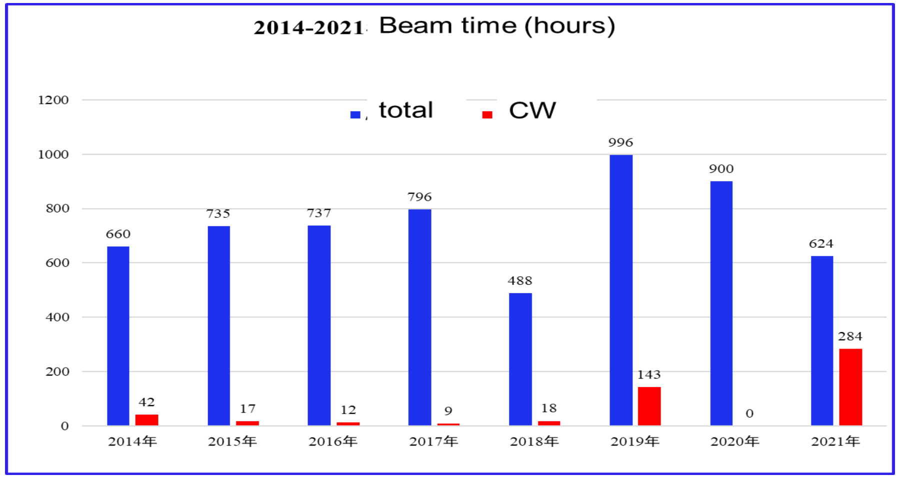
17-20 MeV/5-10 mA front-end demo facility for CiADS linac

