The status of CiADS linac

— Design, Integration & Commissioning

Yuan He

on behalf of CiADS linac team

Institute of Modern Physics, Chinese Academy of Sciences

Outline

- **Intrduction of CiADS**
- Challenge and Design of Linac for CiADS
- Progress of the CiADS Linac
- Future Application Plan

Challenges of Fission Energy

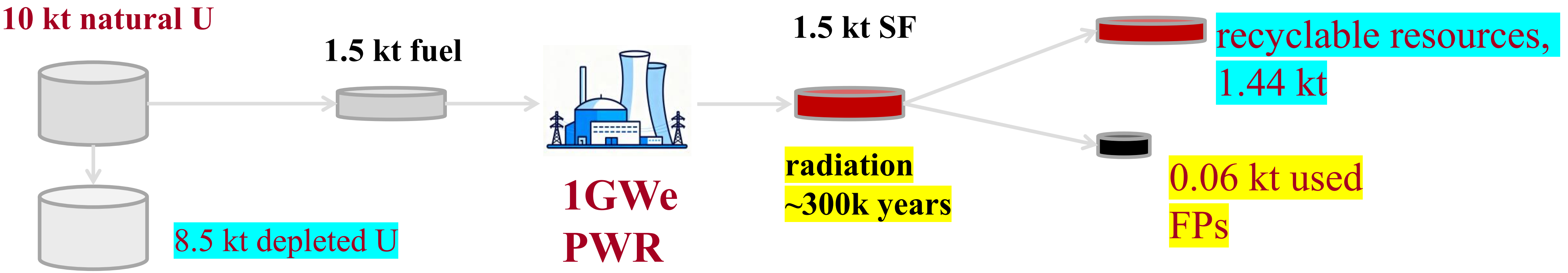
Fission Fuel Scarcity

Spent/Waste Fuel Management

Nuclear Safty

Proliferation Risks

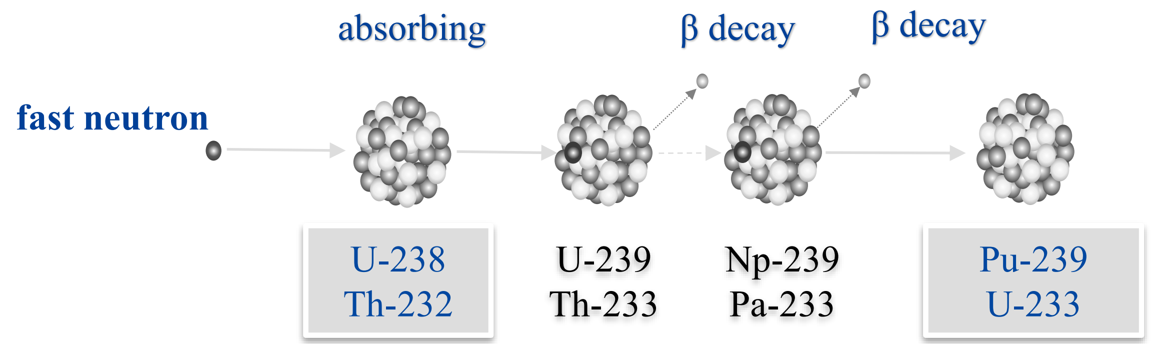
- Early 2026, WNA reported the aggressive plan of NP globally more than 1,446 GWe, means natural U 14 Mts, far more than the Global proven amount 8 Mt



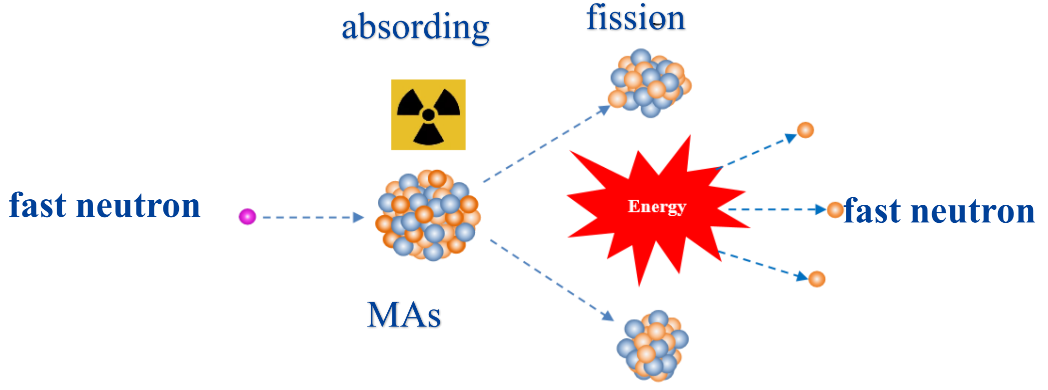
- 1 MWe Reactor needs natural U ~10 kt during lifetime, Resource utilization Efficiency <1%
- High level radiation waste lifetime is more than 300k years, and has not final solution

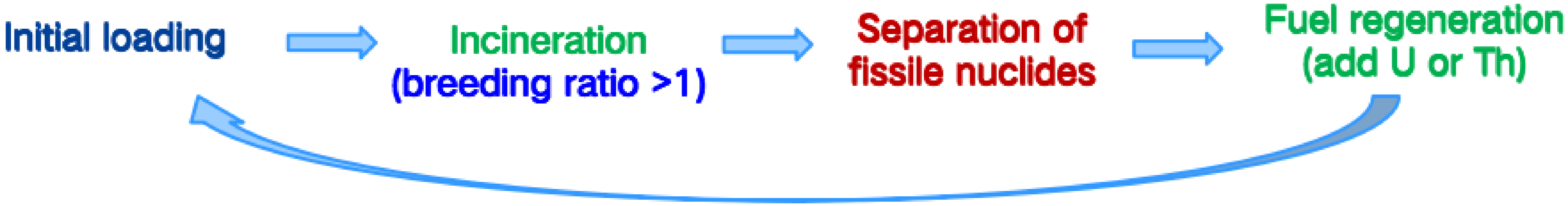
Breeding and Transmutation

- U-238 → Pu-239 (fissile)
- Th-232 → U-233 (fissile)



- MAs → fission products (transmutation)





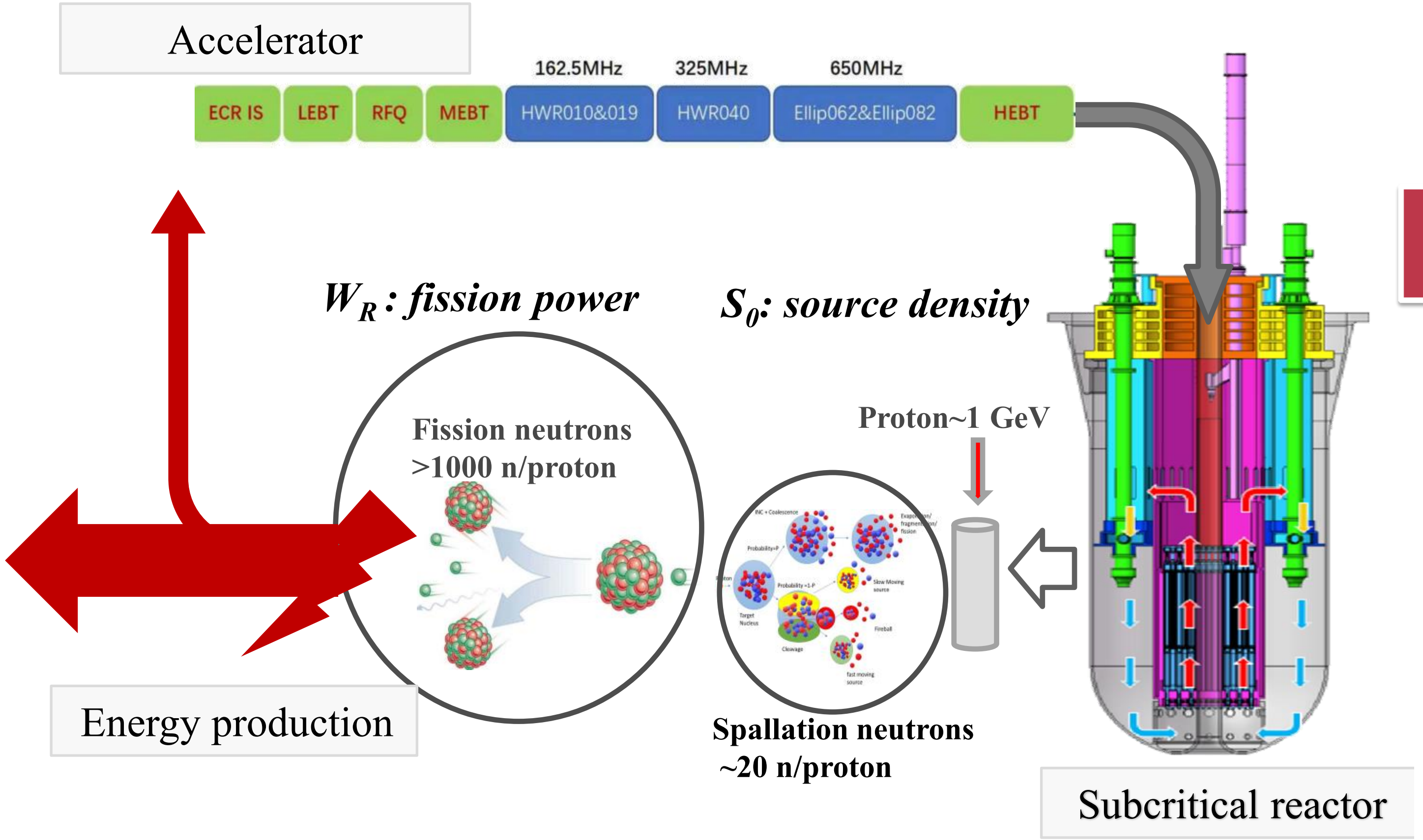
Breeding sufficient fissile nuclides and separating economically

<1% —> ~100%

Promising Solution: ADANES

China Initiative Accelerator Driven System

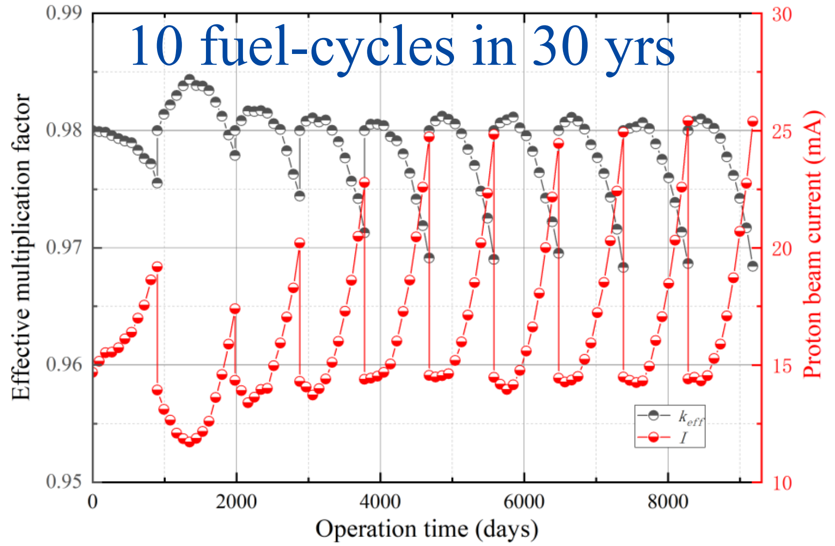
■ ADS enables flexible transmutation and breeding



☐ Reactivity control of subcritical fast reactors:

