Current Status and Prospects of Hadron Linac Facilities at IMP

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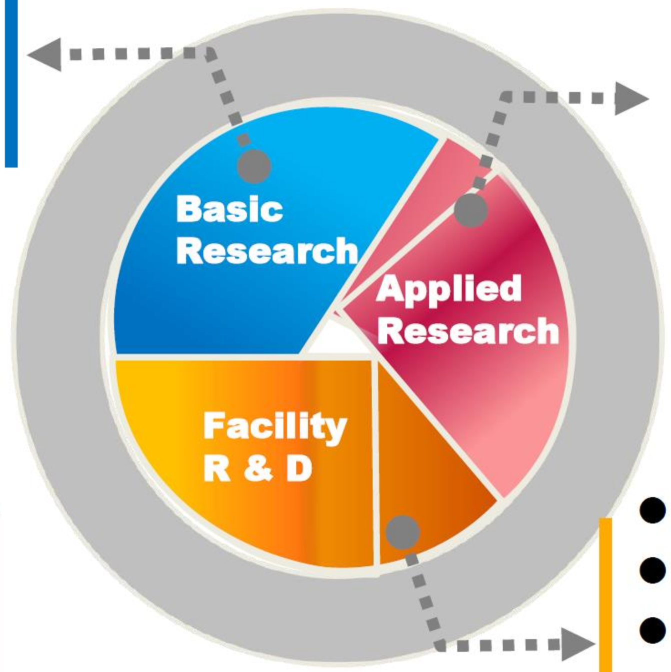
Brief Introduction of the Institute of Modern Physics (IMP), Chinese Academy of Sciences (CAS)

China Initiative Accelerator Driven System

IMP is the biggest nuclear physics research center in China for heavy ion basic-science and nuclear technology application

- Nuclear physics
- Atomic physics
- Nuclear chemistry
- Radiation chemistry
- Material science
- Hadron physics
- High Energy Density physics
- Accelerator physics



- Radiation biology
- Radiation medical science
- Radiation material
- Advanced nuclear energy
- Nuclear-detector technology

- Ion Accelerator facilities
- Large-scale experiment facilities
- Special experiment facilities

High Priorities at IMP

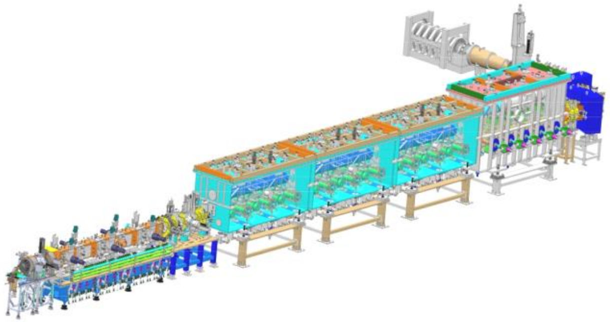
- Precision mass measurement of exotic and stable nuclides, RIB physics, SHE
- CIADS and HIAF project, ADANES
- Tumor therapy
- Irradiation Material sciences

>1200 staff and >700 students

Lanzhou: Main Campus & Existing Facilities

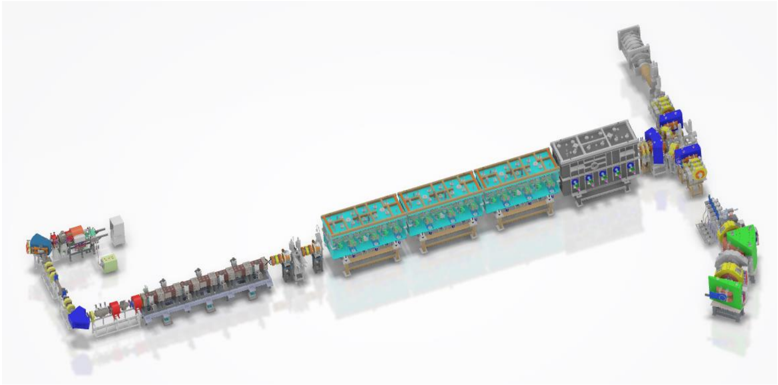
CAFe

Demo front end of CiADS
First stable 10 mA CW proton linac, maximum power 200 kW



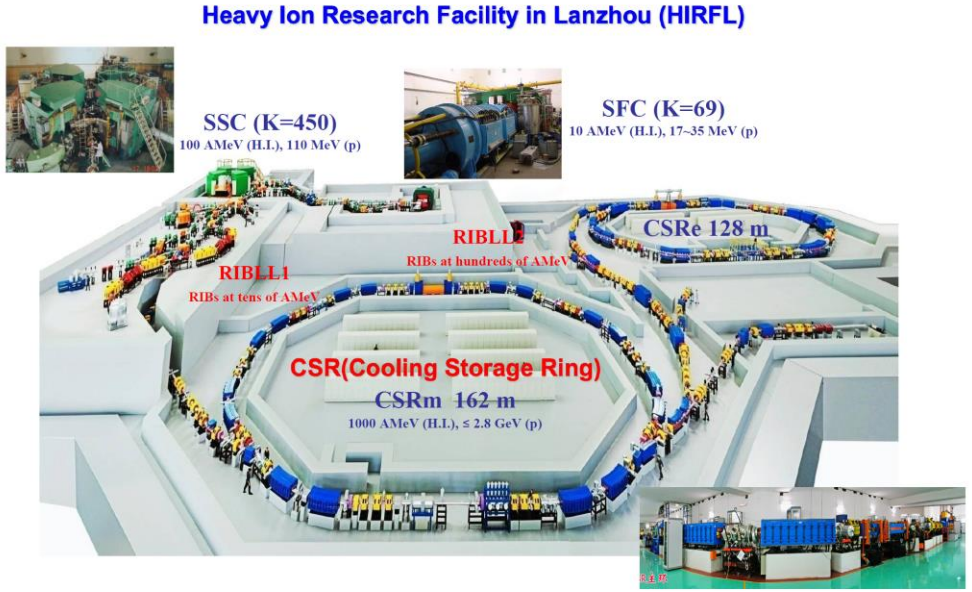
CAFe2

Superheavy Element Synthesis



Heavy Ion Research Facility in Lanzhou (HIRFL)

Nuclear physics research
With high energy heavy ions



Huizhou: Second Campus & Two Large-Scale Projects

High Intensity heavy ion Accelerator Facility (HIAF)

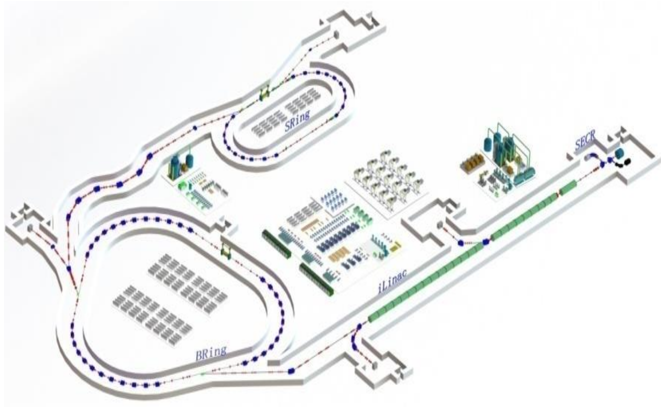
Nuclear physics research

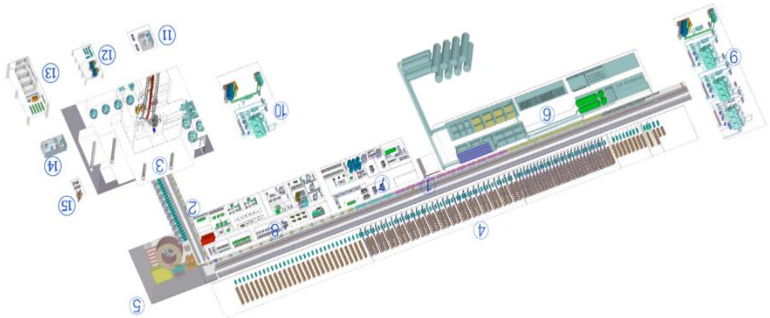
Beam commissioning in 2025

China initiative Accelerator Driven System (CiADS)