- 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

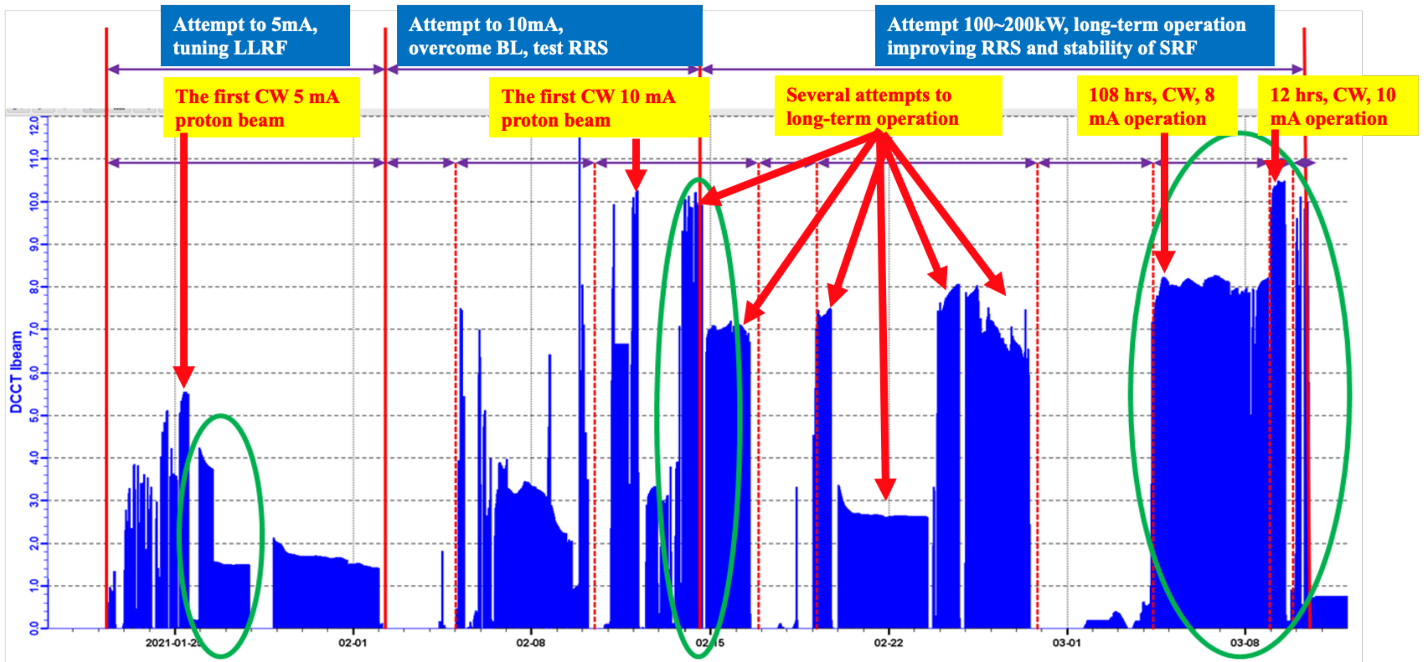


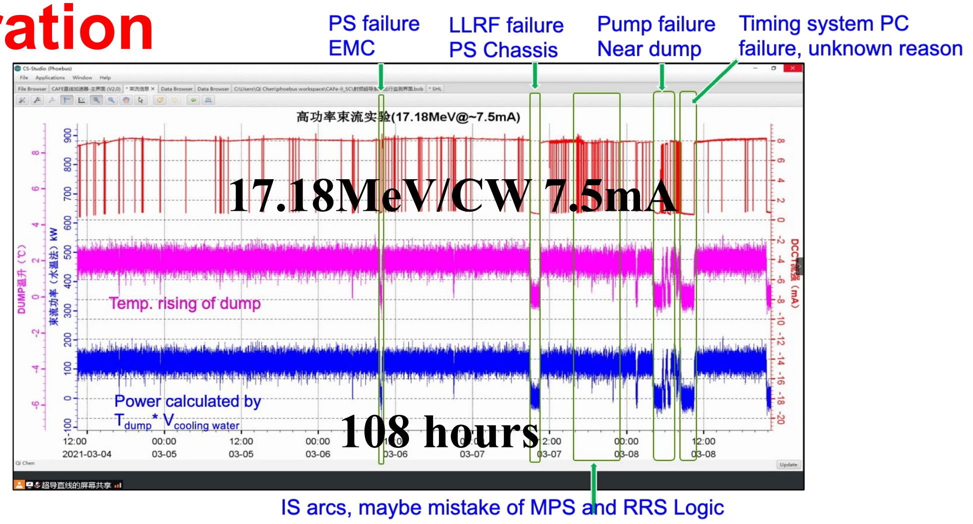
- Supported by “Strategic Priority Research Program” of the Chinese Academy of Sciences.

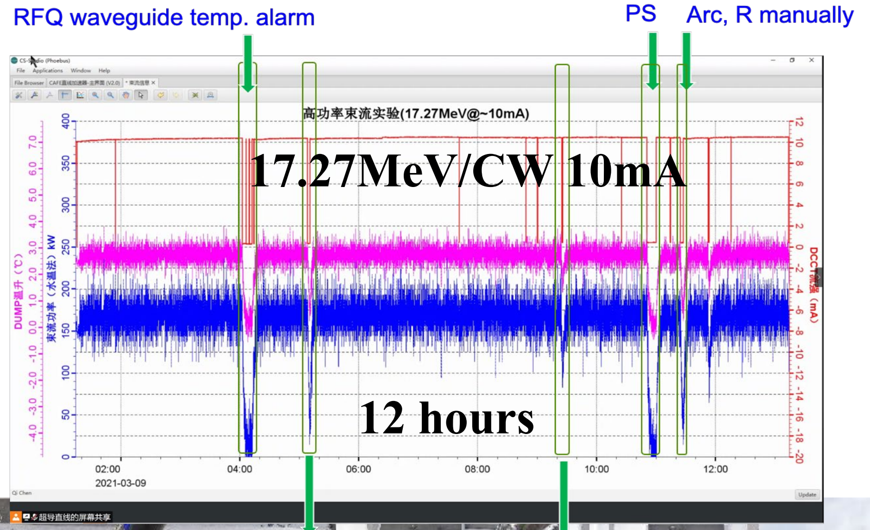
High power CW SC proton linac reliability demonstration

- **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

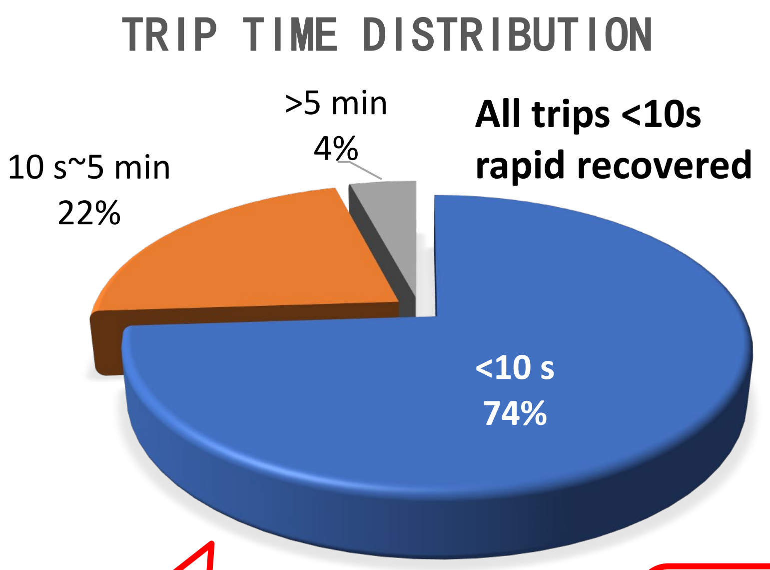
High power: 20.18 MeV、10.18 mA、beam power 205.5 kW