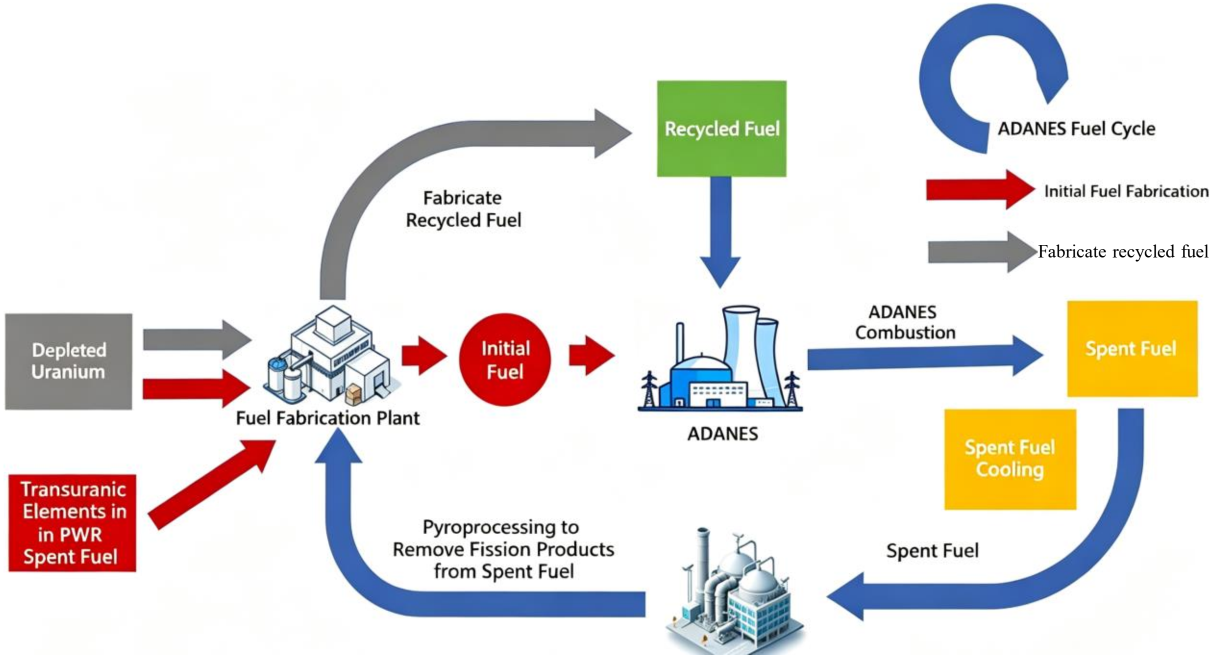
$$W_{reactor} = \boxed{[I \times z_0]} \times \boxed{\varphi^*} \times \boxed{\left[\frac{QK_{eff}}{\upsilon(1-K_{eff})}\right]}$$

External source neutron	External source efficiency	External source Magnification factor



High tolerance for fuel composition; allow to add SF, MAs, and DU in equilibrium cycles

Promising Solution: ADANES



- **Mixed Fuel "PUMA": Pu+U+MAs + a few FPs**
  - High-temperature Dry Processing
  - Eco Regeneration (remove ~80% FPs)
- **Incineration: Acc + Sub-FR (ADS)**
  - Inherently Safer (Sub-Critical)
  - Fast Breeding (1.3 ~ 2 times)
  - Transmutation (10 ~20 PWRs)

- Utilization rate of uranium resources： ~0.6% → ~95%, **100**
- Radioactive waste lifetime： ~400,000 of years → ~400 years, **1/1000**
- Radioactive effluent： ~25t → ~1t （1GWe/pile year） **1/25**
- Reactivity control： Critical operation → Subcritical operation

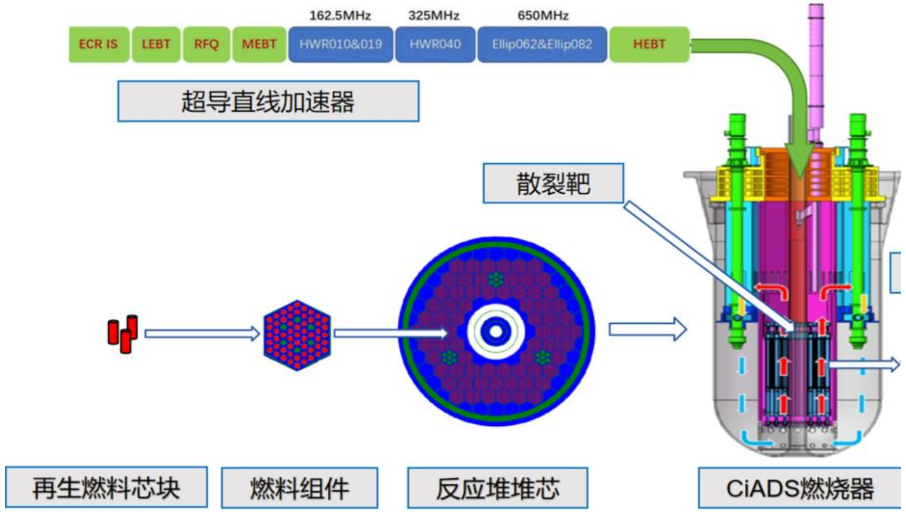
ADANES: Experimental Facility

CiADS (China initiative Accelerator Driven System): the world's first MW-class research facility & fuel cycle capable of high-power coupling operation.

ADS thermal power = 10 MW:

- **Accelerator beam power = 2.5 MW**
- **Pb-Bi spallation target power = 2.5 MW**
- **Subcritical Pb-Bi reactor power = 7.5 MW**

T1: ADS Transmutation Research Terminal
T2: Advanced Target Technology Research Terminal
T3: Nuclear Functional Material Irradiation Terminal
T4: ADS Nuclear Database Terminal



Validation of spent fuel regeneration technology enabling 30% of U-utilization:

- Conduct breeding/transmutation experiments of high-temp dry-processed fuel in the ADS burner to verify 30% U-utilization cycle

Commissioning Plan of CiADS

2026	2027	2028~2029	2030~2031

Accelerator Acceptance

- Accelerator 25kW
- Target >25kW
- Thermal test terminal

- ☐ 600 MeV accelerator trial run
- ☐ 250 kW target trial run
- ☐ Model spent fuel separation & fabrication
- ☐ First regenerated pellet fabricated

Spallation Target Acceptance

- Accelerator 250kW
- Target 250kW
- k_{eff}~0.4
- Reactor 30kW

- ☐ ADANES burner commissioning
- ☐ Pilot fuel assembly insertion
- ☐ Industrial validation of high-temperature dry processing
- ☐ First regenerated fuel rod fabricated

ADS System Acceptance

- Accelerator 0.25~2.5MW
- Target 0.25~2.5MW
- k_{eff}~0.4-0.75
- Reactor Power Ramping

- ☐ Fuel loading license obtained
- ☐ Burner operates at full power
- ☐ Metallic FP separation thermal test
- ☐ First regenerated fuel assembly

Fuel Cycle Validation

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

- ☐ Regenerated fuel loading license obtained
- ☐ First loading of regenerated fuel
- ☐ Full-power breeding and transmutation testing
- ☐ Verified key technology integration for 100-MW-class ADANES facility

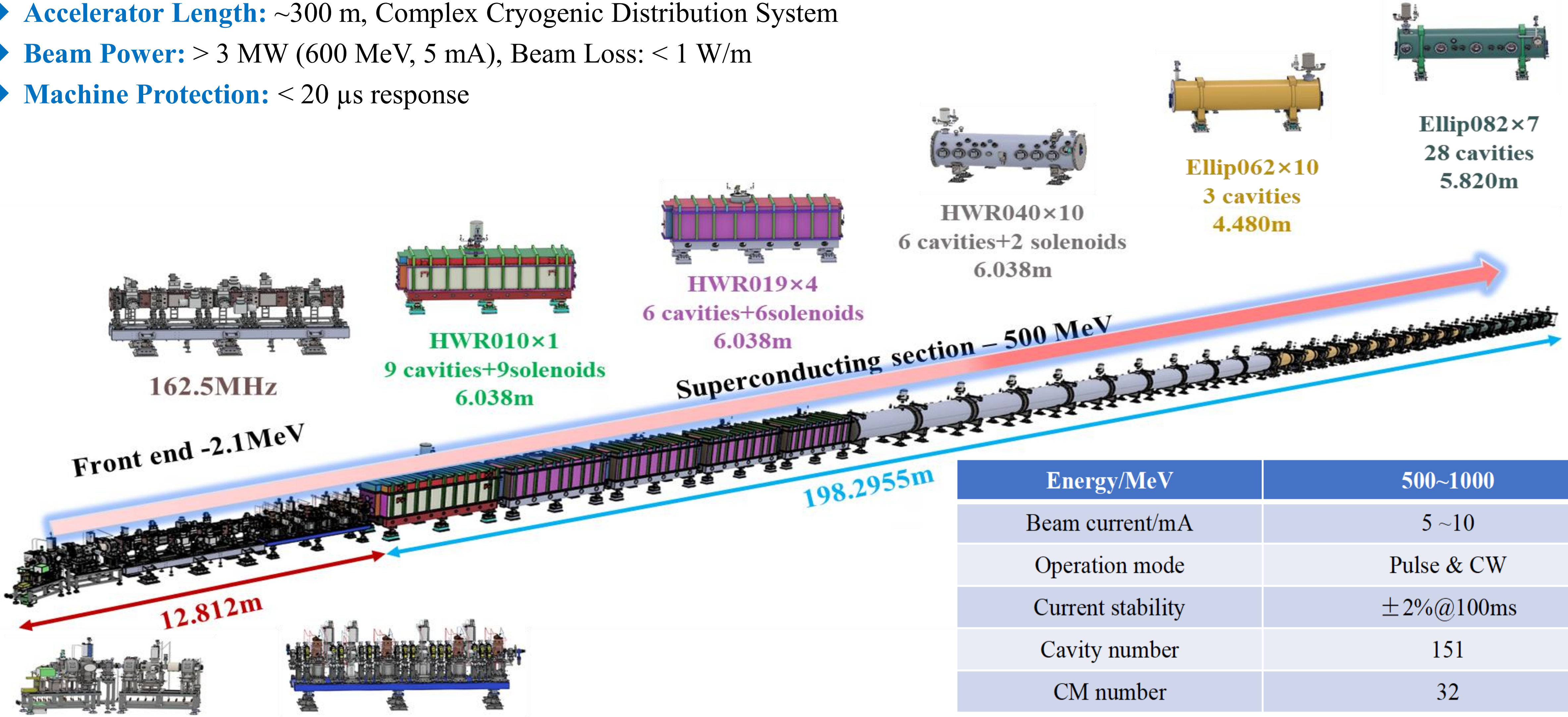
Outline

- Introduction of CiADS
- **Challenge and Design of linac for CiADS**
- Progress of the CiADS Linac
- Future Applicaiton Plan

Overview of SC Linac

Key Performance Specifications:

- **Accelerator Length:** ~300 m, Complex Cryogenic Distribution System
- **Beam Power:** > 3 MW (600 MeV, 5 mA), Beam Loss: < 1 W/m
- **Machine Protection:** < 20 µs response

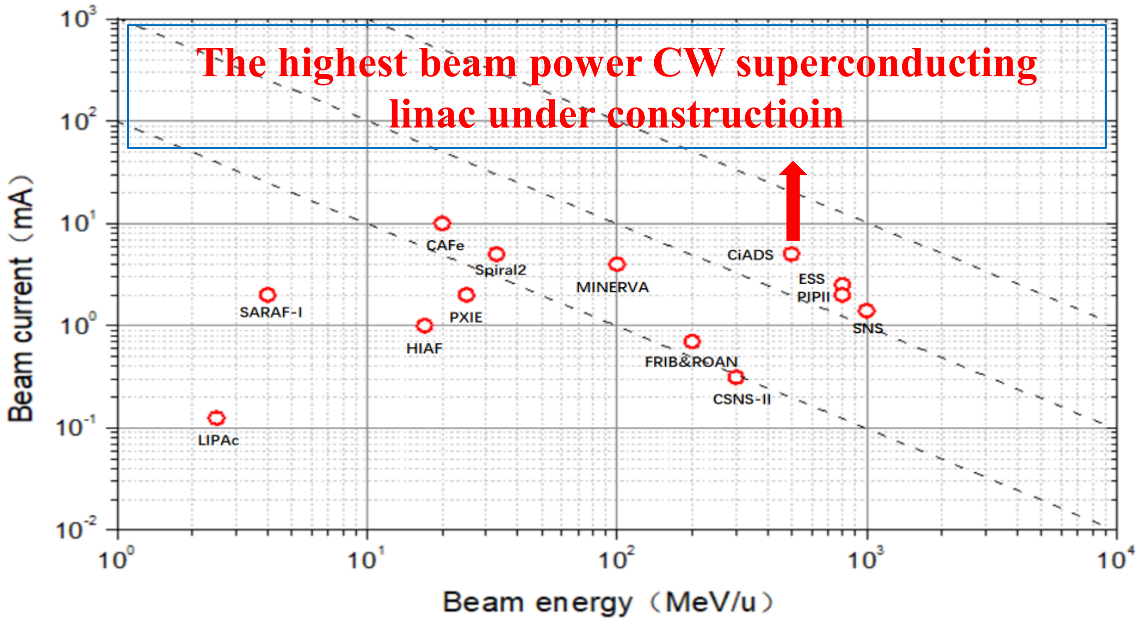


Energy/MeV	500~1000
Beam current/mA	5 ~10
Operation mode	Pulse & CW
Current stability	±2%@100ms
Cavity number	151
CM number	32