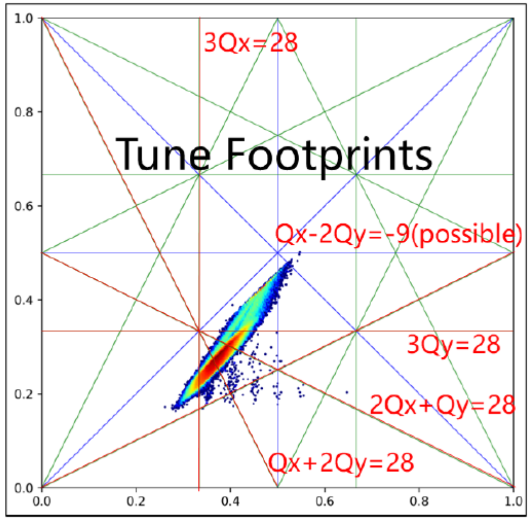
Nuclear waste transmutation

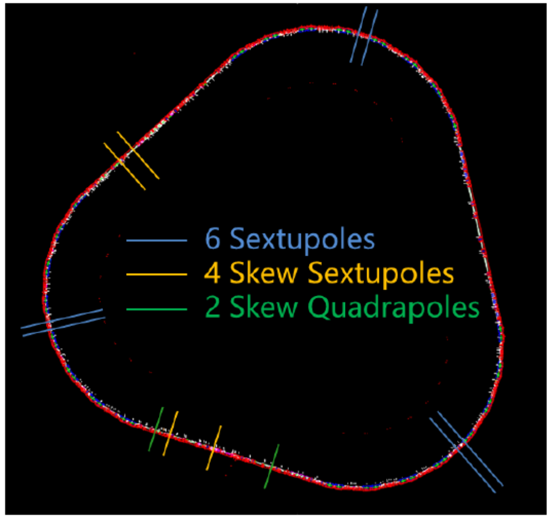
Complete linac installation in 2026

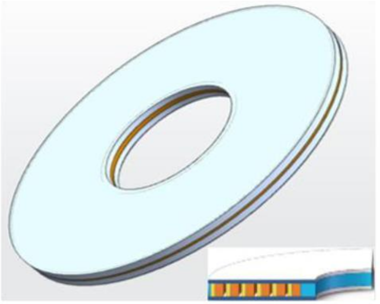


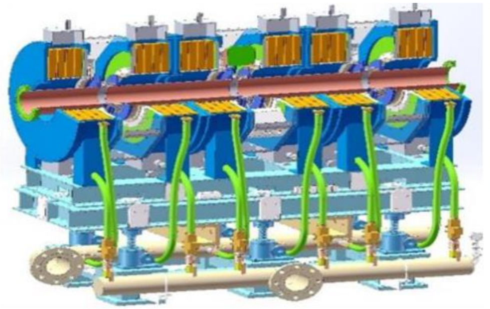


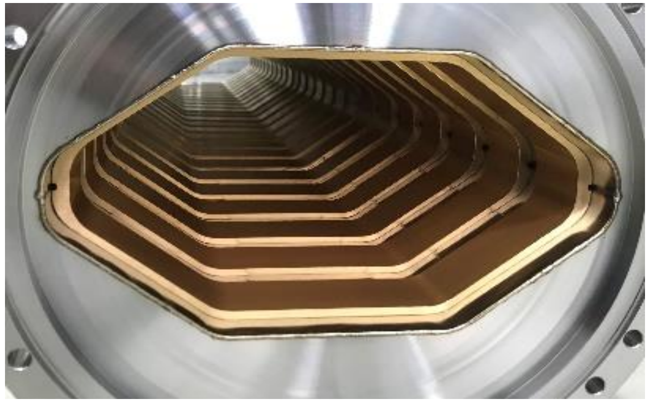
Accelerator Technology Center

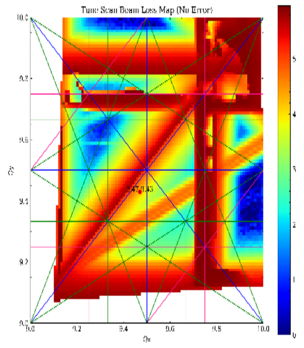


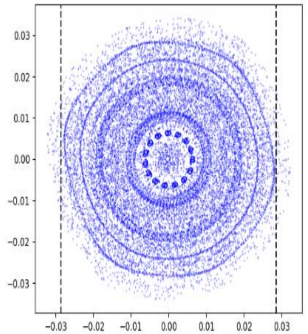




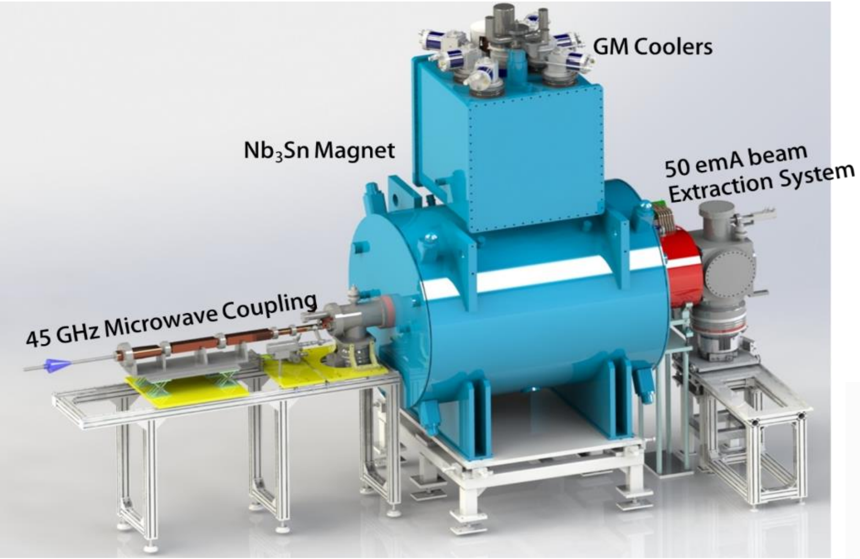


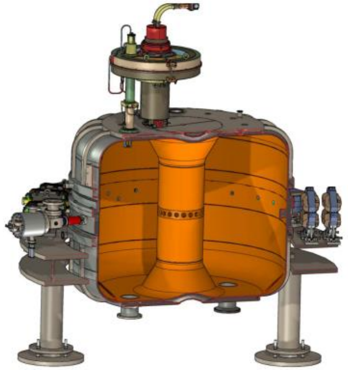


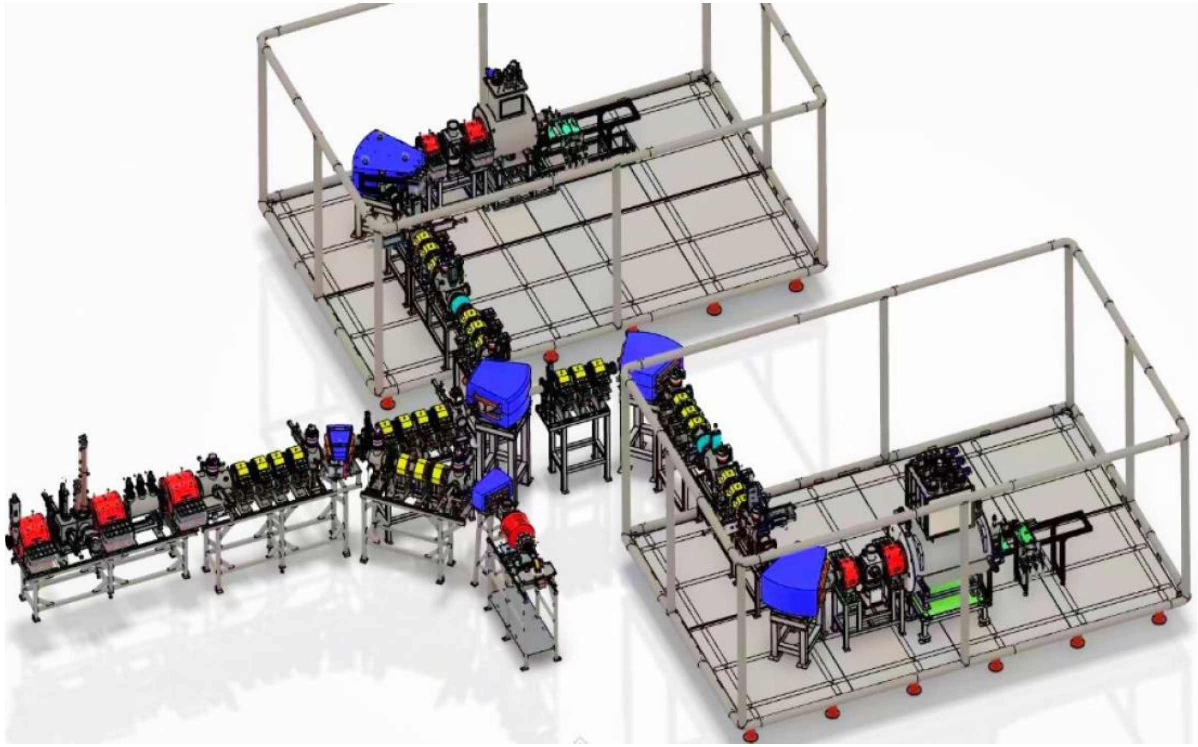




Low-Energy Particle Beam Technology Center

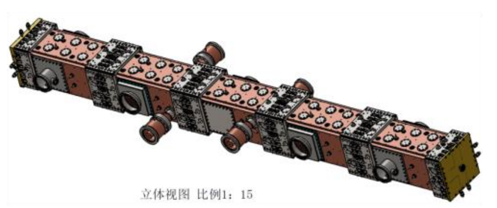


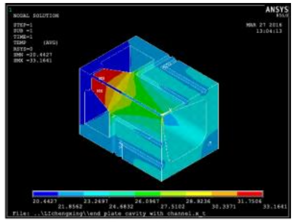




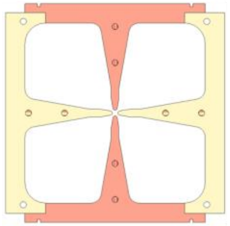
Linear Accelerator Center

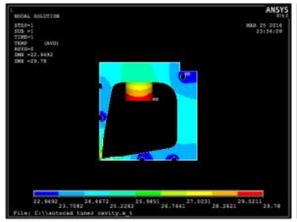
加速器驱动嬗变研究装置
China Initiative Accelerator Driven System



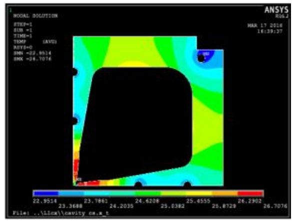


Tmax=33°C



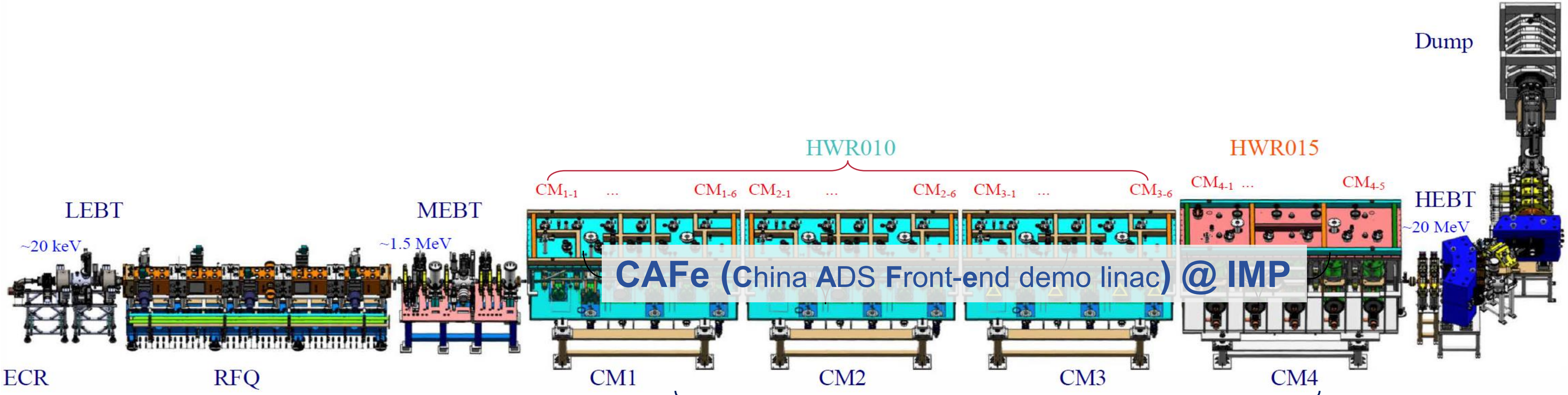


Tmax=30°C



Tmax=26°C

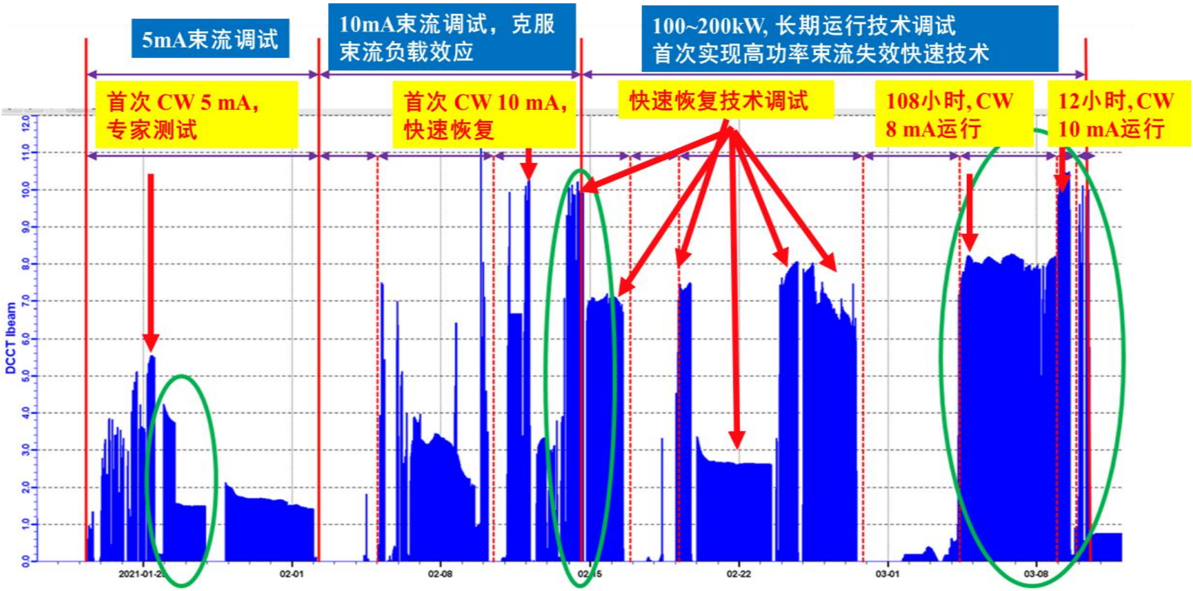
Chinese ADS Front end (CAFe)



Four Cryomodules，23 SRF Cavities，Cavity Bandwidth：80 Hz~200 Hz，HWR_{010}+HWR_{015})

Chinese ADS Front end (CAFe)

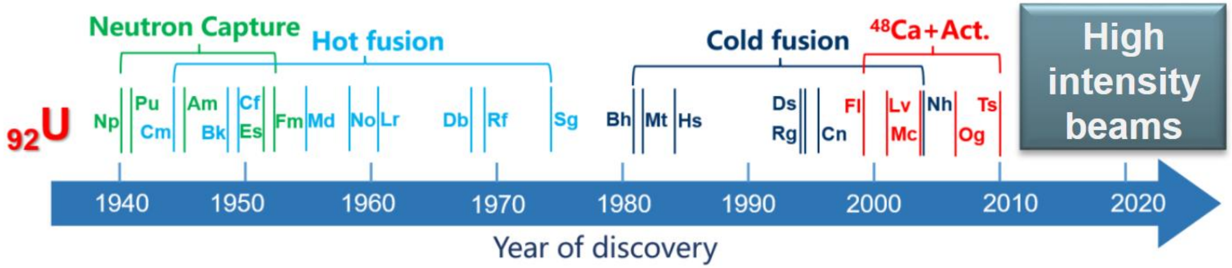
- Resolved critical challenges in high-current CW superconducting hadron linac
- Stable operation >100 kW for >100 hours
- First verification of 10 mA CW proton beam with fully superconducting linac

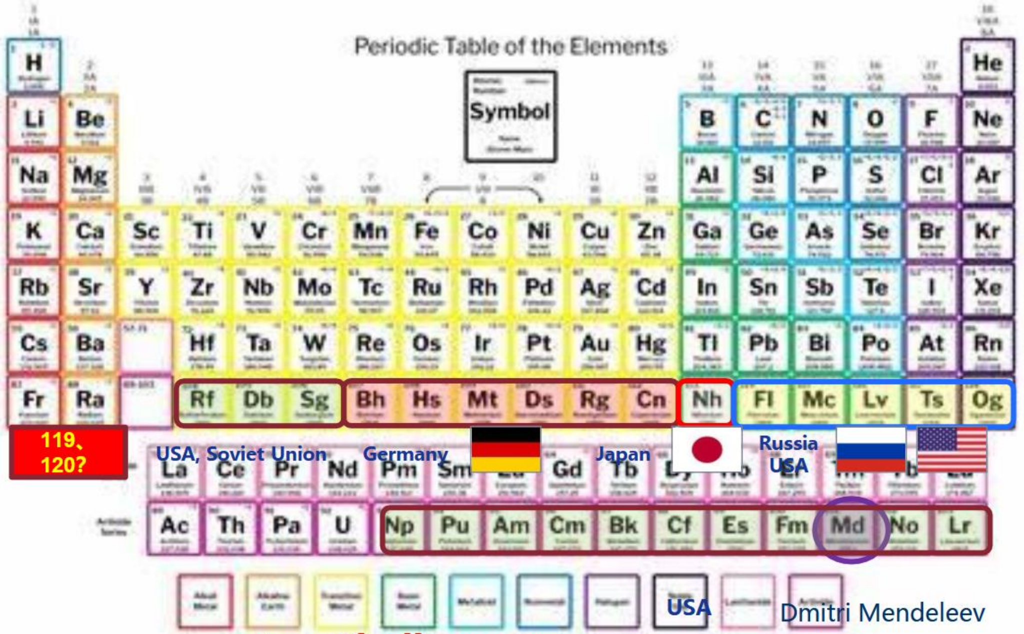


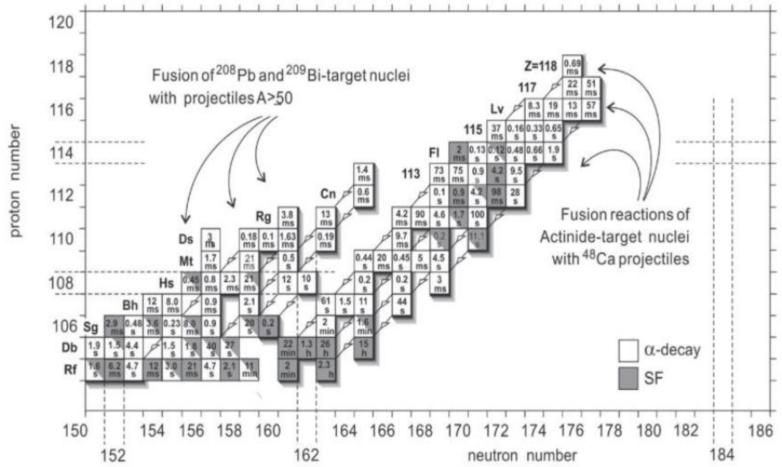
China Accelerator Facility for superheavy Elements (CAFE2)

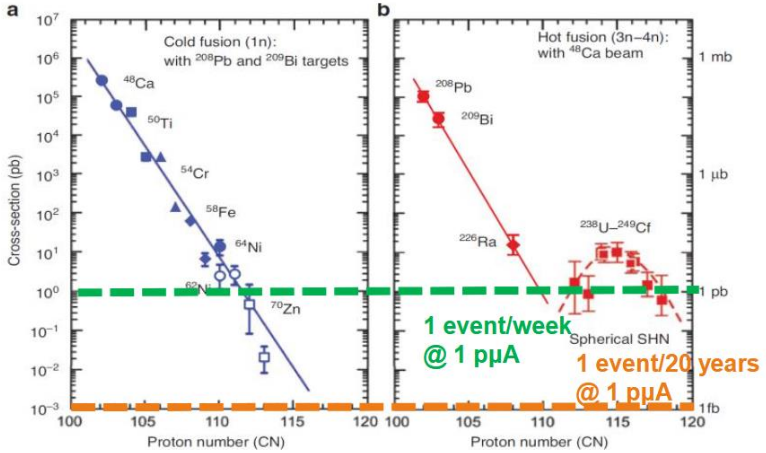
Top science questions：

How many elements can exist on Periodic Table?
Are there stable high-atomic-number elements?
What are their chemistry properties for the heaviest elements?