RAMI analysis for the continuous operation test

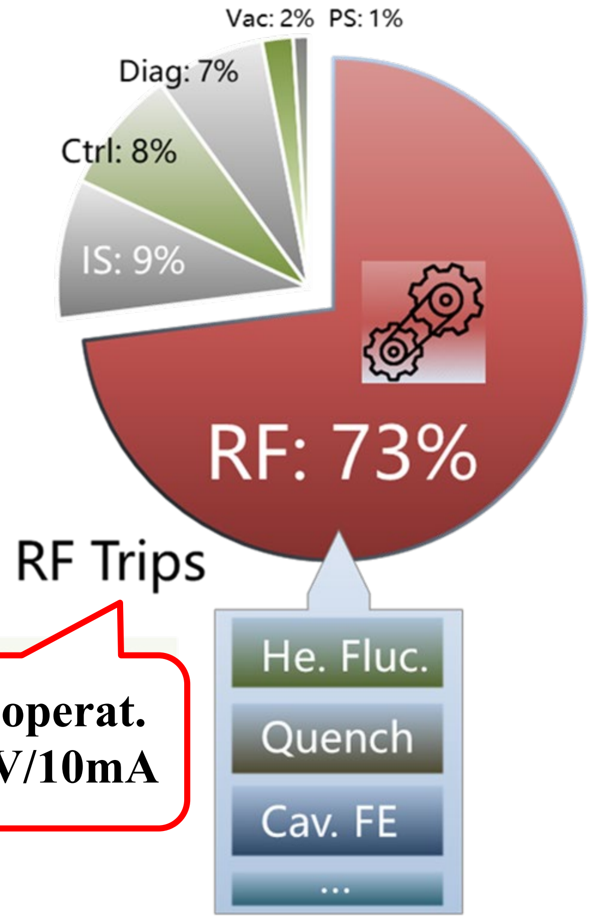
Operation Period： 9:42, Mar. 4, 2021 ~21:43, Mar. 8, 2021;

Operation time: **108 hrs (pre-set by the reviewers)**

Downtime： **6.85 hrs, 93.6% availability**



108 hours operation at 17.18MeV/7.5mA



12 hours operat. 17.27MeV/10mA

Distribution of downtime and trips from subsystem

Trip sources	Downtime (s)		Trips		Avg time (s)
RF	6360	26%	18	41%	353
Cryogen.	0	0%	0	0%	0
Ion source	1103	4%	8	18%	138
Vacuum	7598	31%	3	7%	2533
Magnet	0	0%	0	0%	0
PS	1244	5%	2	5%	622
Diagn.	35	0%	1	2%	35
Control	8317	34%	12	27%	693

- Failures and trips caused by ion source, vacuum, PS and control can be solved.
- RF contributes the main parts of the trips

Summary and Conclusion

- **HIAF and CiADS facilities being built in Huizhou by IMP.**
  - Most of HIAF components in mass production and civil construction completed 50%. The first beam commissioning of iLinac and BRing planed in 2024-2025.
  - CiADS in key technology R&D and facility engineering design. The first beam commissioning of CiADS linac is planed in June 2025.
- **Key technology R&D and demonstration for HIAF&CiADS， achieved a good progress.**
  - A lot of record beam intensities for highly charged heavy ions were produced by SECRAL II. 45 GHz FECR Nb_3Sn magnet almost ready for cryogenic energizing after 7 years development.
  - Fast ramping power supply with full energy storage successfully developed for HIAF BRing dipole magnet, reached 4000 A/3600 V, ramping rate 38000 A/s, 3Hz.
  - Large size and high performance MA core was developed successfully. Oil-cooling MA core loaded cavity and RF system were manufactured and tested, reached designed performance.
  - Reliability and availability at 17 MeV/CW 7.5 mA for 108 hours and 17 MeV/CW 10 mA for 12 hours continuously operation were demonstrated for the first time for a proton SC linac, as a low energy demo-facility for CiADS.

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