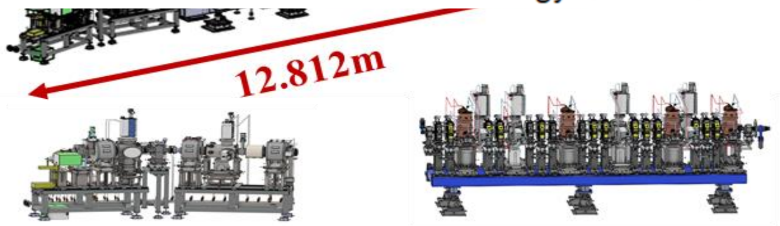
Overview of SC Linac

Key Performance Specifications:

- **Accelerator Length:** ~300 m, Complex Cryogenic Distribution System
- **Beam Power:** > 3 MW (600 MeV, 5 mA), Beam Loss: < 1 W/m
- **Machine Protection:** < 20 μs response



Beam Trip Duration	Industrial Scale Transmutation	Remarks
T<1sec	<25000	Target window lifetime
1sec<T<10sec	<2500	Fatigue failure of fuel cladding
10sec<T<5min	<2500	Fatigue failure of inner barrel and reactor vessel
T>5min	<50	System Availability



Critical physics challenges:

- **Ultra-low Beam Loss Control : < 10^{-6}**
- **Beam trip Availability: > 85%**

ADS-Oriented SC Linac

China Initiative Accelerator Driven System

Concept of hardware design for an ADS-oriented linac

- **Modularization**
  - High-power component topology: parallel multi-module architecture, hot-swappable
- **Redundancy**
  - At least one spare module / pallet of redundancy; hot-swap supported with no functional interruption
  - Compensation capability via spare power margin
- **High power efficiency**
  - Balanced trade-off between power efficiency and redundancy
- **Edge intelligence**
  - Efficient monitoring, logging and fault troubleshooting for component status
- **Cloud brain**
  - AI-driven strategy leveraging full beam diagnostics feedback (position, profile, beam loss, etc.)
  - Automated commissioning and beam tuning

Challenge of sc-Linac for CiADS

Beam loss control

- to make a high-quality beam at the warm front end
- to minimize beam loss at the superconducting section
- to avoid tiny unnecessary beam loss along the linac - Low temperature detector
- to detect sudden loss happens at any position of all the linac -Beam instrumentations

Fast beam recovery

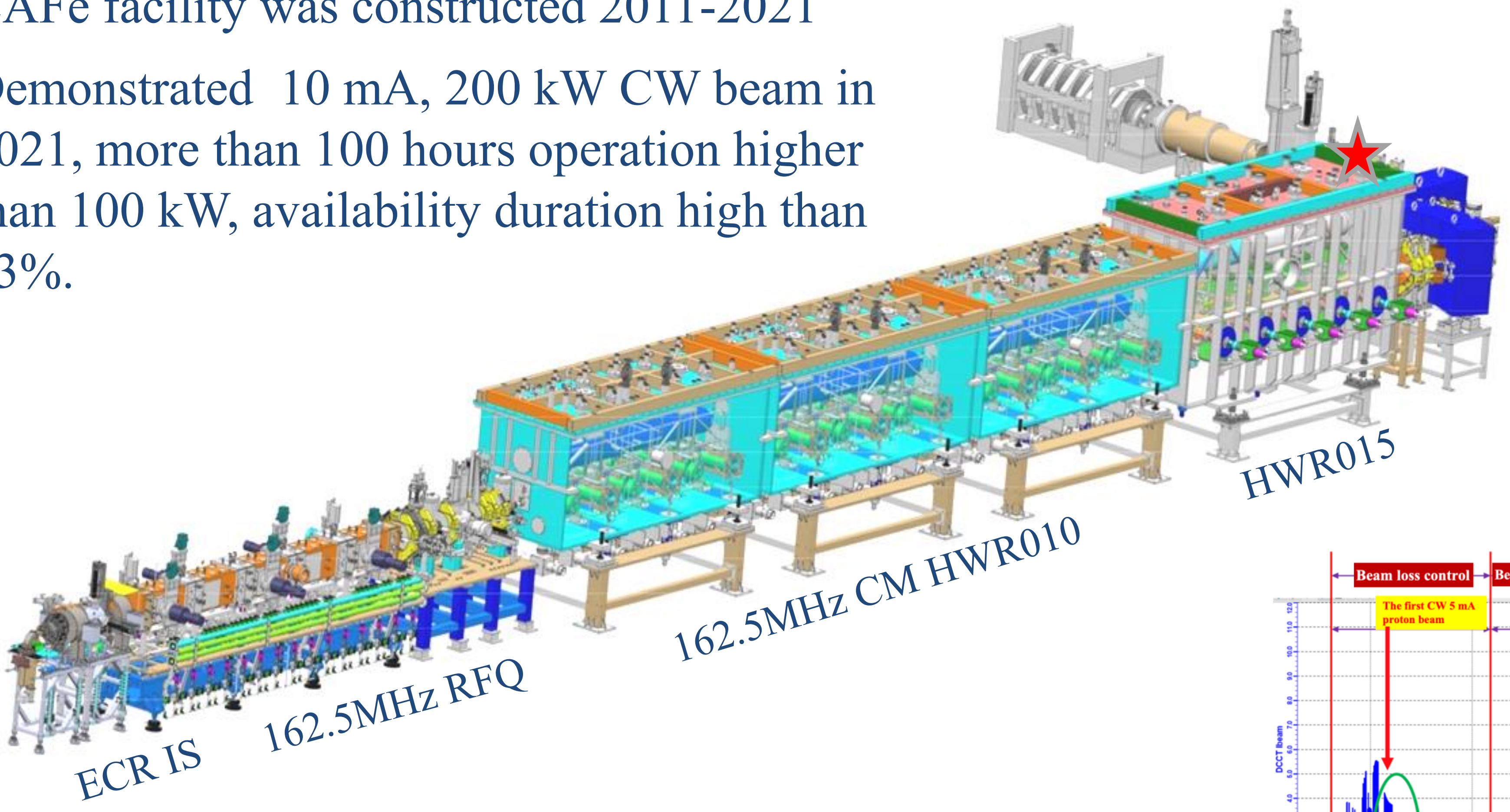
- Hybrid fault-compensation for element fault-compensation
- Auto recovery scenario and technique in a few seconds
- Hot-swap technology based on modularization design of hardware

Operation stability

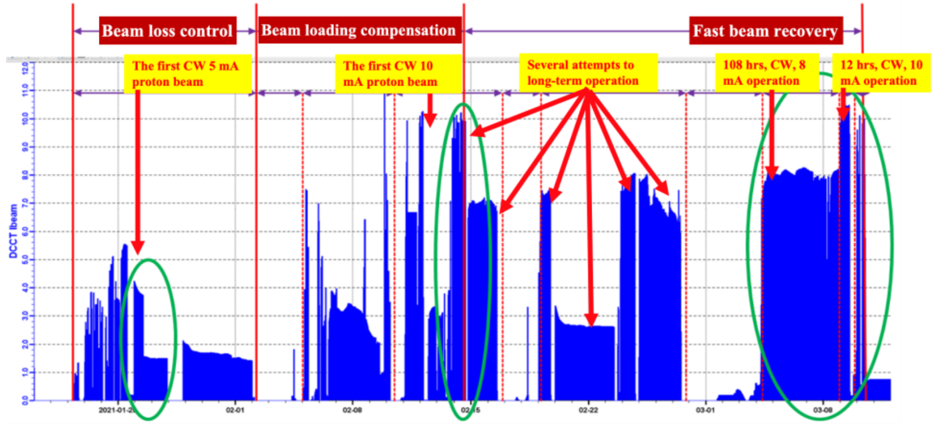
- Beam Control with Reinforcement Learning
- Virtual accelerator program development

CAFe to demonstrate 10-mA CW proton

- CAFe facility was constructed 2011-2021
- Demonstrated 10 mA, 200 kW CW beam in 2021, more than 100 hours operation higher than 100 kW, availability duration high than 93%.



Ions	P
Frequency	162.5 MHz
Current	10 mA
E in RFQ	35 keV
E out RFQ	2.1 MeV
Energy	20MeV
Temp.	4.5 K

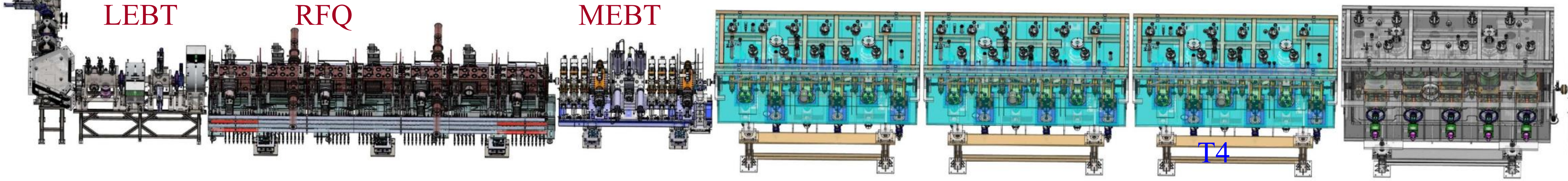


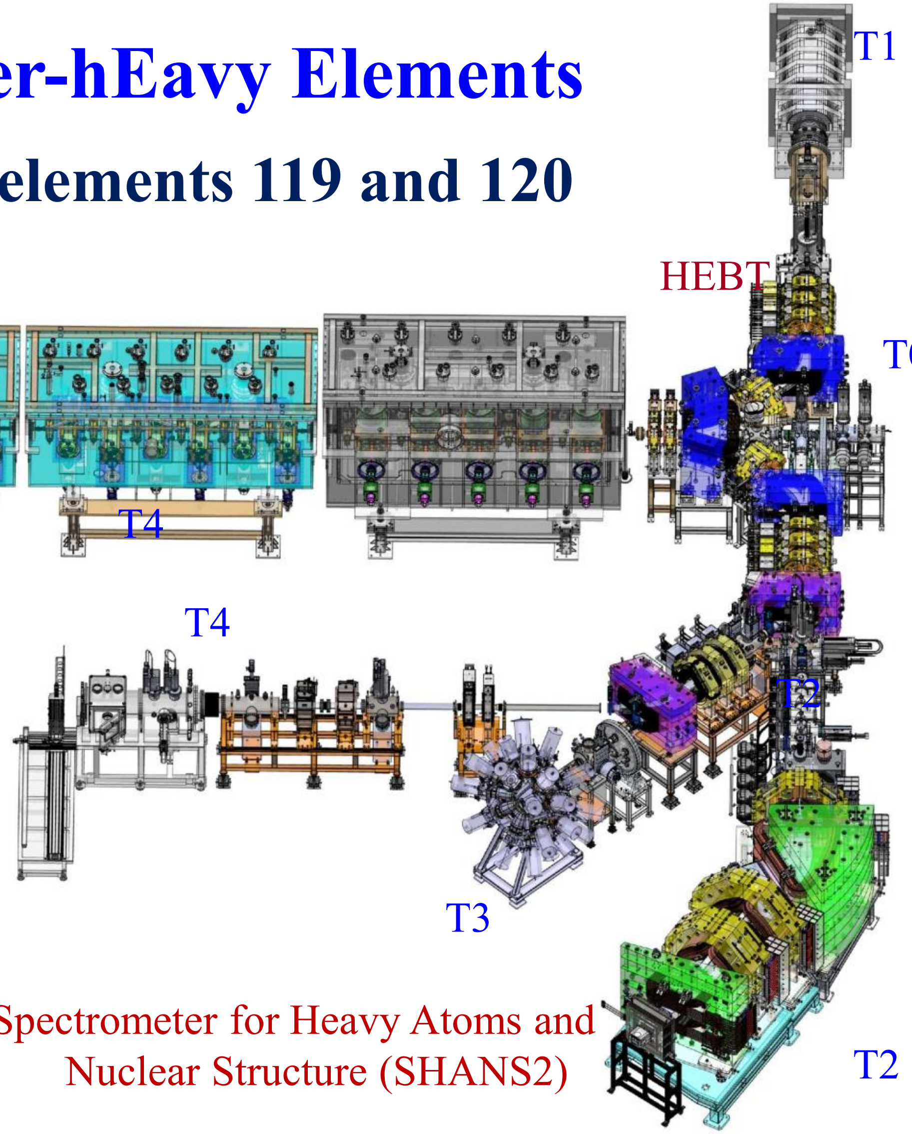
- **Supported by "Strategic Priority Research Program" of the Chinese Academy of Sciences.**