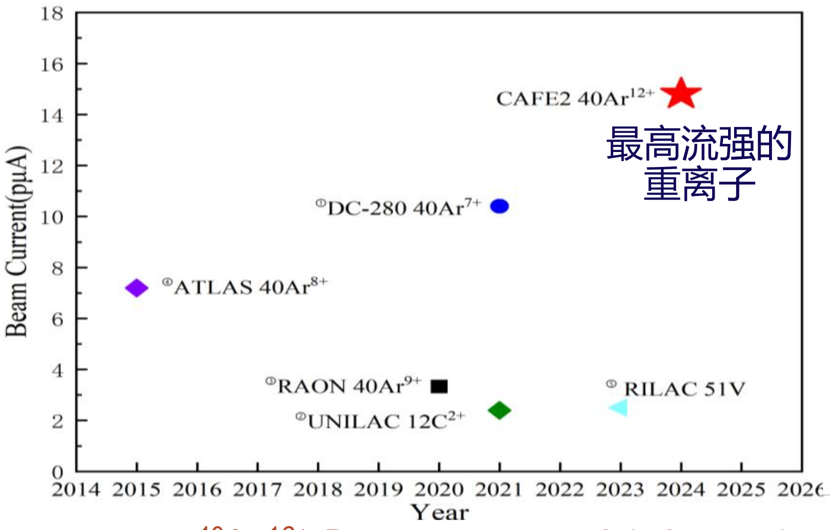


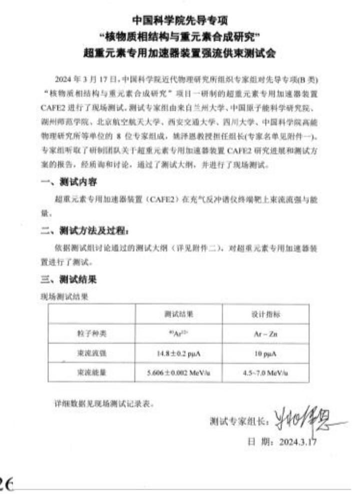


S. Hofmann, in *Radiochimica Acta* **107**, 879 (2019).

- ***Challenges:***
- **High beam intensity with Ca~Zn ions (5~10 pμA)**
- **Long beam time (a few months or years expt.)**
- **Actinide target material (U, Am, Cm, Cf …)**
- **Rotating target withstanding high power beams**
- **High efficiency separator**
- **Atom-at-a-time detection and DAQ**

China Accelerator Facility for superheavy Elements (CAFE2)





中国科学院先导专项
“核物质相结构与重元素合成研究”
超重元素专用加速器装置强流供束测试会

2024 年 3 月 17 日，中国科学院近代物理研究所组织专家组对先导专项(B 类)“核物质相结构与重元素合成研究”项目一研制的超重元素专用加速器装置 CAFE2 进行了现场测试。测试专家组由来自兰州大学、中国原子能科学研究院、湖州师范学院、北京航空航天大学、西安交通大学、四川大学、中国科学院高能物理研究所等单位的 8 位专家组成，姚泽恩教授担任组长(专家名单见附件一)。专家组听取了研制团队关于超重元素专用加速器装置 CAFE2 研究进展和测试方案的报告，经质询和讨论，通过了测试大纲，并进行了现场测试。

一、测试内容

超重元素专用加速器装置（CAFE2）在充气反冲谱仪终端靶上束流流强与能量。

二、测试方法及过程：

依据测试组讨论通过的测试大纲（详见附件二），对超重元素专用加速器装置进行了测试。

三、测试结果

现场测试结果

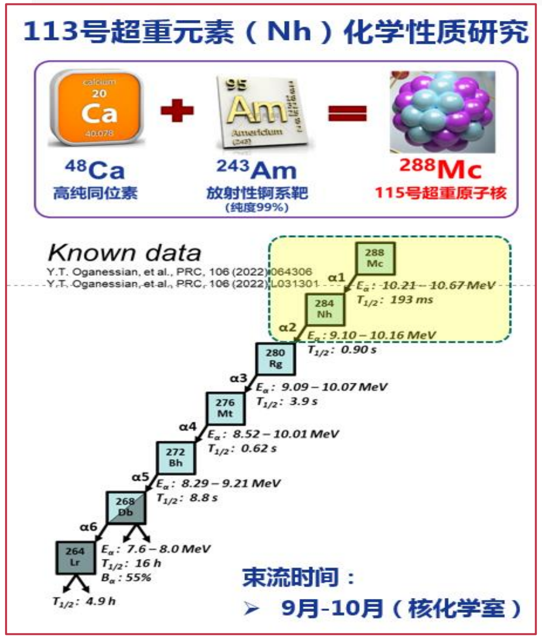
	测试结果	设计指标
粒子种类	$^{40}Ar^{12+}$	Ar – Zn
束流流强	14.8±0.2 pμA	10 pμA
束流能量	5.606±0.002 MeV/u	4.5~7.0 MeV/u

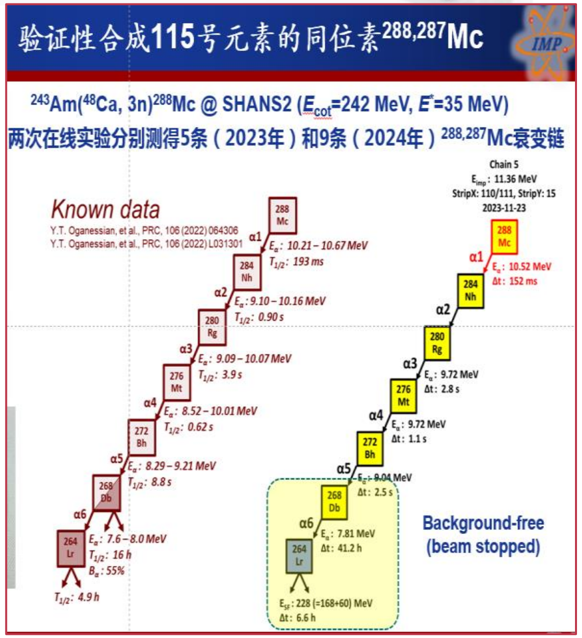
详细数据见现场测试记录表。

测试专家组长：[signature]

日 期：2024.3.17

$^{40}Ar^{12+}$ Beam current highest in the world





Superheavy synthesis: 119、120

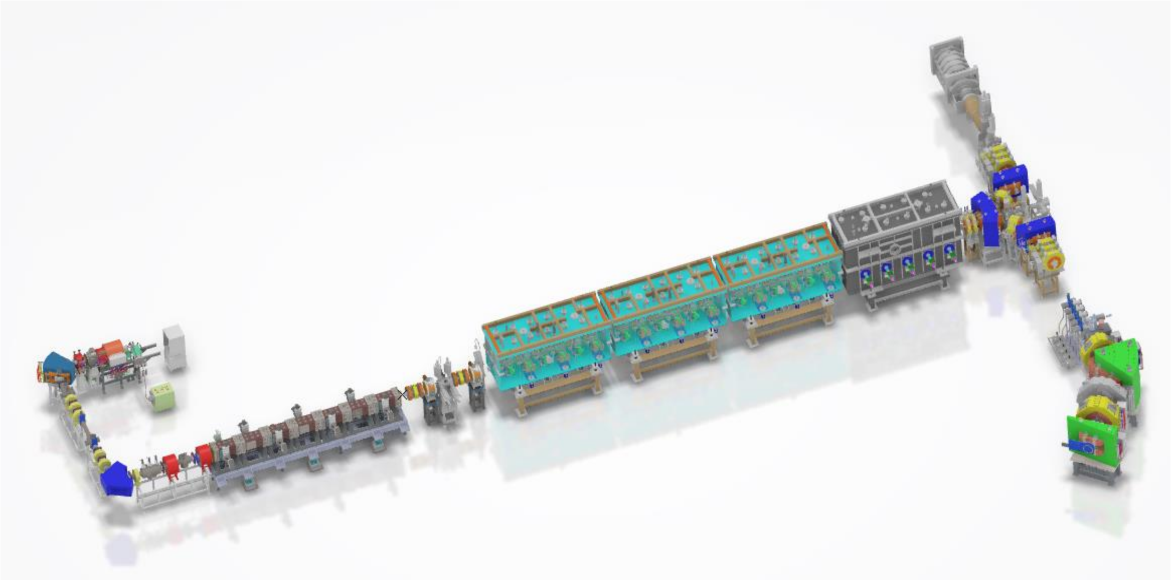
Statistics of SHANS Experiment Time (2022 ~2024)					
Particle	Accumulated Beam Hours	Targeting Hours	Particle	Accumulated Beam Hours	Targeting Hours
40Ar13+	248	248	40Ar12+	1669	1597
40Ca13+	962	717	48Ca14+	1885	1732
55Mn17+	232	134	54Cr17+	4008	3427

Beam on-target 7855h, availability>90%

Future Plans for CAFE2

- **Goal: routine operation with 15 puA 54Cr, >5000h annually, availability >95%**

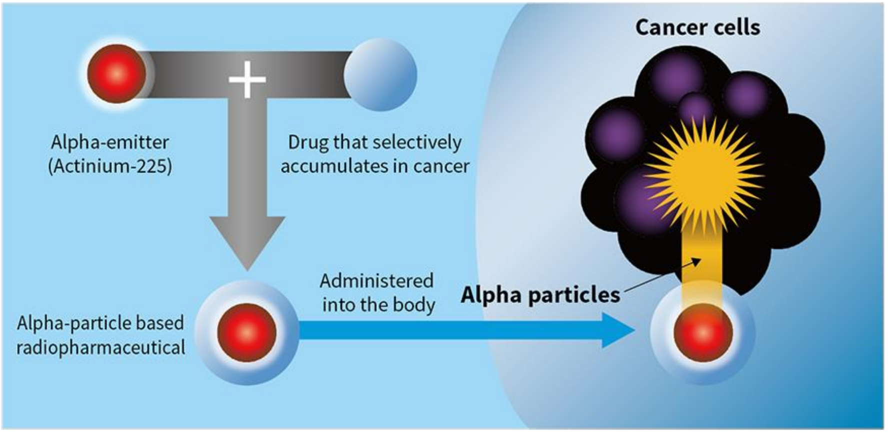
- **This year:**
  - New ion source
  - System maintenance
    - CAFe and CAFE2 together >10 years

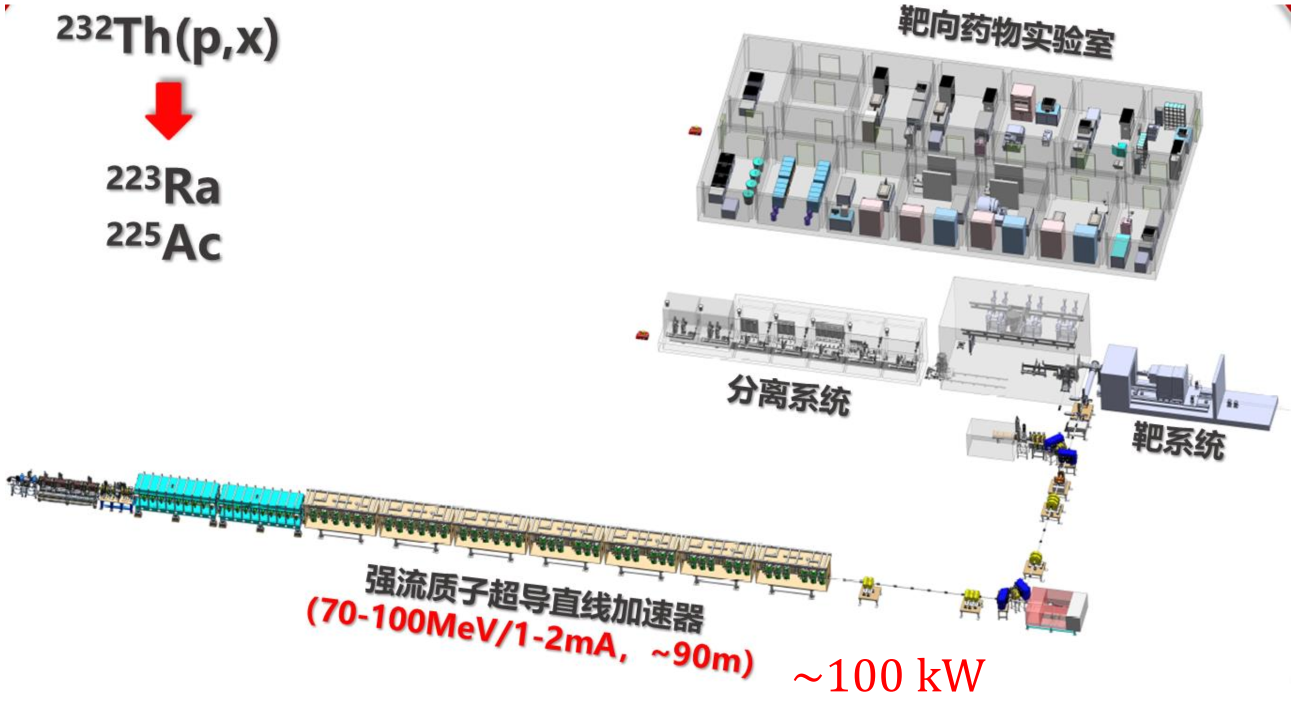


2026	2027	2028	2029-2030
Trial with 10 puA	15 puA operation	5000h, 95% availability	>6000h per year

IP-SAFE: Medical Radioisotope Facility

- Isotope Pharmaceutical production platform based on Superconducting Accelerator Facility for Effective therapy (IP-SAFE)
- World's first demonstration facility that mass produce alpha-emitting medical isotopes using a superconducting linac
- Targeted alpha therapy





Project launched

Warm frontend commissioning

115 MeV, 1 mA beam on target, verify multi-target scanning

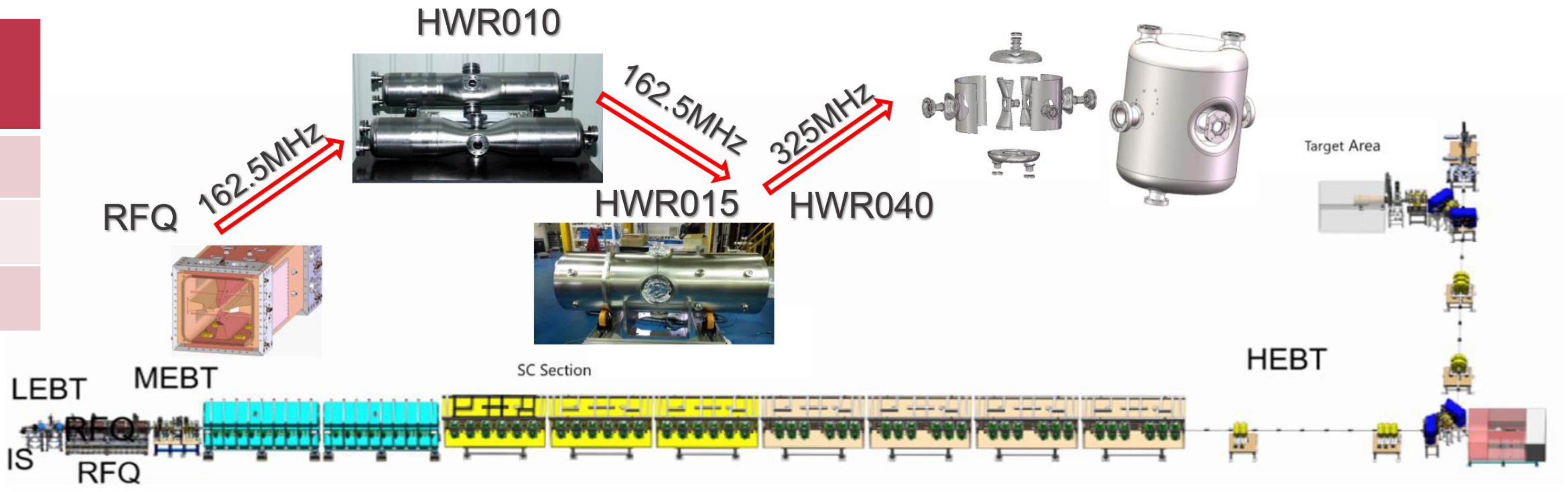
Jul 2024 → Feb 2026 → Ongoing → Dec 2026 → 2028 → 2030