CAFE2 to Demostrate Availability

China Accelerator Facility for super-hEavy Elements

➢ Research on the synthesis of the new elements 119 and 120

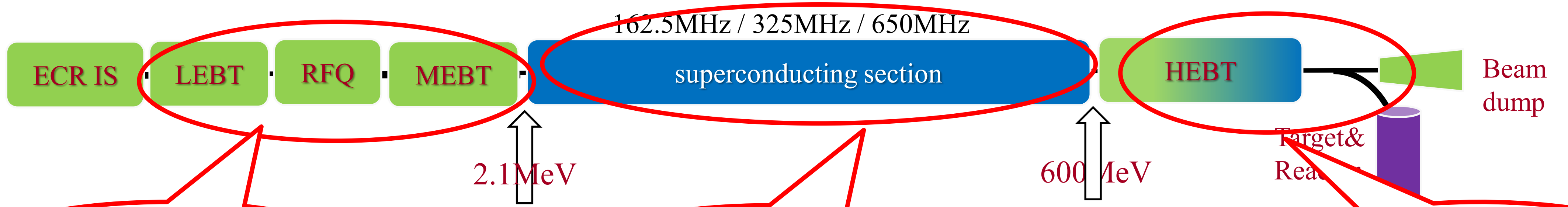




	Parameters	Units
Ions	Ca～Zn	-
A/q	3	-
Energy	4.0-6.5	MeV/u
Current	1~10	puA
Modes	CW	-

- 7000 hrs./yr since 2023
- Availability > 93%
- Produce 11 new nuclides, including the 115th Mc
- Reach 15 puA HI beam

Beam Loss Control



initializaiton

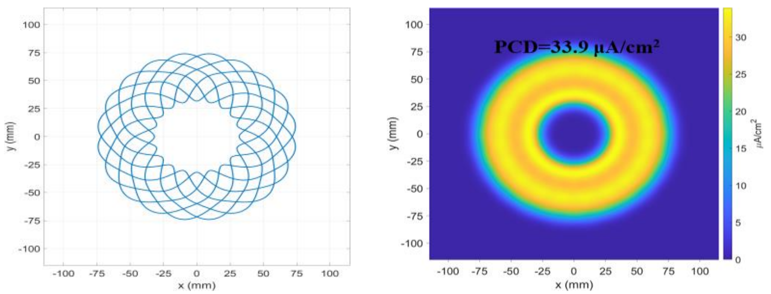
Beam loss control

collimation & uniform

- **LEBT :** Transverse beam quality control- Bend structure + beam scraping
- **RFQ :** Longitudinal beam quality control- Full particle optimization
- **MEBT:** Beam halo control- Full space scraping
  Phase space reconstructing

- **Low beam loss control**
  - ✓ **Lattice optimization** compact qusi-periodic structure and periodic lattice
  - ✓ **Beam matching** for mitigating halo formation and beam emittance growth
  - ✓ **Beam halo collimation** to reduce the probability of beam loss on SC elements

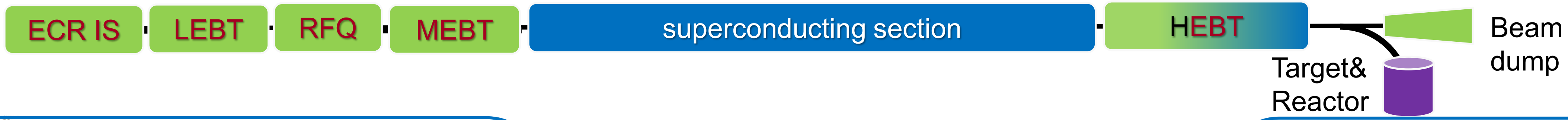
- **Beam uniformity by Multi order Sine wave scanning**
  - Collimation at A2T
  - Fourier harmonic superposition based on RF cavities



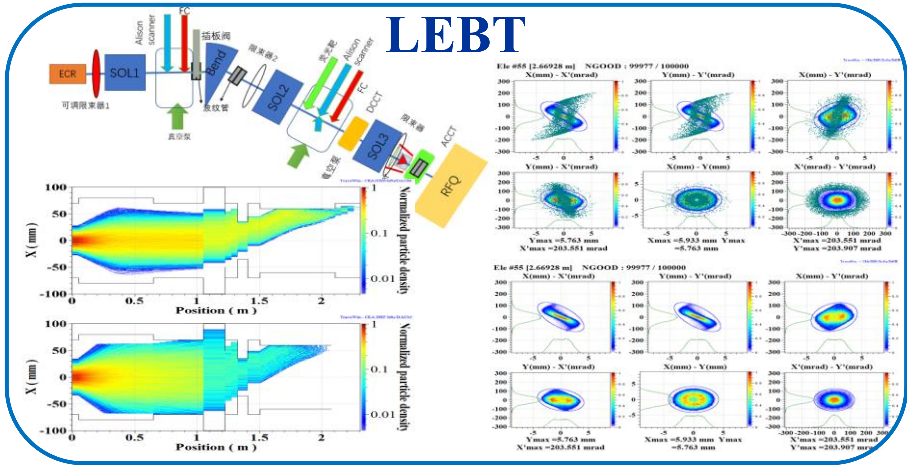
Beam Loss Control

China Initiative Accelerator Driven System

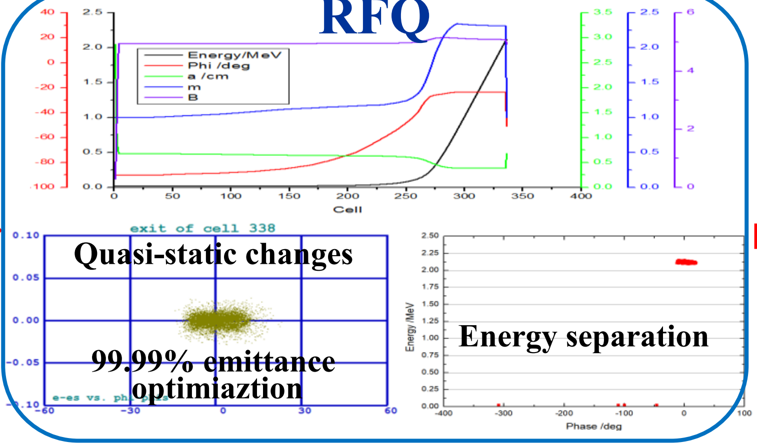
162.5MHz / 325MHz / 650MHz



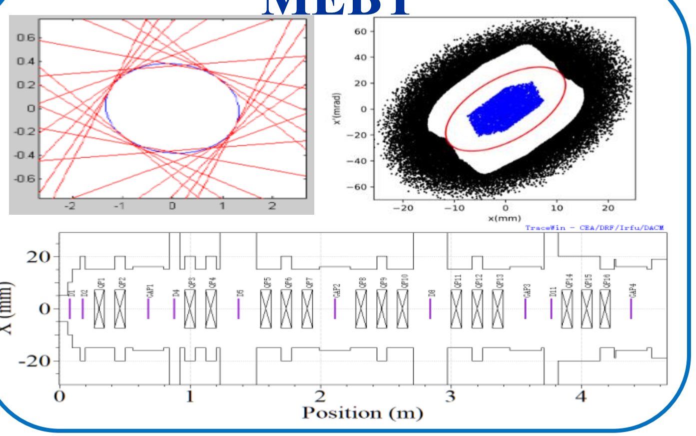
LEBT



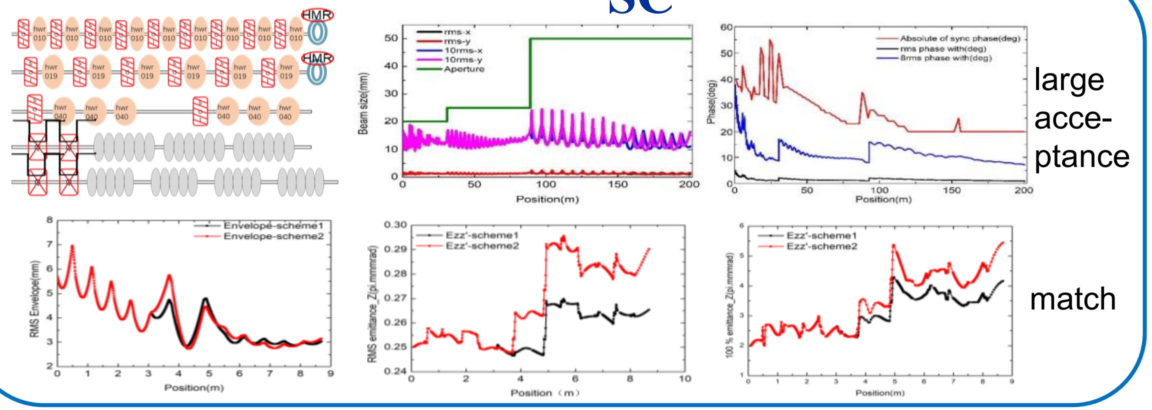
RFQ



MEBT



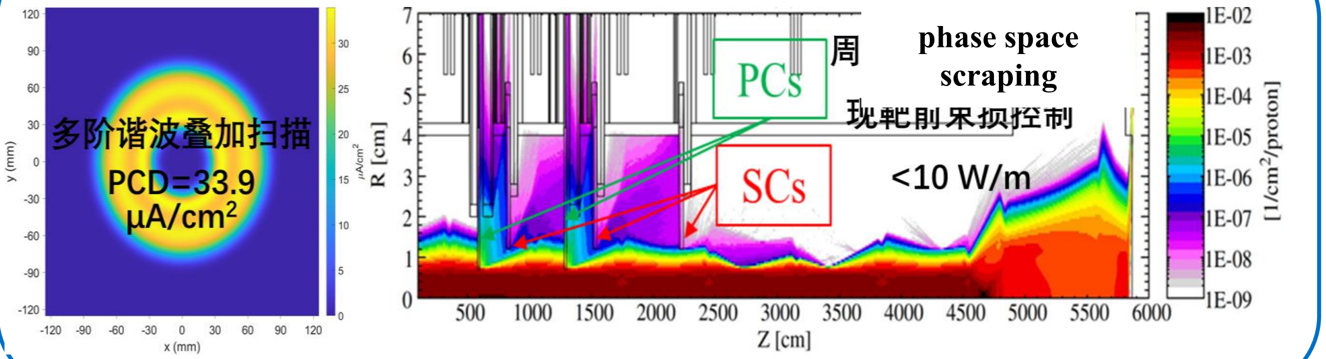
SC



large acce-ptance

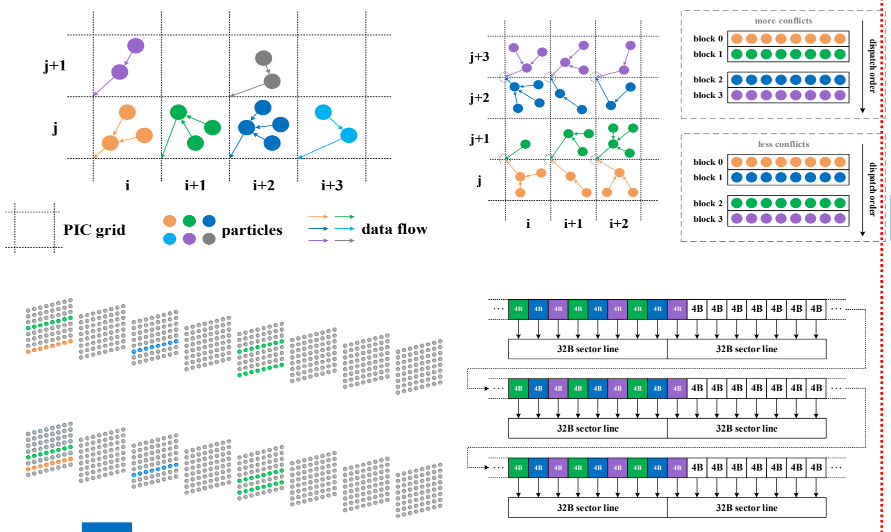
match

HEBT



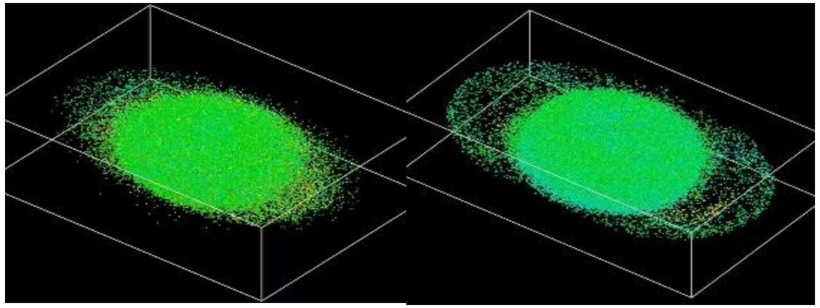
Beam Loss Control

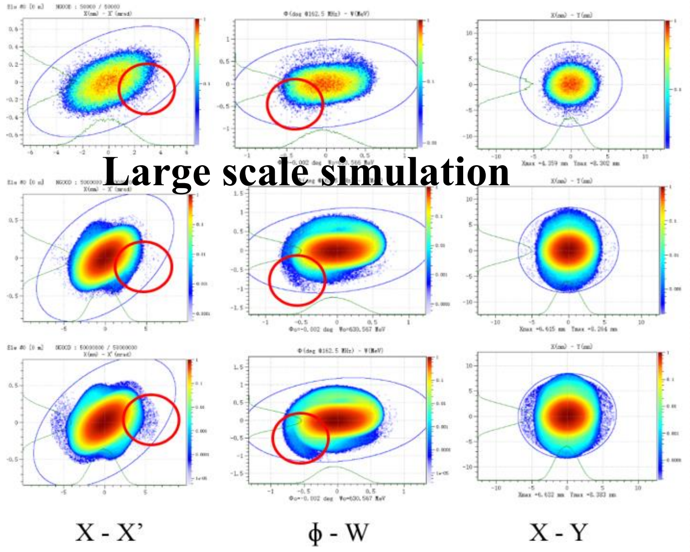
AVAS - a PIC code Base on CPU and GPU, GPU is 1000 times faster than CPU