Linac installation completed

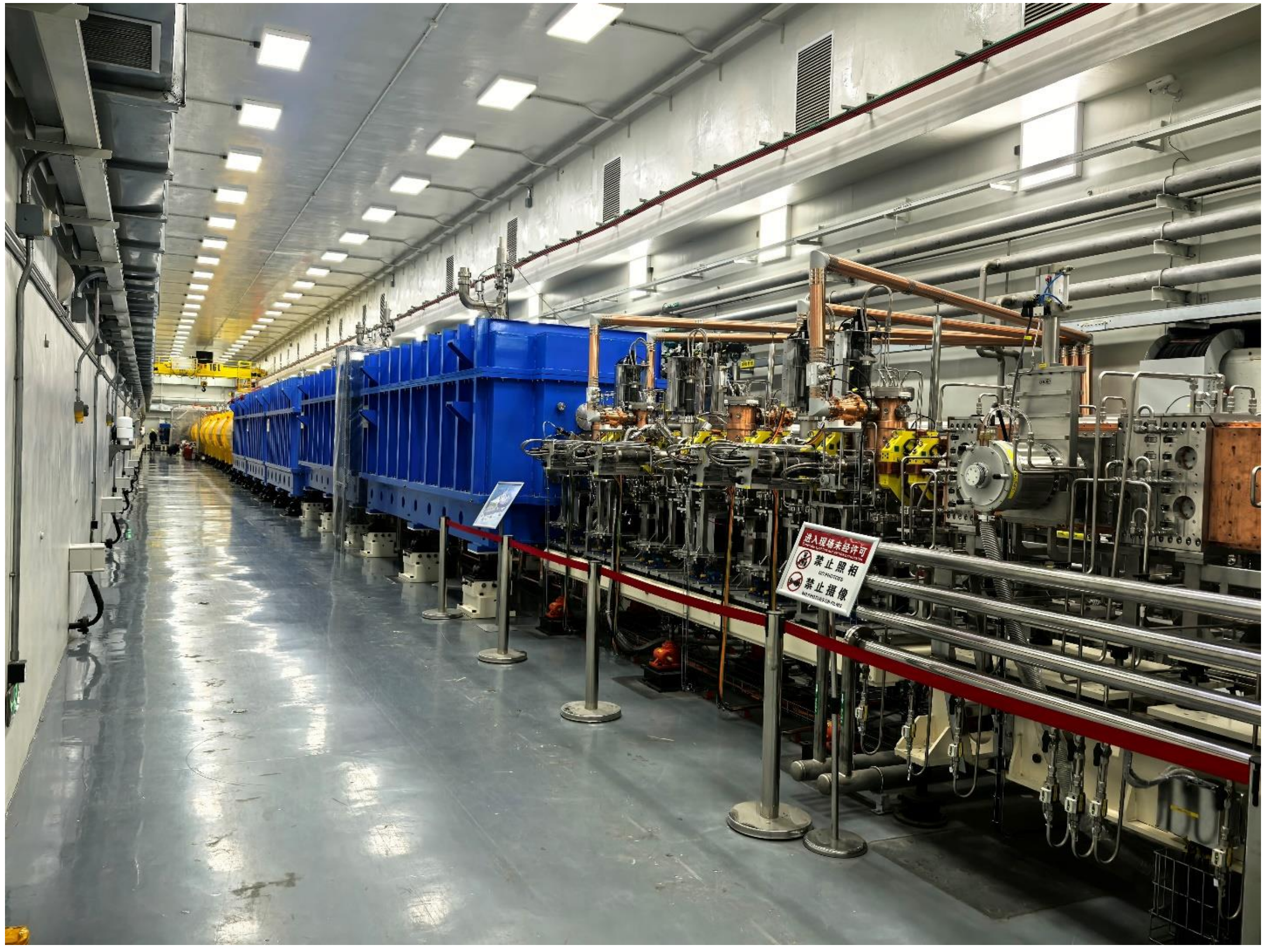
First beam on target at 100 MeV

115 MeV, 2 mA beam in production mode

Cavity Type	Cavities per CM	No. of CM
HWR010	9	2
HWR015	6	3
HWR040	6	6



Photos of IP-SAFE



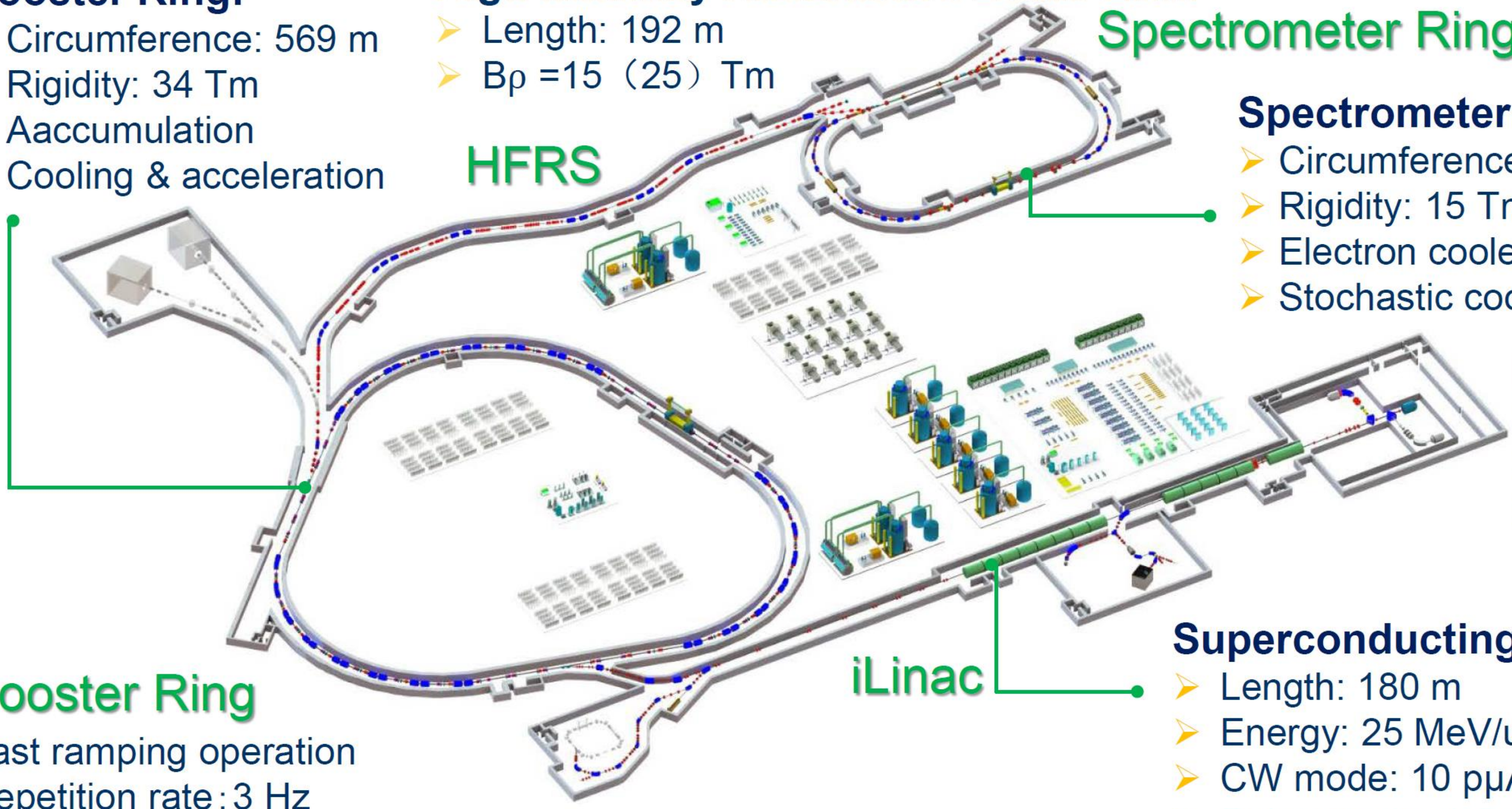
Two Large-Scale Projects in Huizhou

Aerial View (March 2025)

HIAF Layout

Booster Ring:
- Circumference: 569 m
- Rigidity: 34 Tm
- Aaccumulation
- Cooling & acceleration

High Intensity Radioactive Beam Line:
- Length: 192 m
- Bρ =15（25）Tm



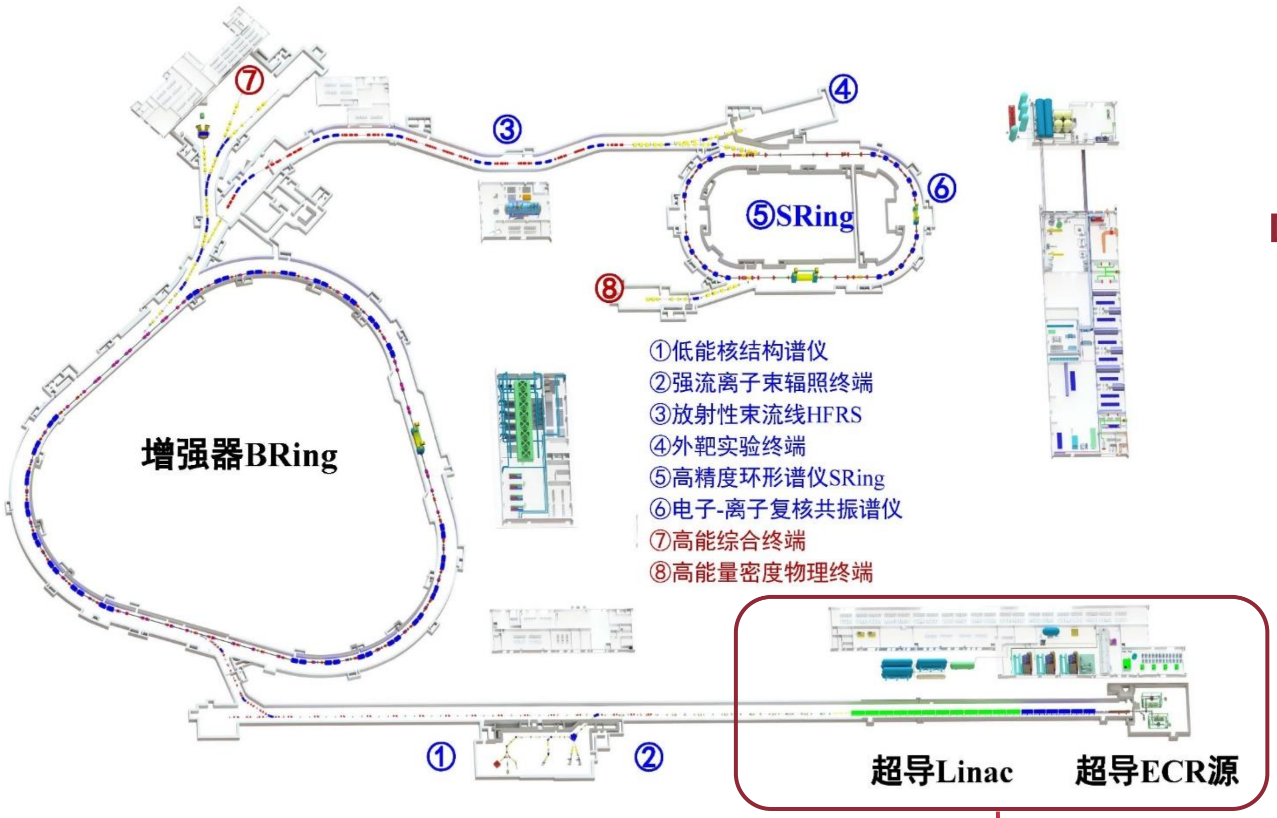
Spectrometer Ring:
- Circumference: 277.2 m
- Rigidity: 15 Tm
- Electron cooler
- Stochastic cooler

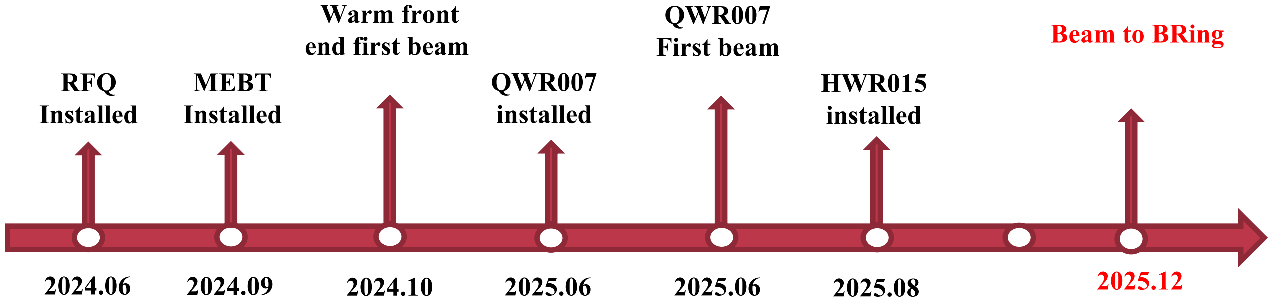
Ion Sources:
- a 45 GHz FECR
- a 28 GHz SECRAL
- a 2.45 GHz ECR

Fast ramping operation
Repetition rate：3 Hz

Superconducting Ion Linac:
- Length: 180 m
- Energy: 25 MeV/u ($^{238}U^{34+}$)
- CW mode: 10 pμA with A/Q=2~5
- Pulse mode: 1.0 emA with A/Q=2~7

HIAF iLINAC





HIAF-iLINAC 参数

ions	Q/A	intensity	Energy (MeV/u)	Operation mode
$^{238}U^{35+}$	**1/7**	**1.0 emA**	**17**	pulse
$^{78}Kr^{19+}$	1/4.1	1.0 emA	27	
$^{18}O^{6+}$	1/3	1.0 emA	33	
H_2^+	1/2	0.6 emA	48	
48Ca-70Zn	-	10 puA	4-8	CW
Xe-U	-	10 puA	5-22	

HIAF iLinac: Photos and Beam Parameters Dec 2025

Ion	Current (emA)	Energy（MeV/u）
$^{18}O^{6+}$	0.462	33.5
$^{209}Bi^{31+}$	0.270	17.04

HIAF Beam Commissioning in Oct-Dec 2025

Typical Beam Parameters From the Booster Ring

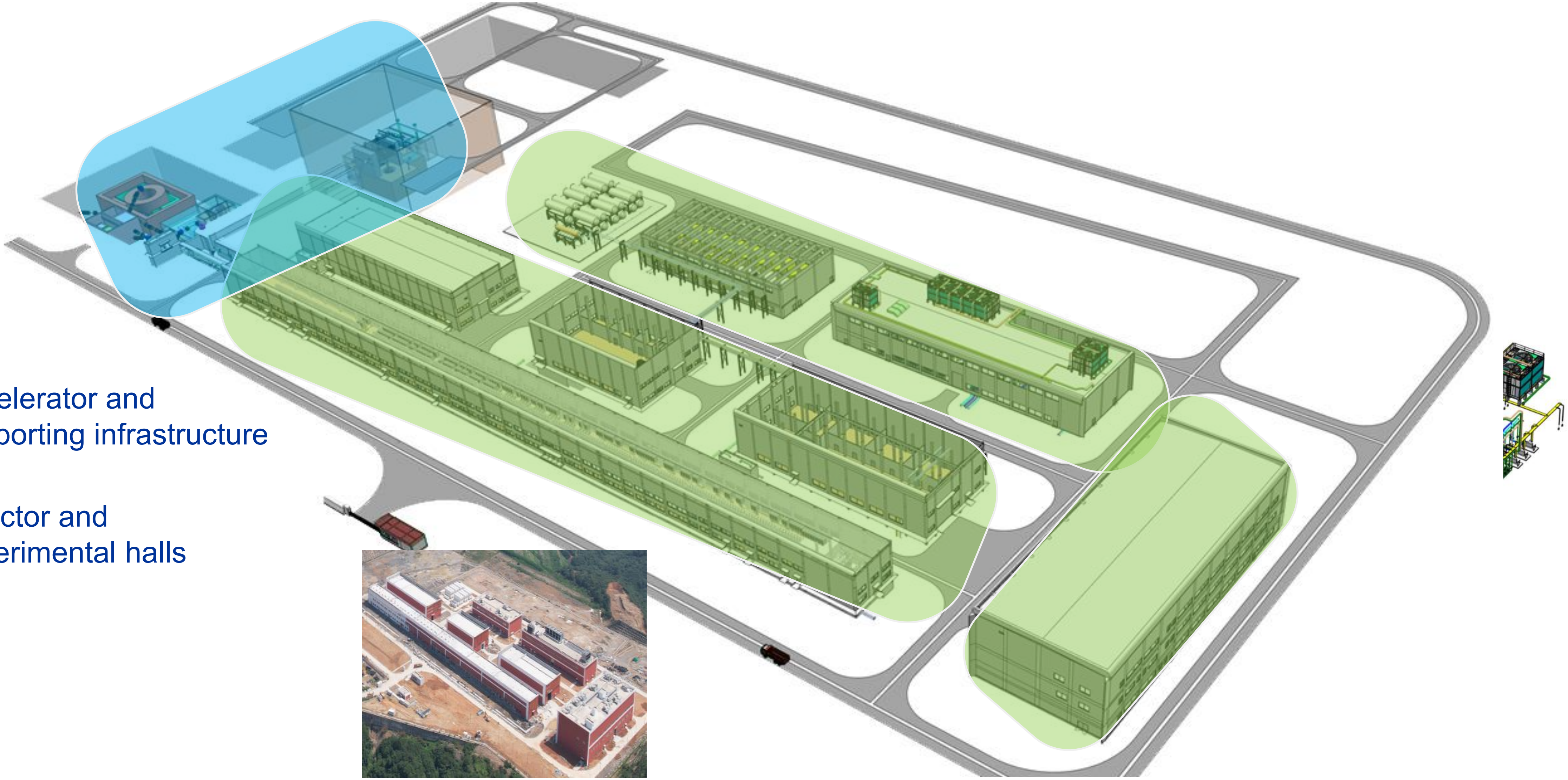
Ions	Energy(GeV/u)	Intensity (ppp)	Achieved Dec 2025
p	9.3	2.0×10^{12}	
$^{18}O^{6+}$	2.6	6.0×10^{11}	2.5×10^{11}
$^{78}Kr^{19+}$	1.7	3.0×10^{11}	
$^{209}Bi^{31+}$	0.85	1.2×10^{11}	3.0×10^{10}
$^{238}U^{35+}$	0.835	1.0×10^{11}	

Both world's highest to-date

The maximum beam intensities were estimated by optimizing the charge number

Higher beam energies available on a tradeoff of the beam intensities

CiADS Overall Layout

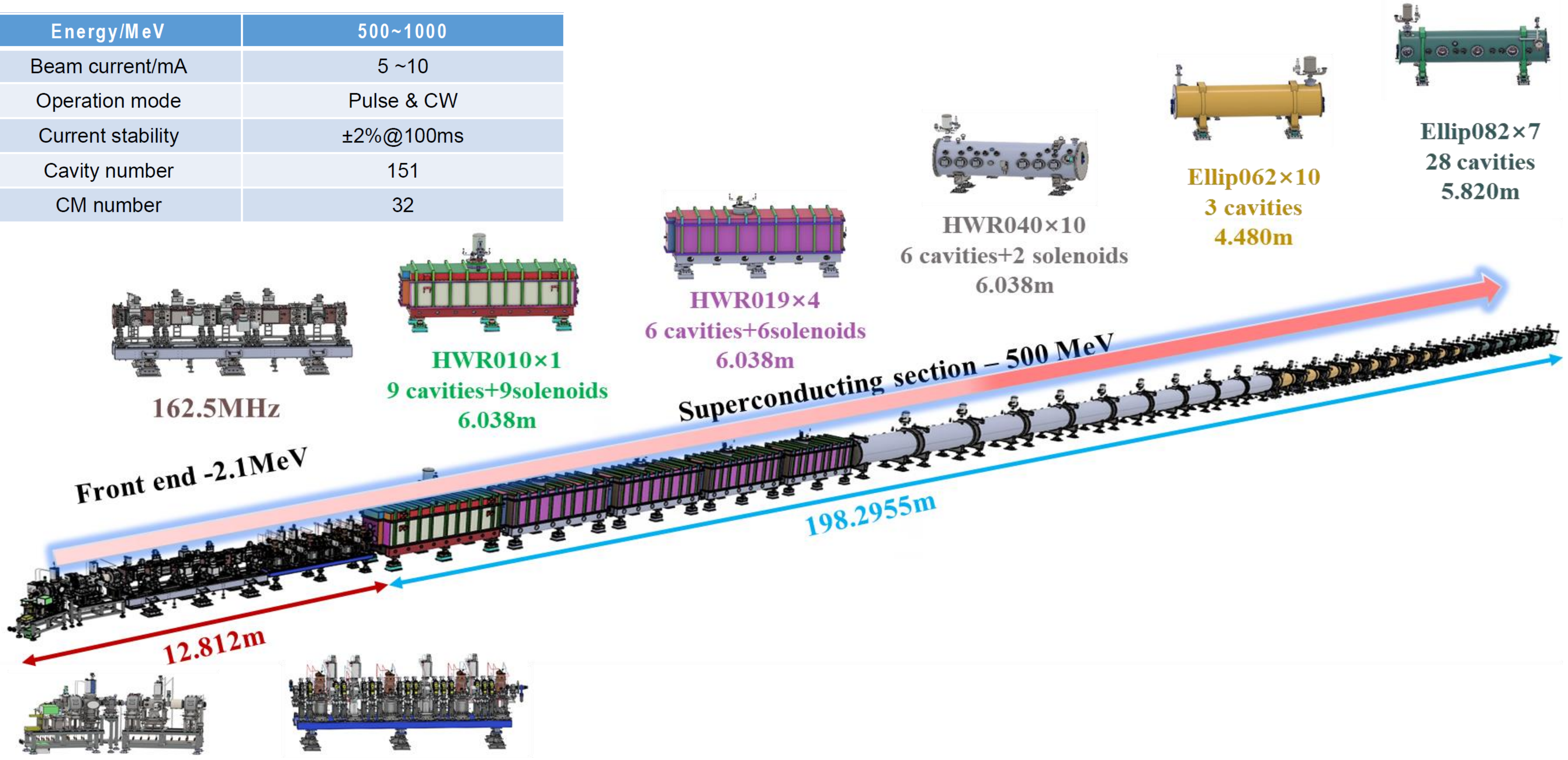


Accelerator and supporting infrastructure

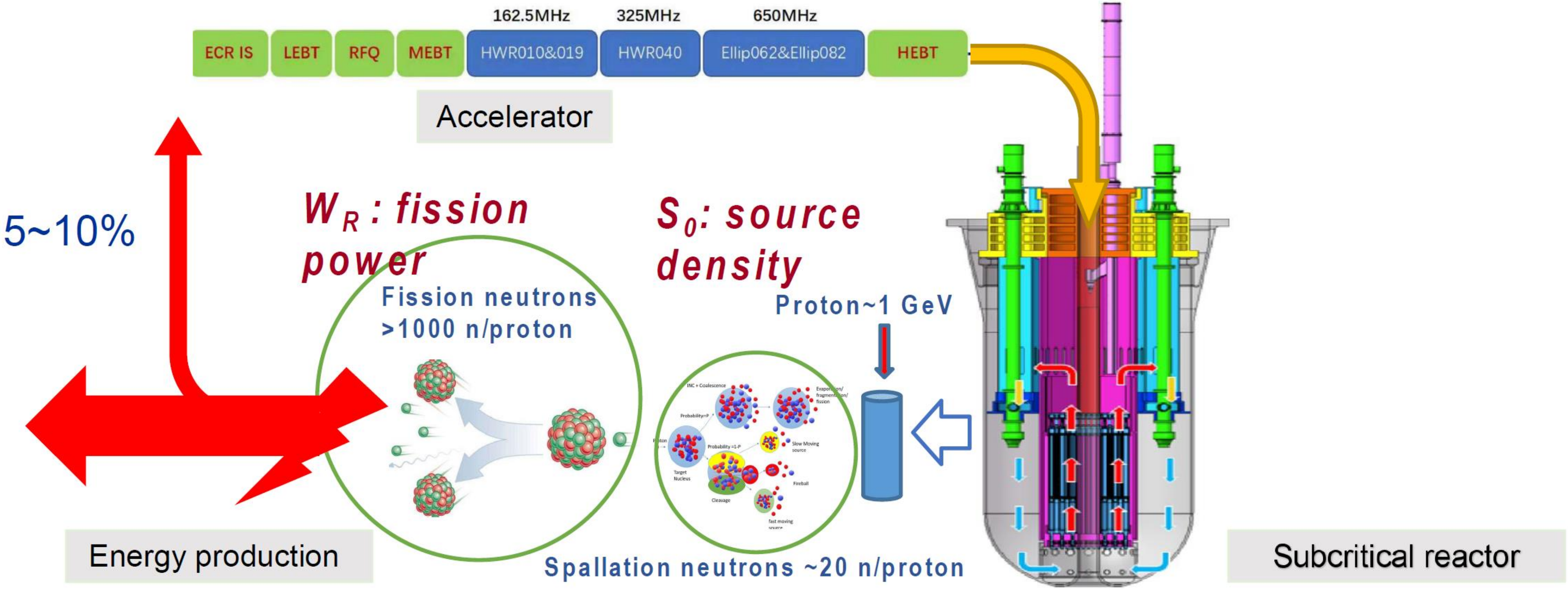
Reactor and experimental halls

CiADS Linac Layout

Energy/MeV	500~1000
Beam current/mA	5 ~10
Operation mode	Pulse & CW
Current stability	±2%@100ms
Cavity number	151
CM number	32

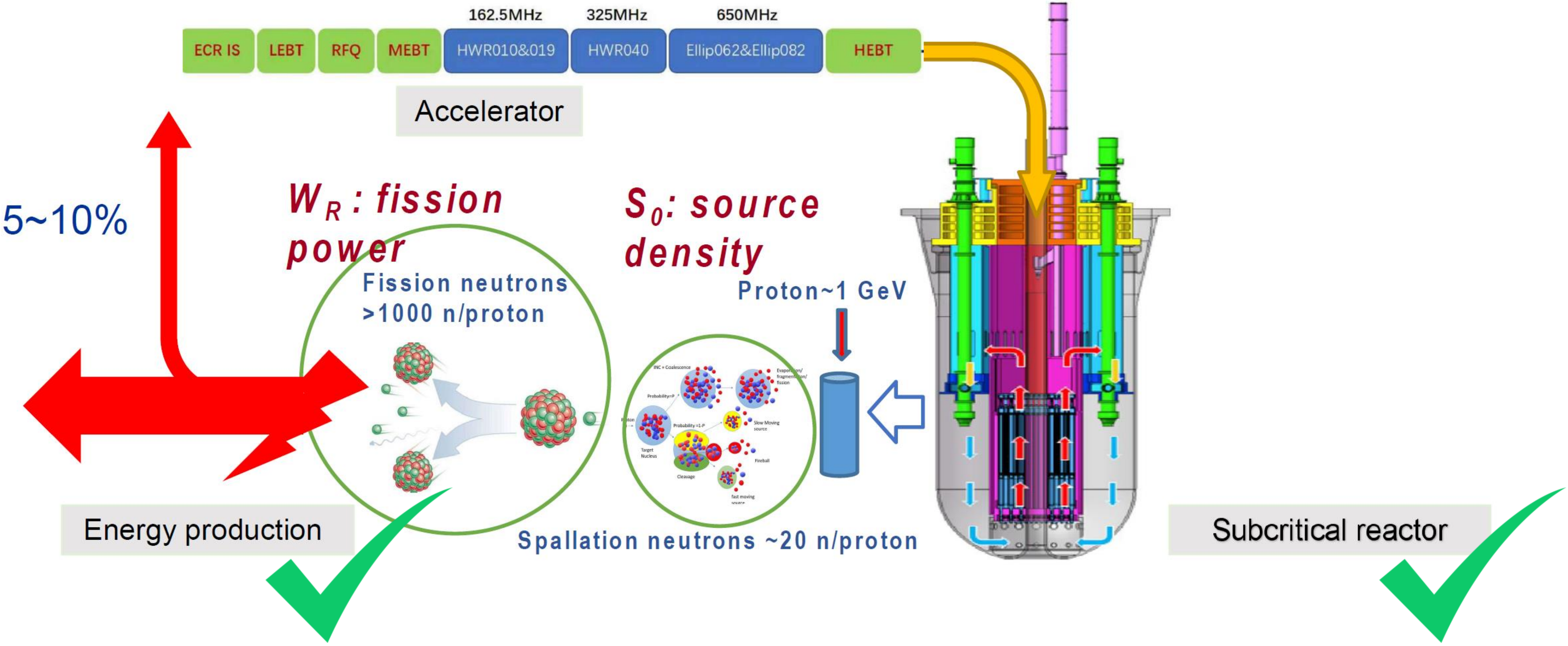


ADS consists of an accelerator, a spallation target, a subcritical reactor, and energy systems. The subcritical reactor is driven by a high energy proton, works like an energy amplifier.