Ultra-large-scale simulation：

Accurately locate beam loss status, analyze fine beam structure and beam halo evolution， 50k, 5million, and 50million





Ultra-high-speed simulation:

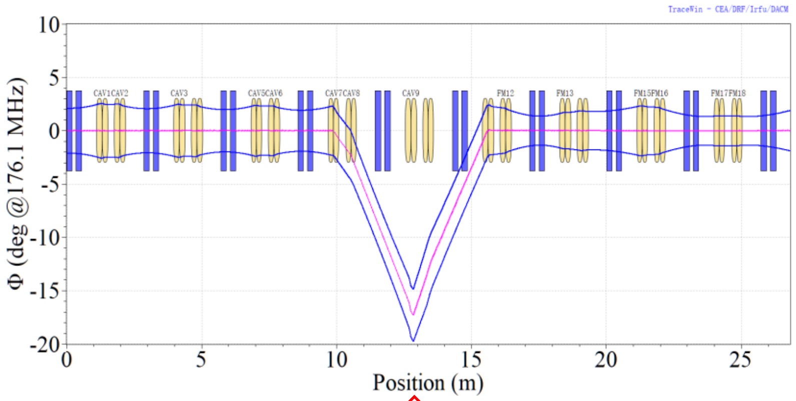
increasement of three orders , 50-million scale can be completed within 2 minutes for the CiADS linac

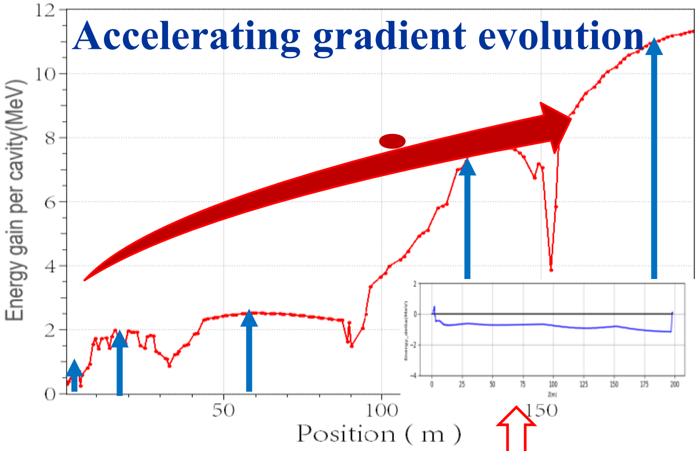
parti-num	Time (s) (1 CPU Core)	Time (s) (56 CPU Core)	Time consumption (s) A100	
			1 A100	4 A100
10^6	17486.28	5242.57	11.55	-
10^7	179255.50	26021.41	80.50	36.43
$5*10^7$	896277.50	119213.64	367.76	107.78

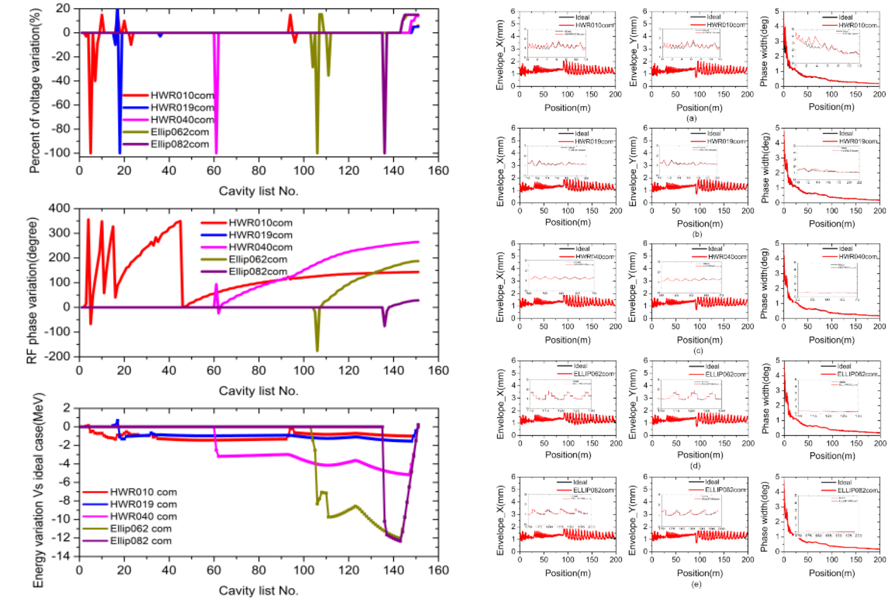
Failure Compensation

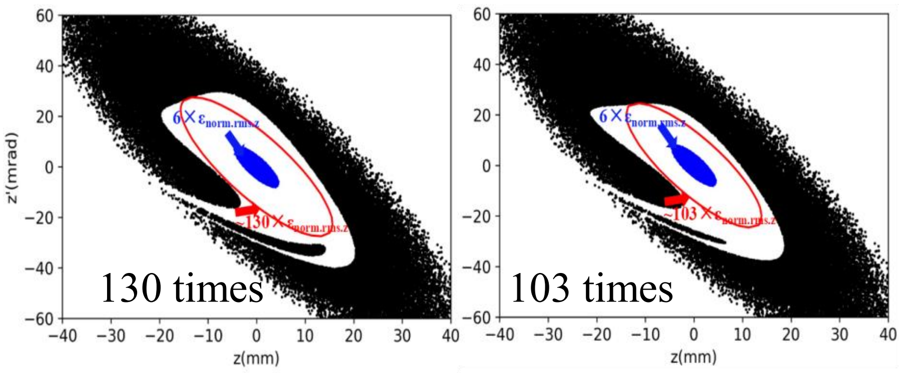
Match compensation to avoid beam loss by adjusting the neighboring cavities and magnets of the failure cavity

Energy compensation by the reserved cavities in the high energy part

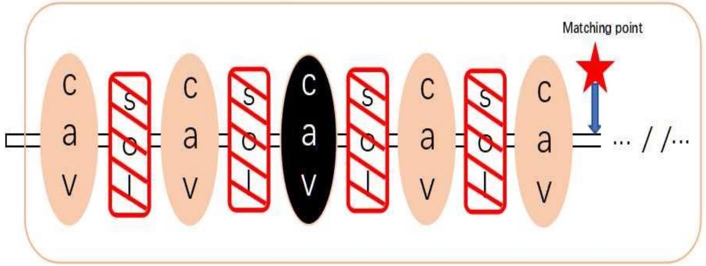




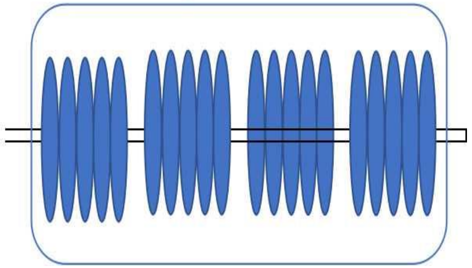




Twiss parameters matching



Energy compensation



Larger acceptance vs Local compensation

Hybrid fault compensation scheme： Balancing Parameters Matching and Compensation Efficiency

LINAC 2026

Failure Compensation

Design method based on Reinforcement Learning

Twiss parameter matching at failure cavity

Matching Agent

Observation study

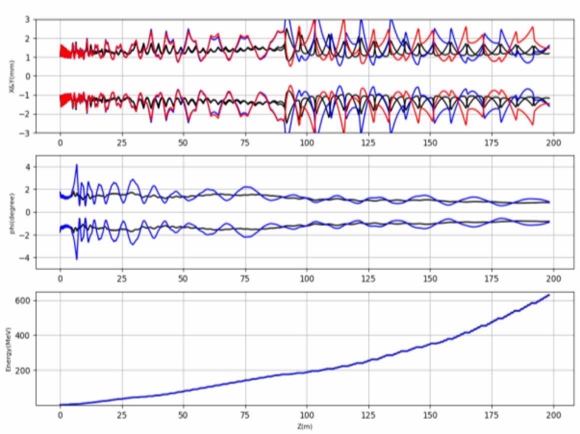
Simulation enviroment

Energy compensation at high energy part

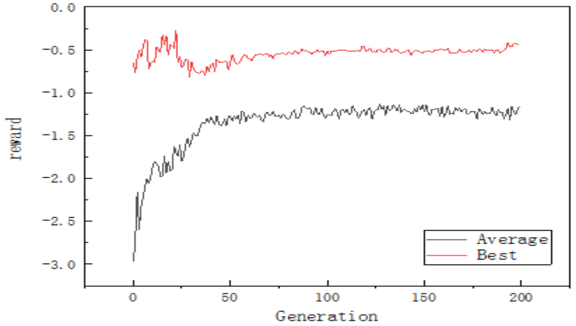
Match lattice

Select cavity Adjust Eacc and phi_s

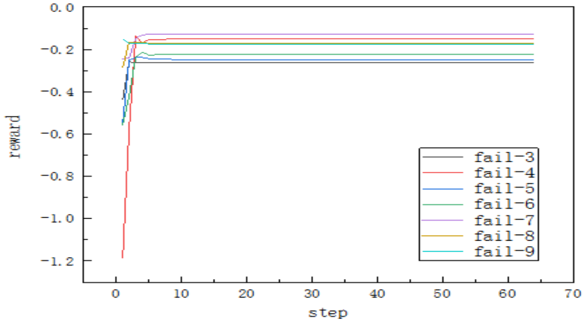
Recovery output energy



- Quick response ability



Genetic Algorithm



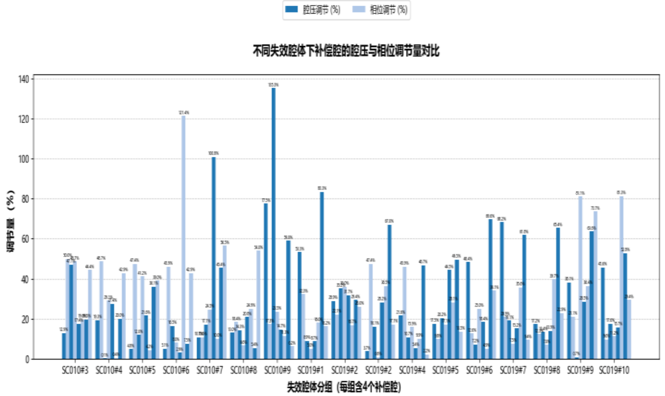
Reinforcement Learning Algorithm

- Strong generalization ability

One reinforcement learning network

Hwr010 **Hwr019** **Hwr040** ...

100+ fail situations



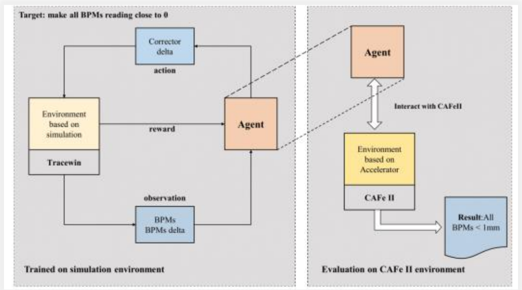
Compare with Traditional optimization algorithms:

① Less step better performance ②works in more situations

In the face of the high-dimensional and nonlinear challenges posed by failure compensation problems, reinforcement learning algorithms represent a more optimal choice.