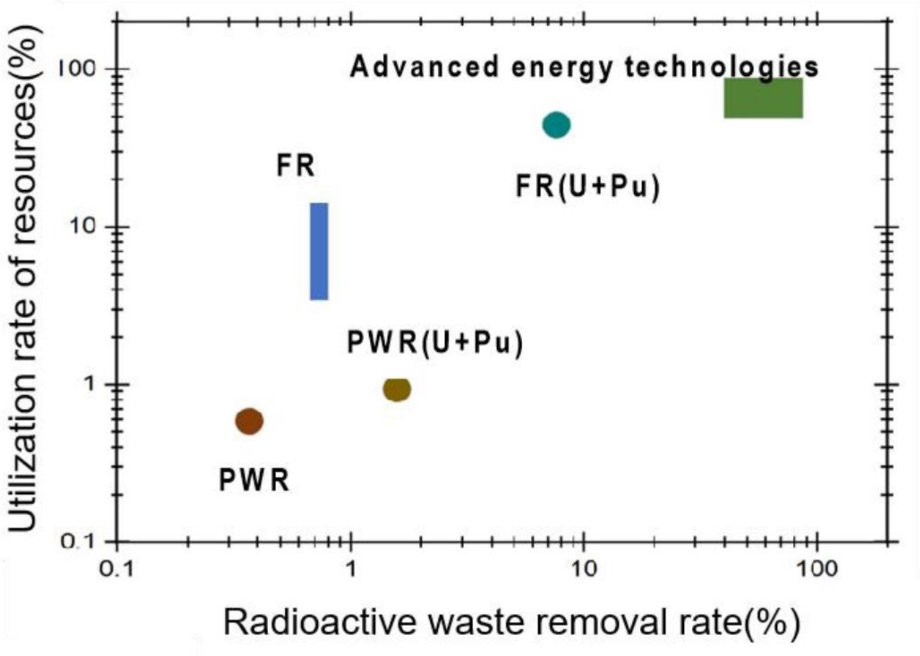


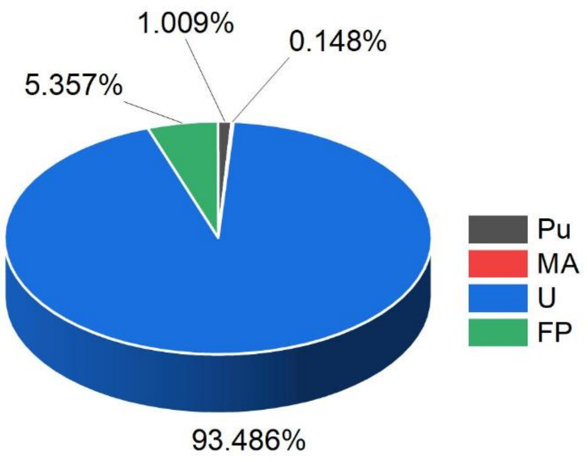
Accelerator Driven subcritical System (ADS)

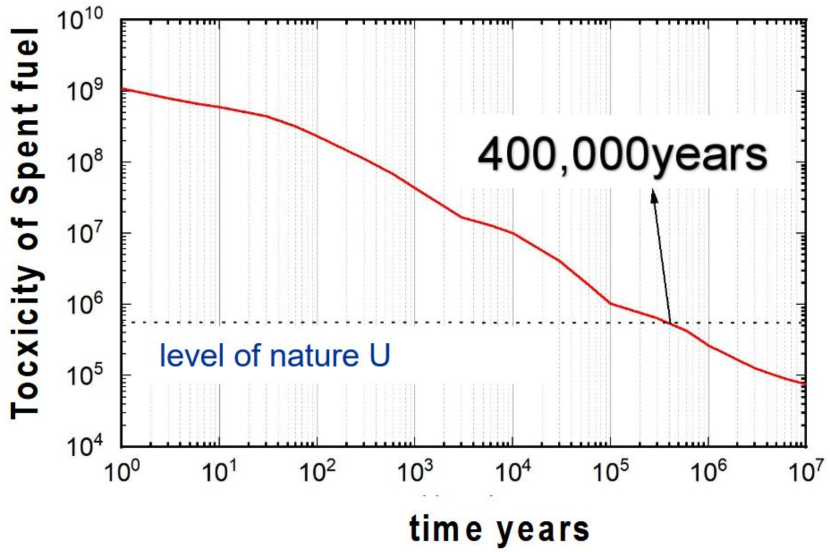
ADS consists of an accelerator, a spallation target, a subcritical reactor, and energy systems. The subcritical reactor is driven by a high energy proton, works like an energy amplifier.



Sustainability Issues of Nuclear Fission Energy: Waste & Wastage



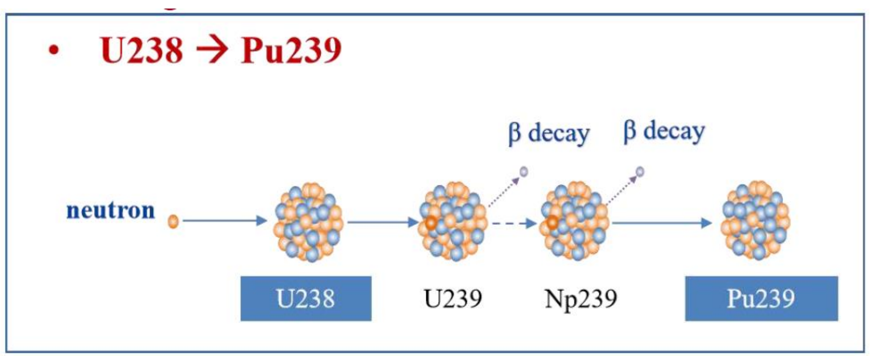




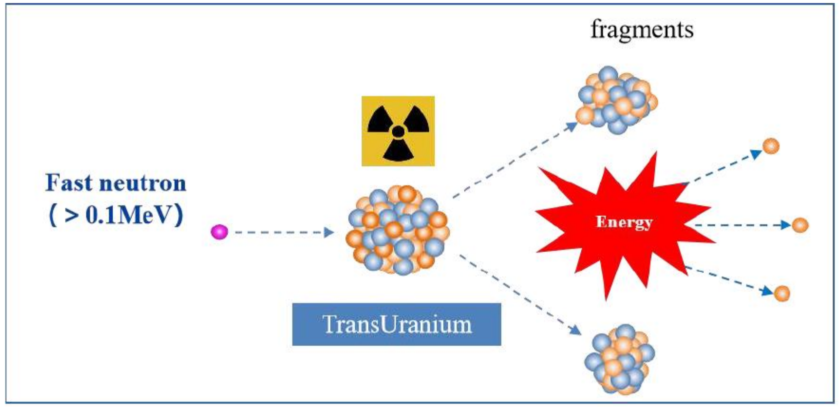
- **8 tons of natural uranium --> 1 ton of nuclear fuel -> only 50 kg is burntup into fission products**
  - Reusable fuel (950kg) + depleted uranium (7 tons) has huge untapped potential for energy
- **About 11,300 metric tons of spent fuel discharged annually around the world**
  - Radioactive lifespan extending hundreds of thousands of years
  - It is projected that by 2050, China's annual discharge of spent fuel will reach about 6,500 metric tons.

Road to Sustainable Fission Nuclear Power

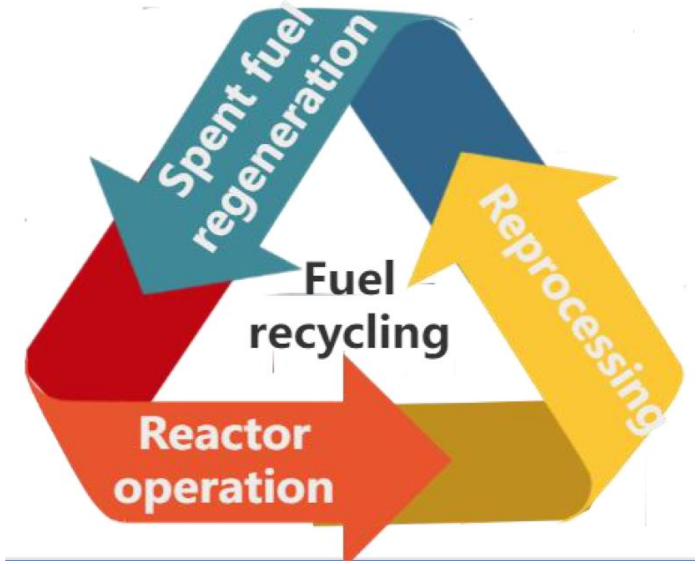
- **Breeding**



- **Transmutation**



- ~100 times increase in amount of nuclear fuel
- ~10 times reduction in amount of nuclear waste
- ~1000 times reduction in waste radioactive-lifetime



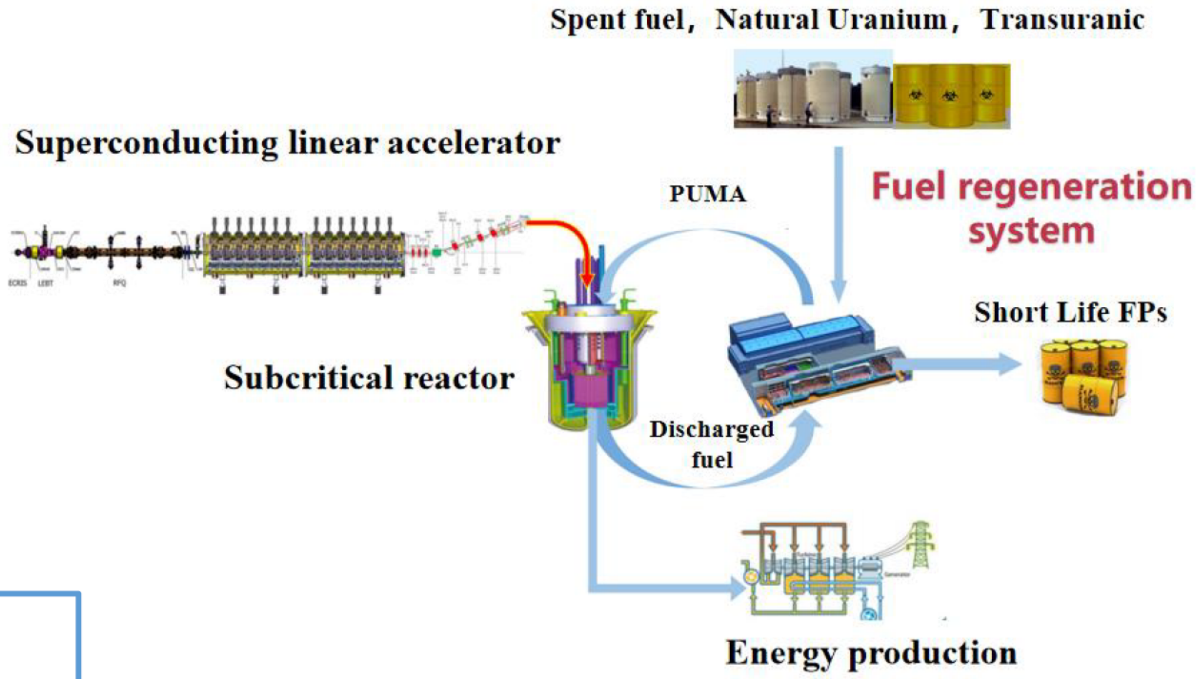
Accelerator Driven Advanced Nuclear Energy System (ADANES)

"Full" use of depleted uranium and spent fuel, and "flexible" integration of the existing nuclear power industrial system

Accelerator Driven Advanced Nuclear Energy System

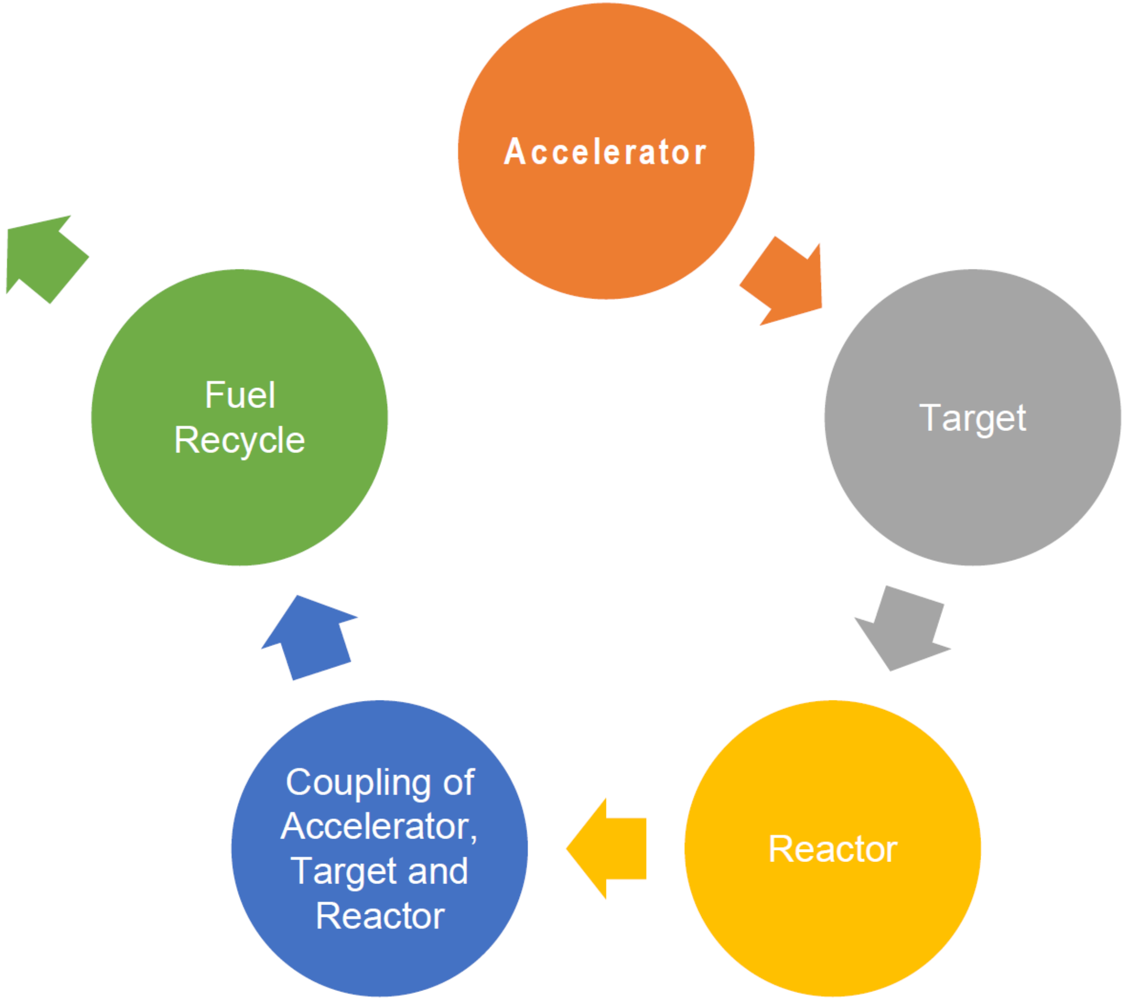
- Spent fuel reprocessing: Partially remove fission fragments from spent fuel, Mix fuel PUMA = Pu+U+MA : (**NO fine separation of uranium, plutonium, and minor actinides, even a few FP**)
- Advanced burner ADS: —— External neutron driven subcritical reactor (LFR), transmutation, breeding, and energy production

- Utilization rate of uranium resources： ~1% → ~95%
- Radioactive waste lifetime： Hundreds of thousands of years → Several hundred years
- Radioactive effluent： ~25t → ~1t （1GWe/pile year）
- Reactivity control： Critical operation → Subcritical operation



- Complete reprocess of ADANES fuel cycle
- Each time the fission products are removed, and add some spent fuel or depleted uranium

Challenges of ADANES



- **High power (tens of MW) accelerator**
  - CW beam 10-30mA, Energy: 0.8-2GeV
  - High availability
- **High power (tens of MW) target**
  - ≥40 dpa target window
  - ≥10-20MW heat removal
- **Subcritical LBE reactor**
  - Fast neutron reactor
  - Material for LBE
- **Spent fuel reprocessing**
  - remove most of fission fragments by high temp. dry processing

Roadmap of ADANES/CiADS

2025 ~ 2026

Construction Accelerator and Target

- Accelerator 25kW
- Target >25kW
- At HiTa

- Accelerator Commissioning
- Target thermal study
- **Beam-target coupling tech**
- **Reactor thermal study**
- Beam-target coupling

2026 ~ 2027

ADS Coupling Early Fuel test

- Accelerator 250kW
- Target 250kW
- K_{eff}~0.5
- Reactor~30kW

- 3 Fuel Assemblies online
- Accelerator stability study
- Reactor stability study
- **Beam-target-reactor coupling**
- **Low power test for fuels**
- Low power exp for reactor