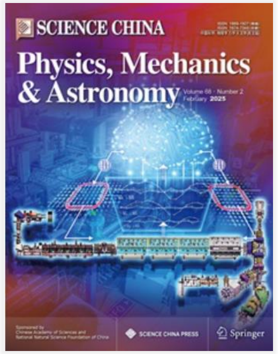
RL-Based Predictive Control

LINAC2026



PRAB 2023，Medium-Energy Orbit Correction

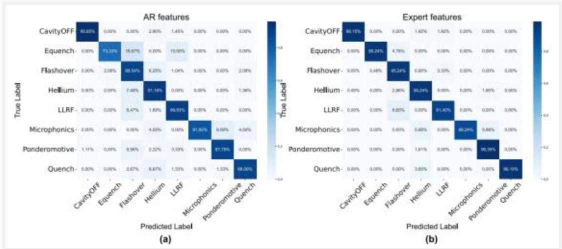
Demonstration of transferable RL orbit correction algorithms



SCPMA 2025，超导段轨道校正SC Section Orbit Correction

Proposed nonlinear-dynamics-based accelerator controller design; achieved 42-dimensional full-beamline orbit correction.

Both approaches now routinely used in CAFE2 daily commissioning, significantly enhancing operation efficiency



NST 2025 (Editor-Recommended), CAFE2 Cavity Fault Detection, Accuracy: 96% (FPGA deployment pending)

Efficient beam tuning

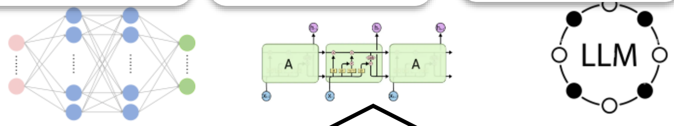
Acc. commissioning

Reinforcement Learning | Maching Leaning

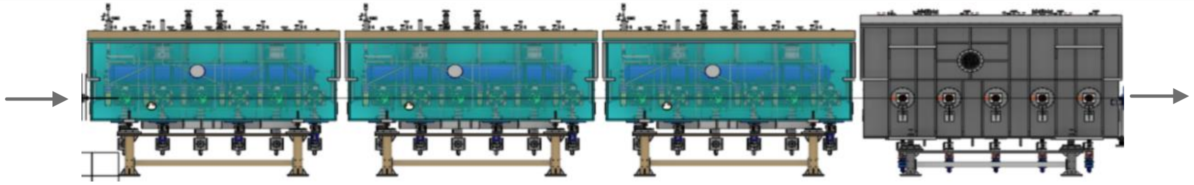
Reliable operation

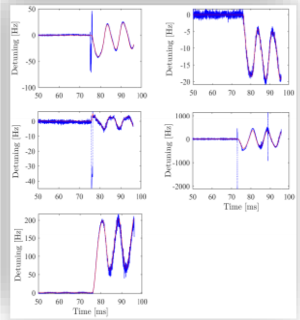
Long-term stable operation

Fault Detection | Fault Prognostic | Fault Recovery



High-fidelity fast surrogate model

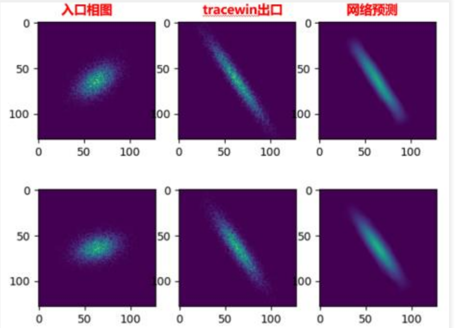




NIMA2021, CAFE2 EM Oscillation Fault ID

AI modeling of SC cavity mechanical modes

Deployed for CAFE2 operation, drastically reducing EM oscillation frequency (10→0.4/day)



IJMPA 2023, CAFe2 Phase-Space Surrogate Model

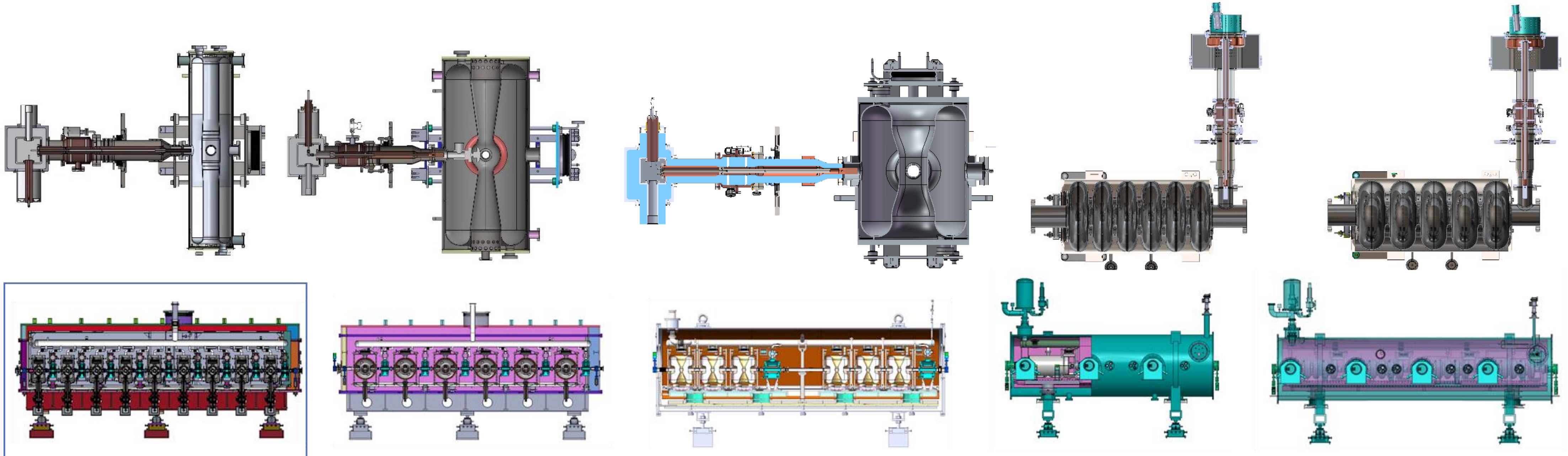
High-speed lattice optimization with real-time fault compensation

Driving full smart accelerator O&M from software to hardware

Outline

- Intrduction of CiADS
- Challenge and Design of linac for CiADS
- **Progress of the CiADS linac**
- Future Application Plan

Families of SRF



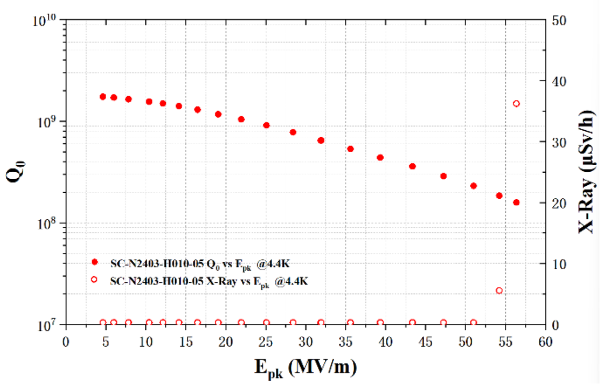
CM010 HWR cavity, beta= 0.10 | CM019 HWR cavity, beta= 0.19 | CM040 HWR cavity, beta= 0.40 | CM062 Elliptical cavity, beta= 0.62 | CM082 Ellipticalcavity, beta= 0.82

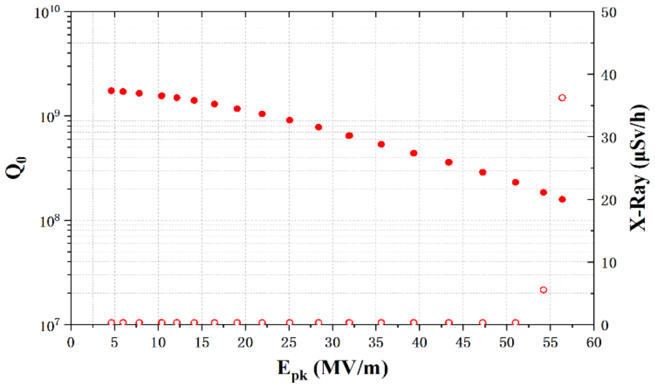
- **Total 151 superconducting cavities with five cavity types for the CiADS linac**
  - HWR010(9)/HWR019(24)/HWR040(60) & Elliptical062(30)/Elliptical082(28)
- **The baseline is bulk niobium cavity**
  - Prototype meets the requirement of operation at 2K
- **Cu/Nb and Nb_3Sn/Nb Composite Cavity as an alternative choice for 4.2K operation**
  - Thermal stability, Mechanical stability

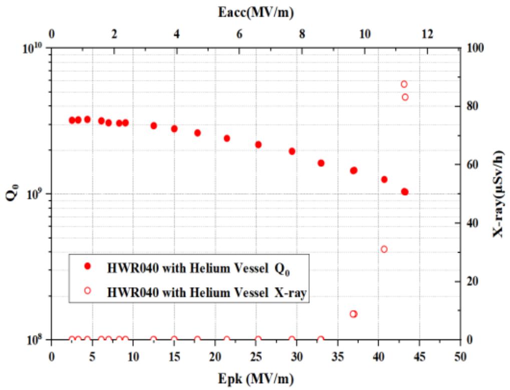
Progress of the CiADS Linac - SRF

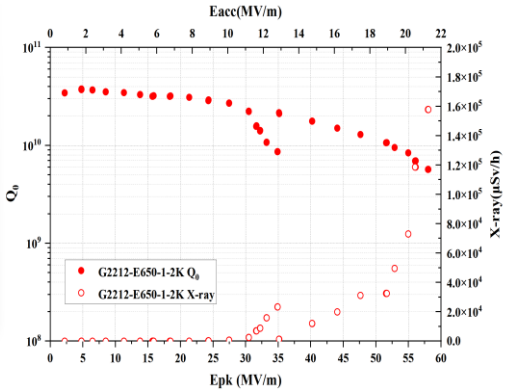
- HWR010 * 9
- HWR019 * 24
- HWR040 * 60
- Ellip062 * 30
- Ellip082 * 28

2025.08 → 2025.11 → 2026.04 → 2026.09









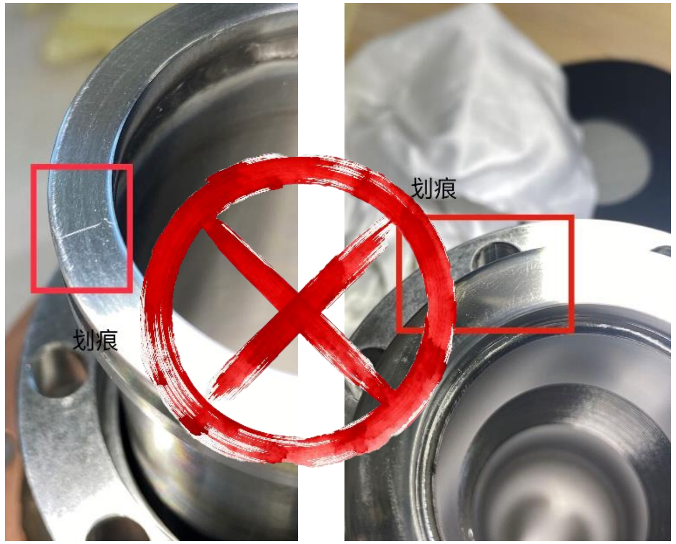
- 5 types of superconducting cavities, 151 units; a Universal Power Coupler Developed for 5 types of cavities

Cleanroom Assembly


Four HPR systems


Two Strings assembly workstations

Quality Inspection upon Entry



Adopt strict quality inspection standards and prohibit risk components entering the cleanroom

Building an Electronic Task Management System

Progress of the CiADS Linac - CMs

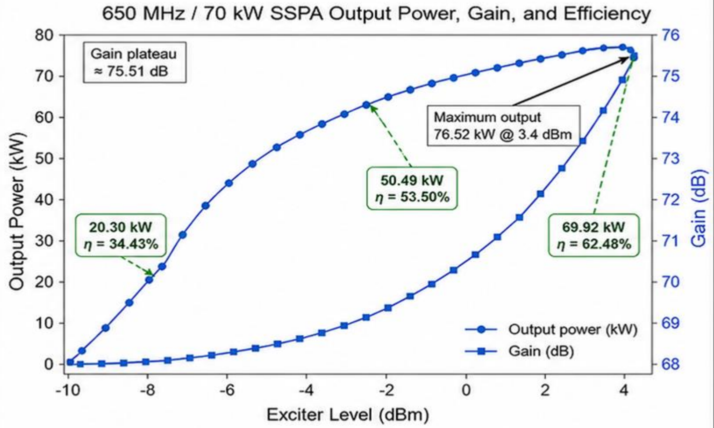
- **2024.10**: The horizontal test of prototype cryomodule was completed, with mass production initiated concurrently.
- **2025.09**: The integration and assembly of cryomodule has commenced.
- **2026.05**: HWR-type cryomodules have been installed in the tunnel (H010*1, H019*4, H040*10)
- **2026.09**:
  - E062*10 have installed and E082*7 will be ready in Sept.
  - All CMss will cooldown in Oct.
  - Helium processing and plasma cleaning system will be online version.

- 32 Cryomodules in 5 families, 4 types were installed
- Elliptical 082 cryomodules will be presented in Sept.
- 6 assembly lines in parallel, 25 days for dirty assembly

Progress of the CiADS Linac - SSAMP

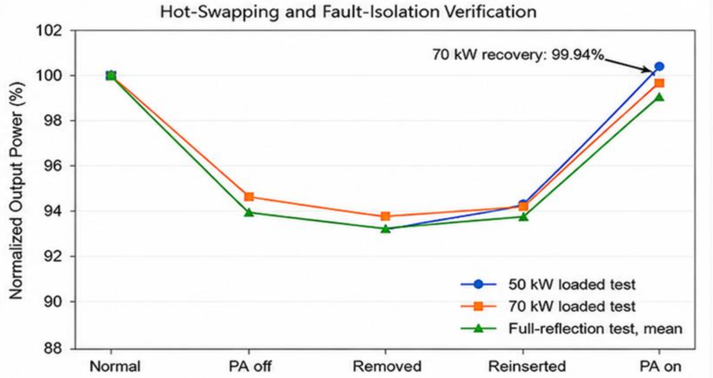
- System-level performance and hot-swapping verification of the SSPA.

(a) 650 MHz / 70 kW SSPA System (Front View)



(b) 650 MHz / 70 kW SSPA Output Power, Gain, and Efficiency

(c) Hot-Swapping of a Faulty PA Module During Operation



(d) Hot-Swapping and Fault-Isolation Test Results

High-power performance

- Maximum power reach 76.5 kW, exceeding the norminal 70 kW, with a gain plateau of approximately 75.5 dB.

High-efficiency operation

- The system achieved an efficiency of 62.5% at 70 kW, demonstrating efficient operation near the nominal power.

Hot-swapping capability

- A faulty PA module was removed and reinserted during operation, with the output power recovering to 99.94% of the initial 70 kW level.

CIADS HPRF Power System Overall Integration Progress: 80%

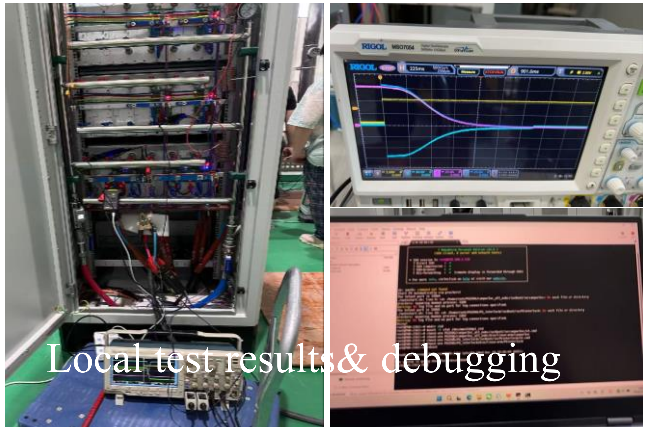
The on-site installation and commissioning of the CIADS HPRF power system are steadily advancing.

Progress of the CiADS Linac – PS

➢Modulization of Power Supply

- ✓ All 74 cabinets have been installed in position, with both power and water supplies in place.
- Expected completion of off-line commissioning for all line power supplies by the end of August.

Section	Cabinet Count	Commissioning Status & Follow-up Plan
LEBT&MEBT	9	Real-load long-duration rated-current output test completed.
LBHL	5	Local off-line commissioning completed (short-circuit output current, main coil energy dumping). Awaiting superconducting conditions for integrated testing and real-load power-on testing.
MBHL	12	
HBHL	10	
LBEL	10	Complete local off-line commissioning.
MBEL	11	
HBET	13	Local off-line commissioning (short-circuit output current) expected to be completed by end of August.
A2D	4	



LINAC 2026

Intelligent Edge Controller

China Initiative Accelerator Driven System

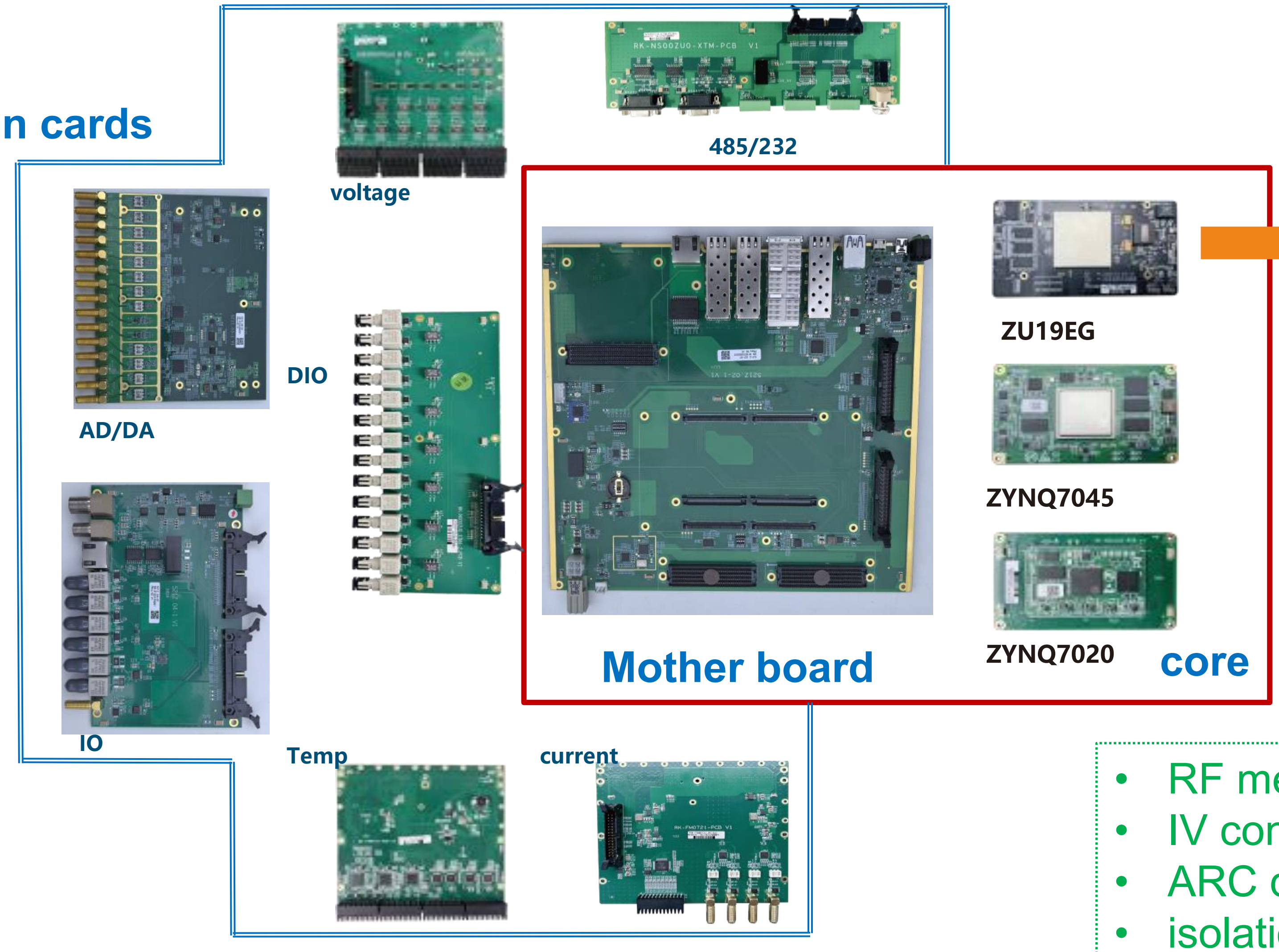
GIANT-General Intelligent Accelerator information Terminal

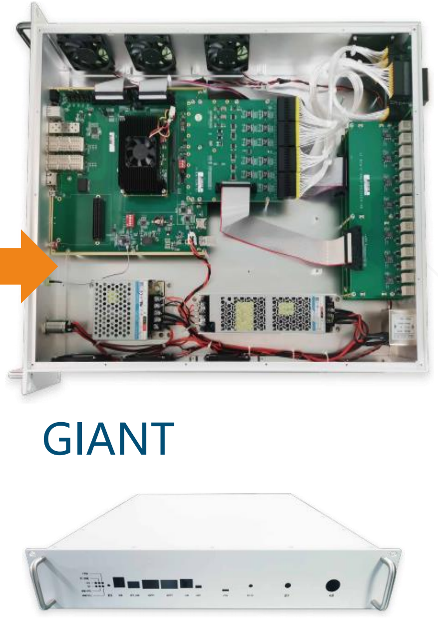
- ✓ LLRF
- ✓ BPM
- ✓ PS controller
- ✓ DCCT/ACCT
- ✓ Interlock/MPS/BPS
- ✓ CM controller
- ✓ AMP
- ✓ Temp

GIANT Generations：

- G1 is online for HIAF；
- G2 with WR on board is online for IP-SAFE；
- G3 with WR and safty ready for CiADS

fuction cards



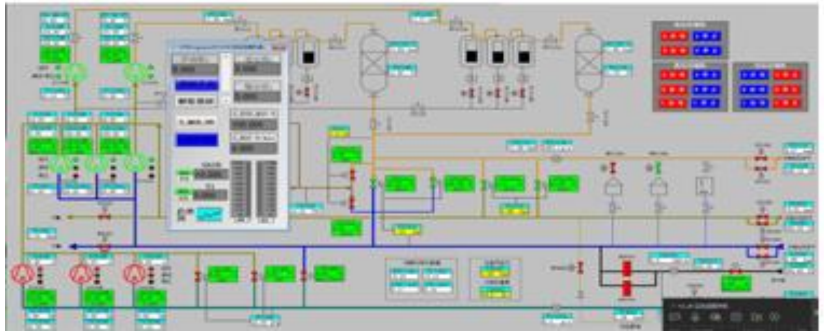


- RF measurement
- IV convertion
- ARC detector
- isolation

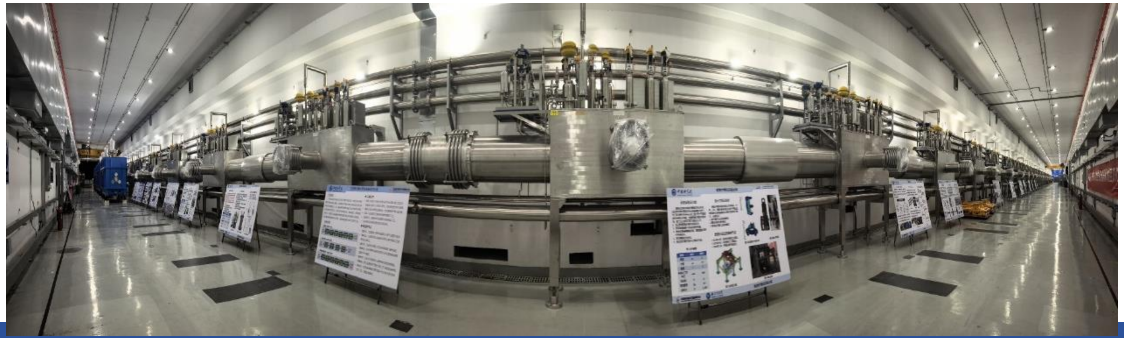
Progress of the CiADS Linac – cryogenic

the first 18 kW cryoplant made in China

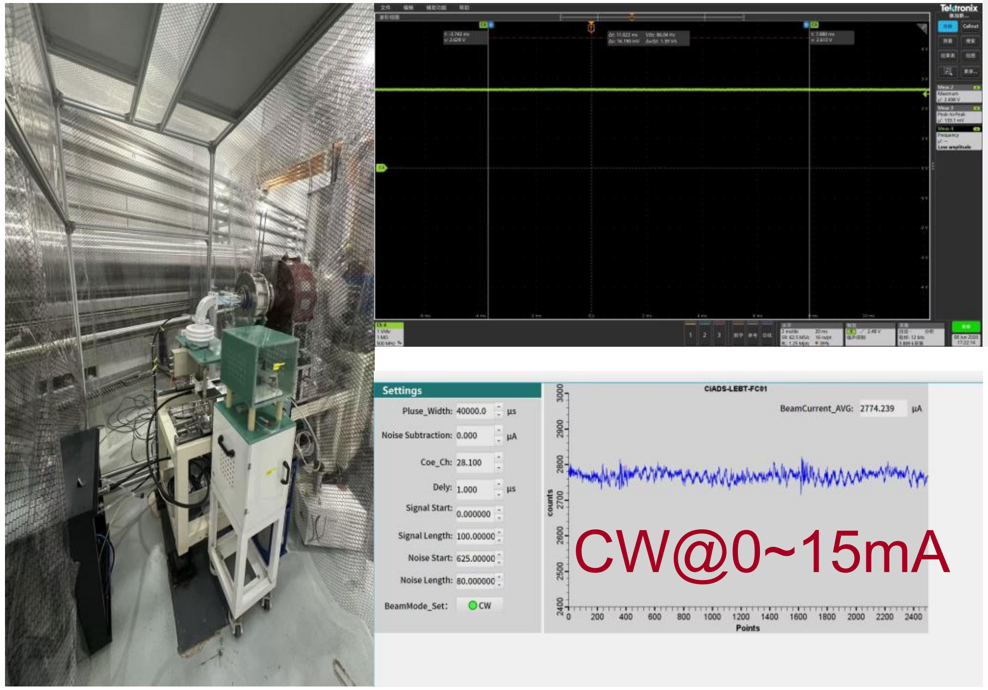
2025.05	2025.12	2026.06	2026.08
18kW@4.5K (4kW@2K) helium refrigerator relocated and positioned	first liquid helium successfully produced	4K commissioning completed with 120-hour continuous operation	cryogenic system (refrigerator, cryogenic distribution system and supporting facilities) fully installed; and is commissioning with cryomodules