2027~2029

ADS/ADANES demonstration 10MW system coupling

- Accelerator 2.5MW
- Target 250kW
- K_{eff}=0.96
- Reactor ~9.75MW

- Full fuel online
- Neutronic study of Subcritical Reactor
- **Operation study of Subcritical Reactor**
- LBE cooling demonstration with power
- **ADS systematic study**
- **ADS operation key tech study**
- **2.5MW beam test for accelerator**
- ADANES design demonstration

2029~2030

ADS/ADANES transmutation research

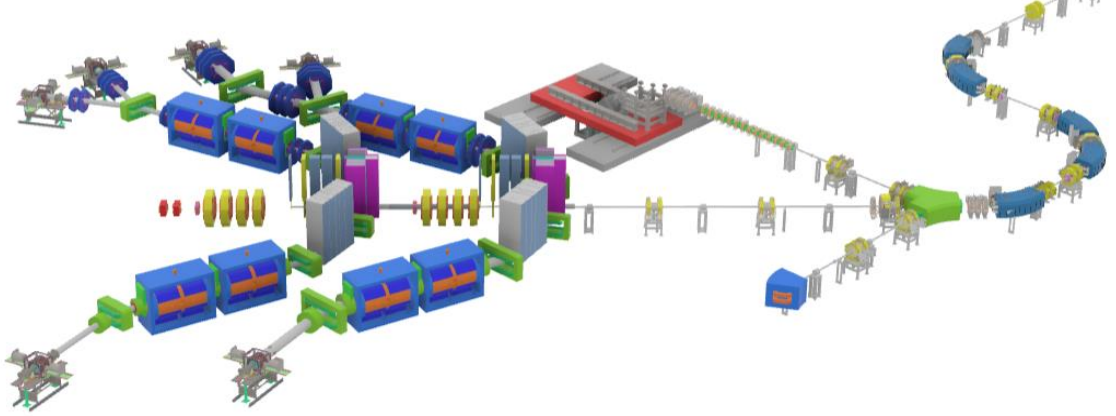
- Accelerator ~2.5MW
- Target ~2.5MW
- K_{eff}~0.75
- Reactor ~7.5MW

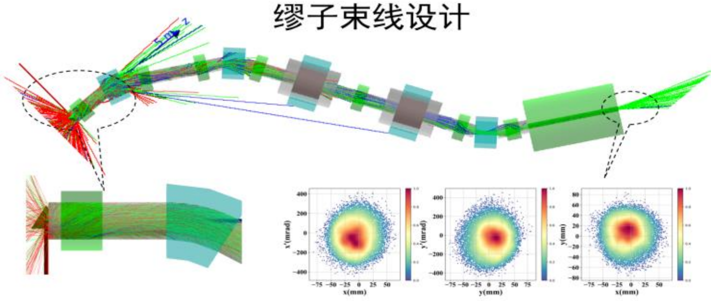
- **High power target demonstration**
- ADS operation with high power
- **Transmutation demonstration**
- Test fuels with deep burnup
- Fuel test with high power density
- ADANES preliminary design report

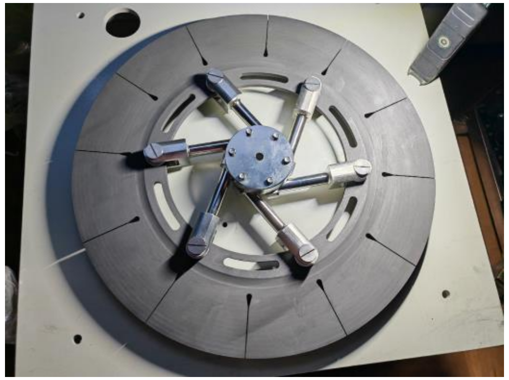
Muon Beamline at CiADS

- **First continuous wave muon beamline, 10^8 μ/s**

- **Ongoing R&D**
  - High power muon target
  - Muon collection and transport system

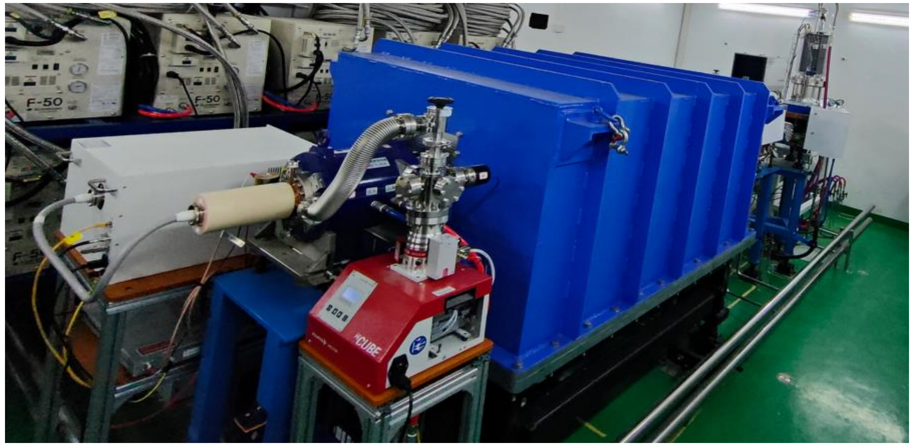


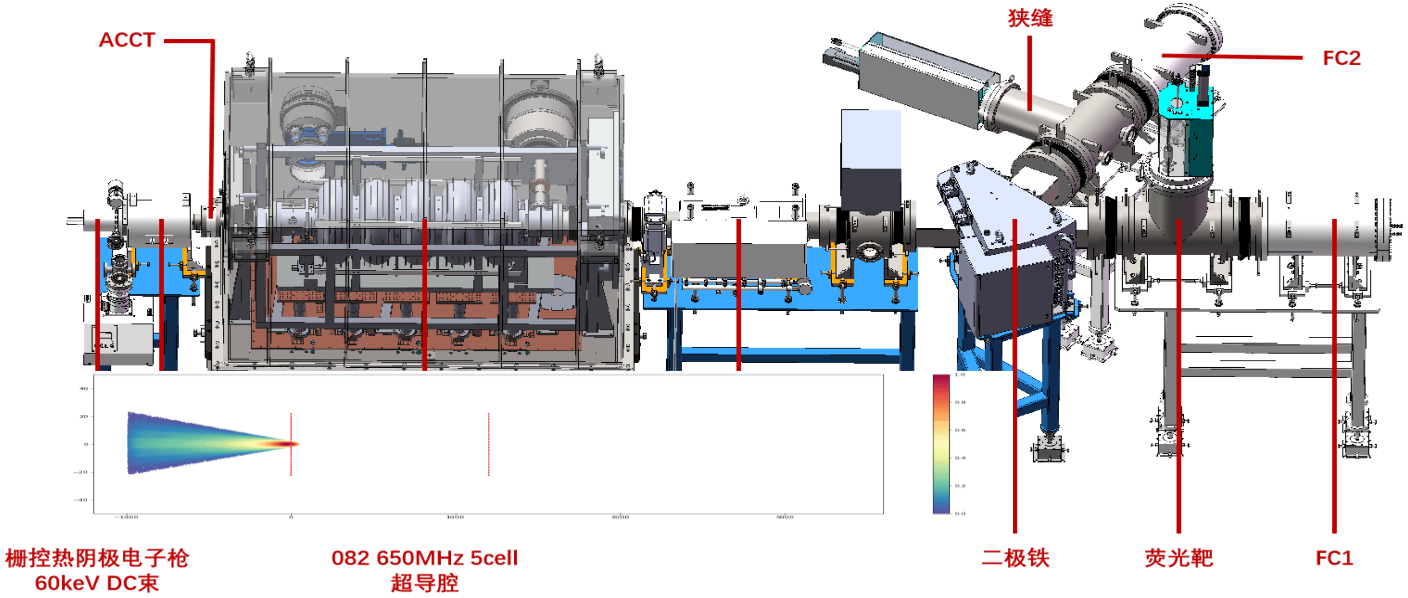




Spin-off: Compact CW Electron Linac

- **Conduction-cooled liquid-He-free Nb3Sn cavities**
- **Commissioned in pulsed mode, developing electron gun for CW operation**
- **Goal: 4 MeV, 10 mA CW**





Two major goals:

1) High availability and reliability
2) Low beam loss

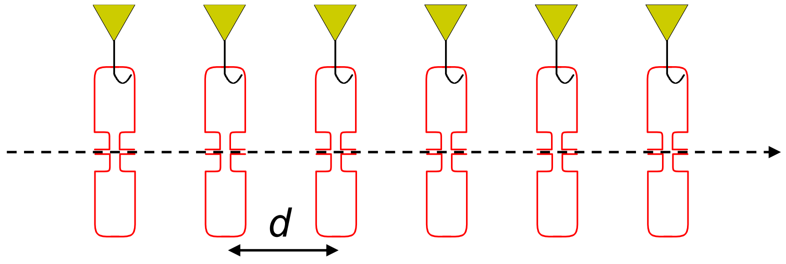
Conventional Method: Phase Scan

Input phase + Phase offset

$$\varphi_{arrival} = \varphi_{ref} + (\varphi_{input} + \varphi_{offset}) - n \times 360°$$

Beam synchronous phase   Ref. phase

- **Two unknowns**
  - When the beam arrives（corresponding to φ_{ref}）
  - Cavity phase offset（φ_{offset}）
- **Phase scan circumvents the lack of information**
  - Complete setting without knowledge of φ_{ref} 和 φ_{offset}
- **Problems with phase scan**
  - Time-consuming, has to be done each time
  - Cannot achieve online fault compensation



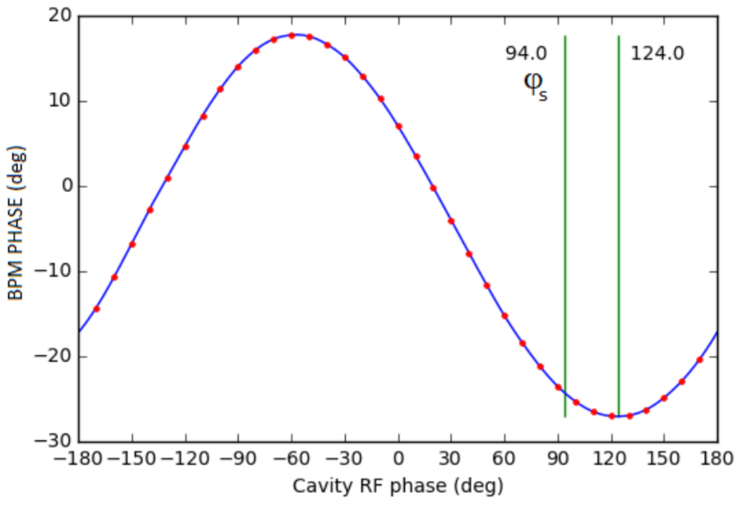
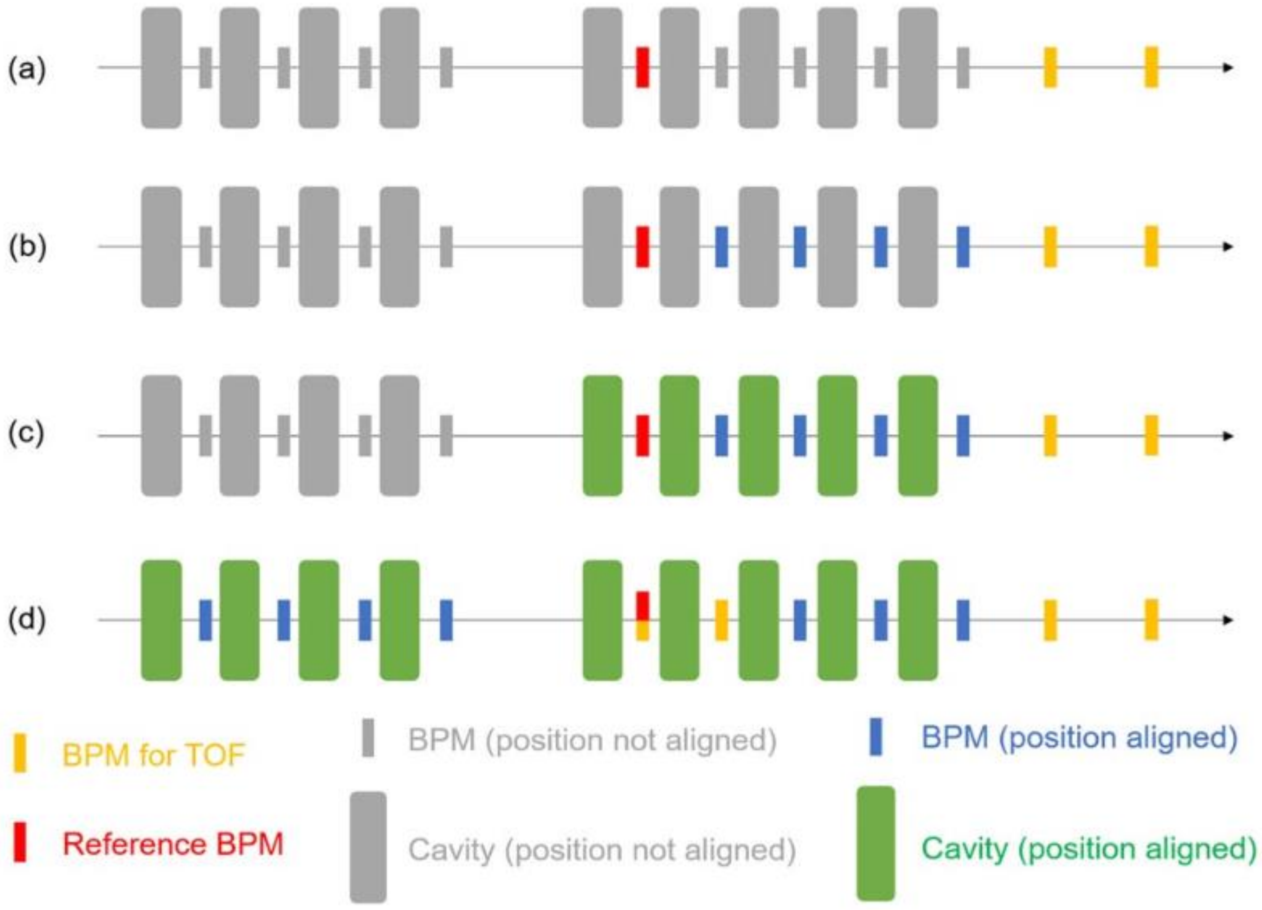
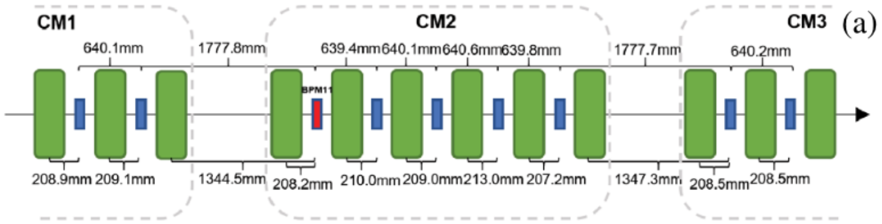
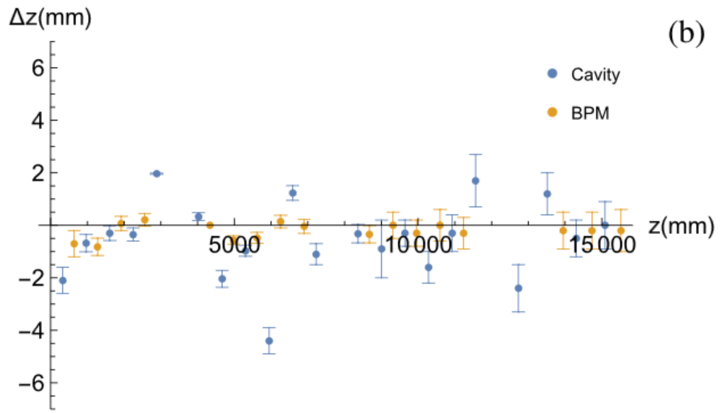


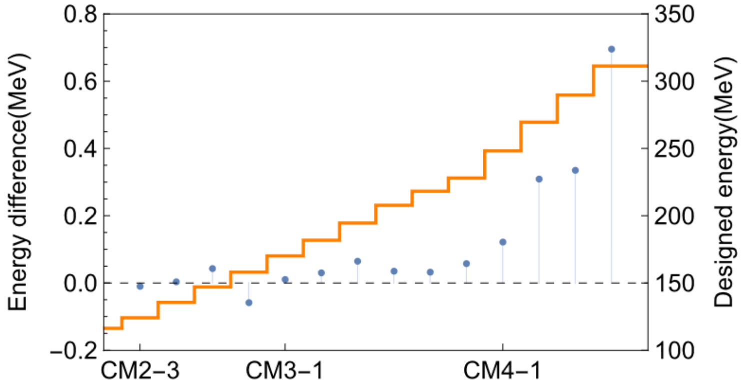
Figure 17. Phase scan signature.

Beam-based Position Alignment & Phase Calibration



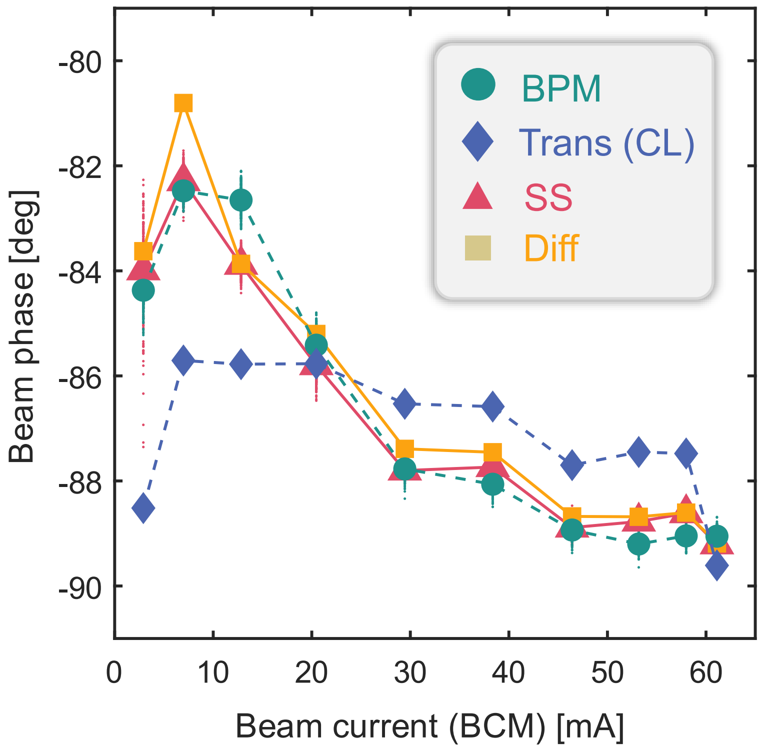


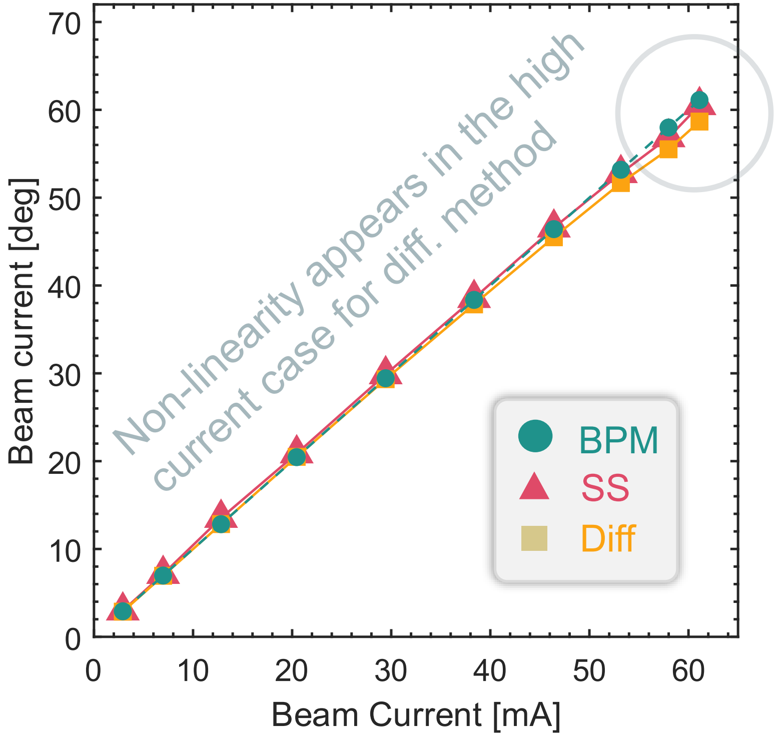


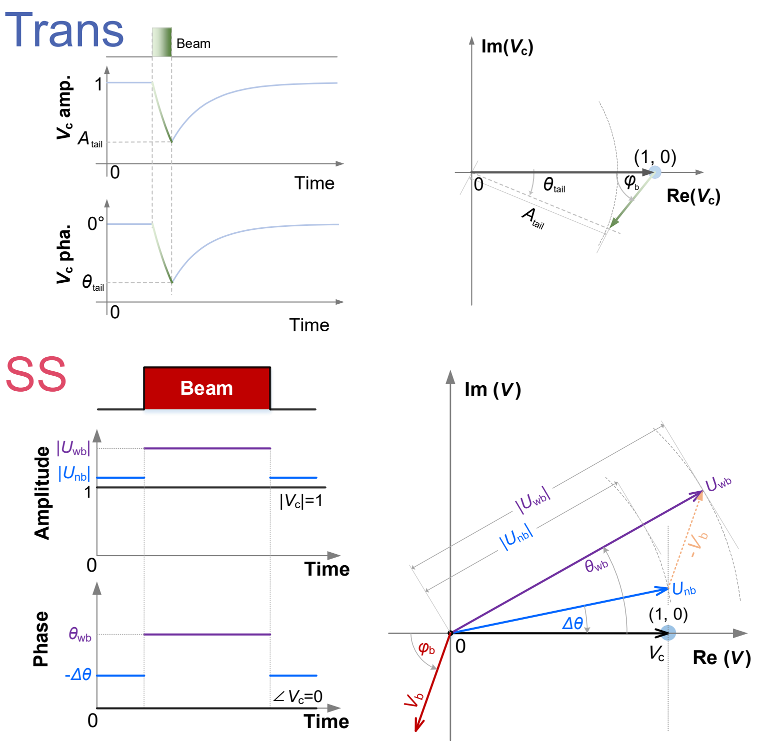


On-line beam synchronous phase calibration

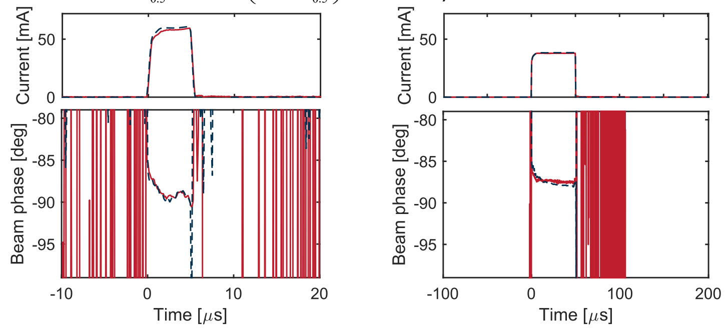
- **Problem: hard to track phase drift caused by environmental factors**
- **Goal: on-line continuous beam phase monitoring**



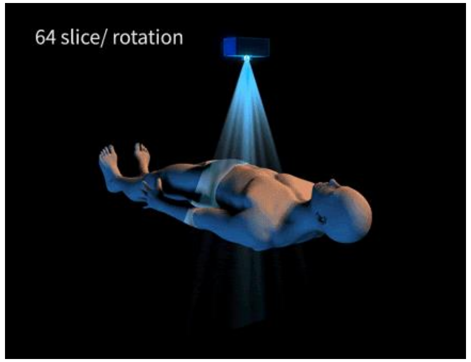




$$V_b(t) = \frac{1}{\omega_{0.5}} V_{cb}'(t) + \left(1 - j\frac{\Delta\omega}{\omega_{0.5}}\right) V_{cb}(t) - \frac{2\beta}{1+\beta} V_{fb}(t)$$

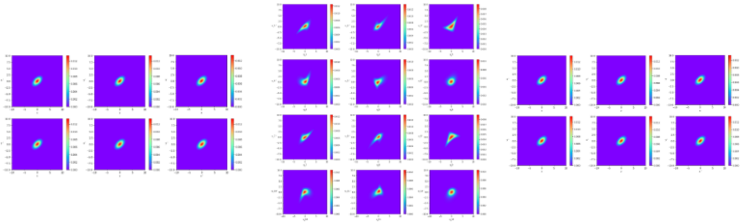


High Dimensional Phase Space Tomography



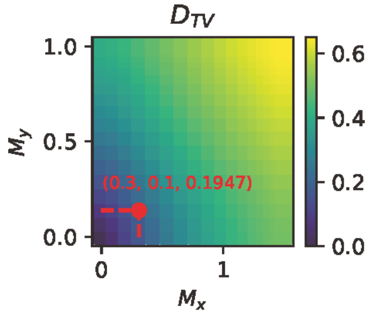
1. **Measurement methodology**
   - Schemes to obtain cross-plane information
   - Choice of measurement parameters to improve accuracy

2. **Tomography theory and algorithm**
   - Maximum entropy reconstruction from nonlinear projections



3. **Difference quantification between distributions**
   - What difference values are large?
   - Choice of measure depending on one
   - Any connection with familiar beam physics concepts?

$$D_f[\rho_1(\mathbf{x})||\rho_2(\mathbf{x})] := \int \rho_2(\mathbf{x}) \cdot f\left[\frac{\rho_1(\mathbf{x})}{\rho_2(\mathbf{x})}\right] d\mathbf{x}$$

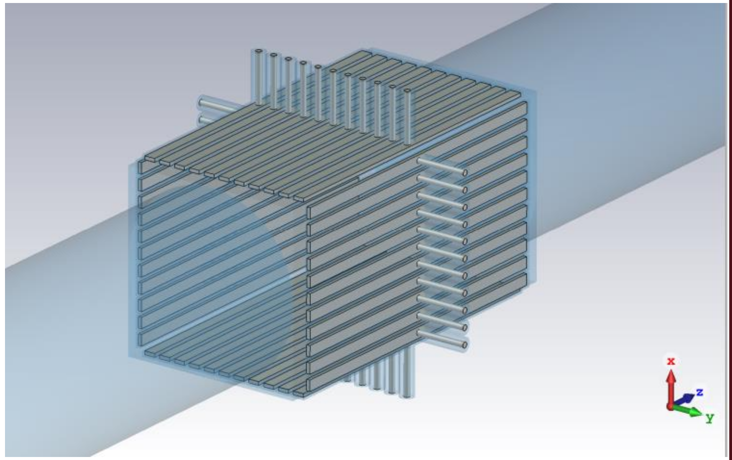


- **Complementary to machine-learning-based efforts**

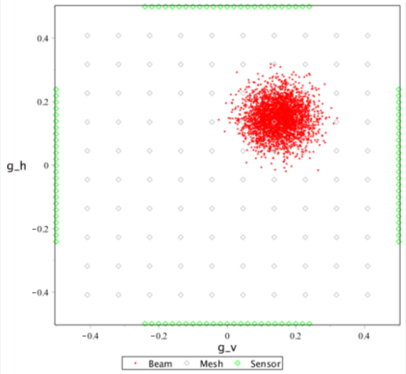
Multi-electrode Beam Position Monitor

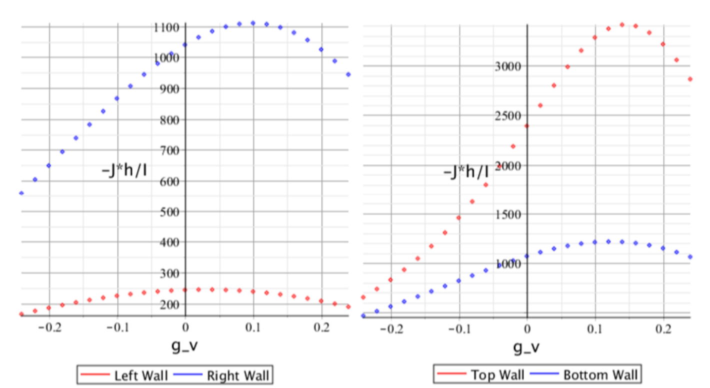
Application: Non-invasive measurement of the transverse information from the beam bunc

- **Physical Design** (First Proposed)



Beam Bunch Transverse Distribution





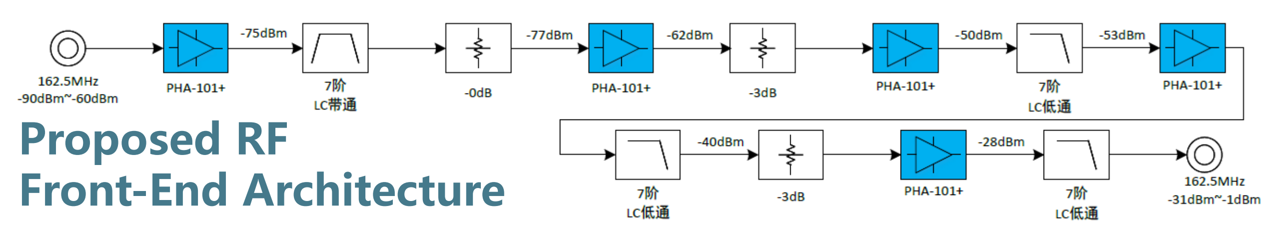
Induced Currents by the Beam Bunch on the Electrode Arrays

Major Difficulties in Signal Measurement

- **ultra low power**
  - down to **- 90 dBm**
- **ultra low SNR**
  - down to **+15 dB**

Crucial Technical Challenges!

- **Key Requirements of the RF Front End Design —— Ultra-high Gain & Ultra-low Distortion**



Proposed RF Front-End Architecture

Highly linear 5-stage cascade amplification

Call for Cooperation!

Design and/or manufacture of the state-of-the-art electronics system for acquiring, processing and analyzing signals from the electrode arrays


Exchange & Collaboration
Strongly Welcomed!
Thank You!