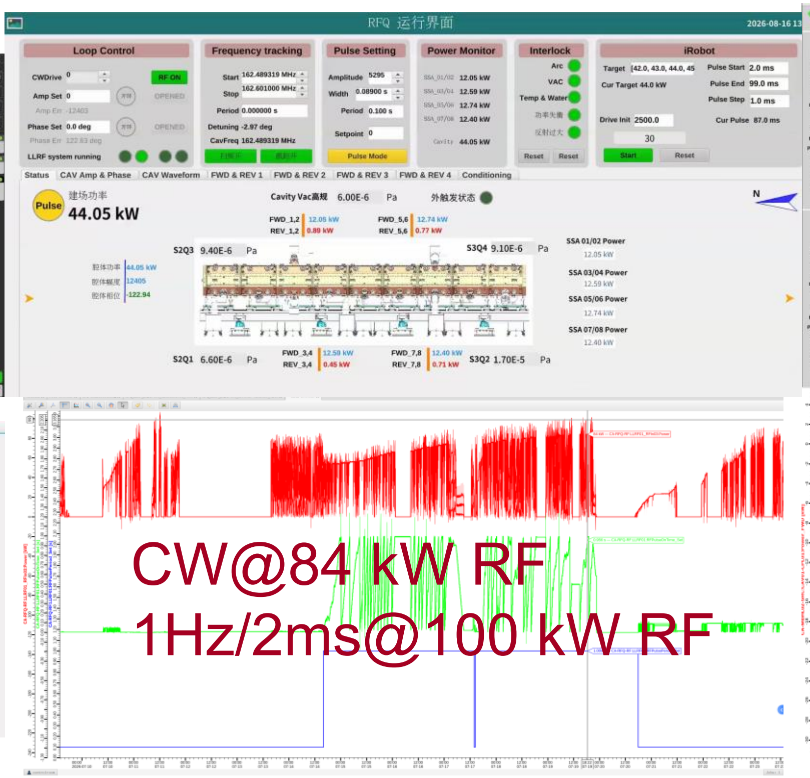


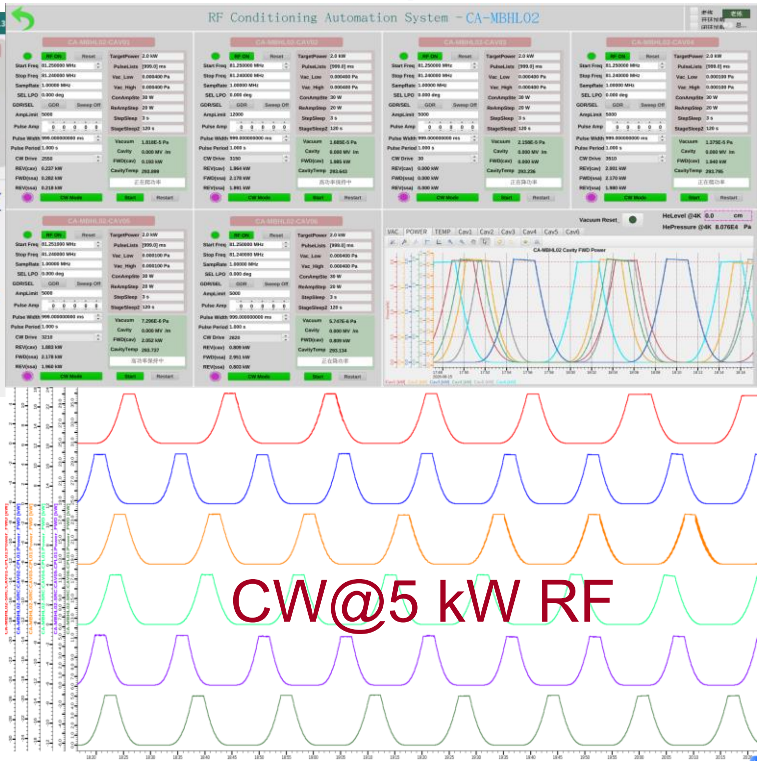
Conditioning and Commissioning



Ion Source beam commissioning



RFQ conditioning

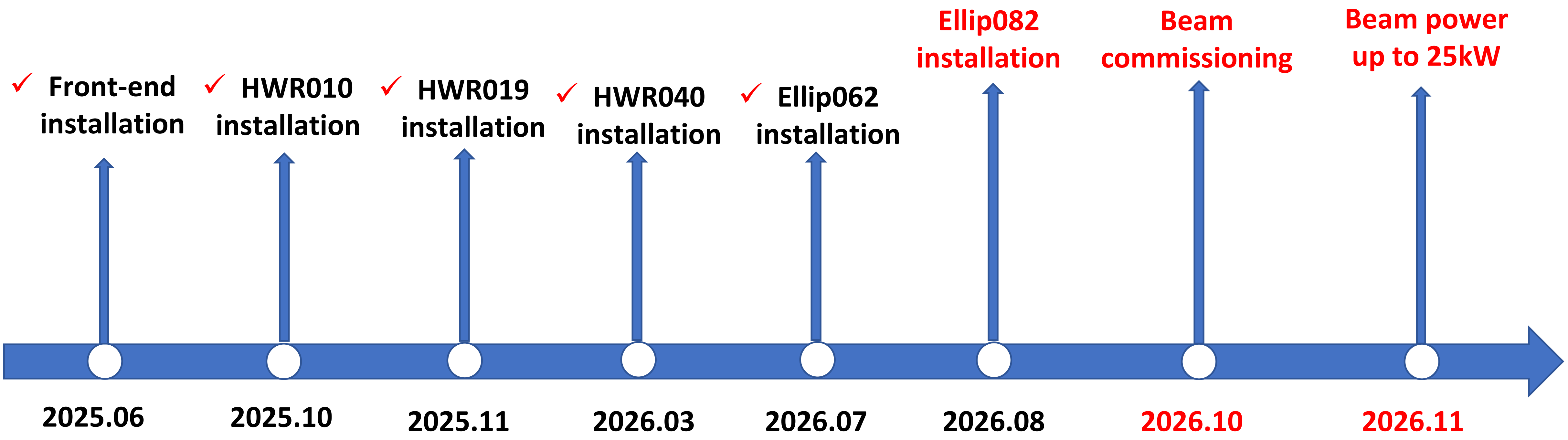


SC section warm conditioning

162.5MHz / 325MHz / 650MHz

ECR IS | LEBT | RFQ | MEBT | superconducting section

Installation Plan of CiADS Linac



Site Construction

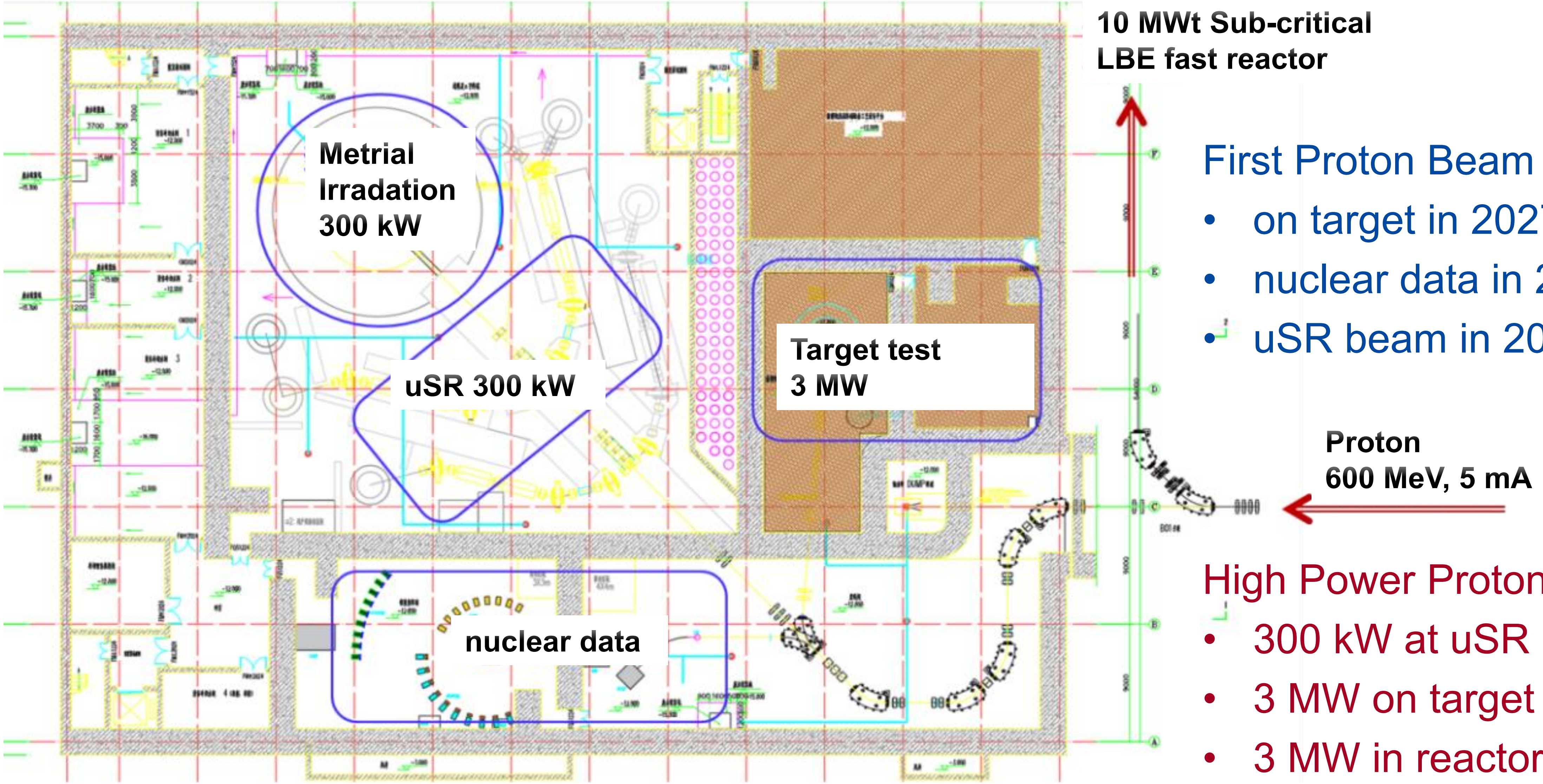
Licensing:

- Safety Design Criteria is on the first turn of Q&A.
- The review of PSAR (priliminary safty analysis report) will start in months.

Outline

- ☐ Intrduction of CiADS
- ☐ Challenge and Design of linac for CiADS
- ☐ Progress of the CiADS linac
- ☐ **Future Application Plan**

Terminals of HP proton beam



First Proton Beam

- on target in 2027
- nuclear data in 2027
- uSR beam in 2028

High Power Proton

- 300 kW at uSR in 2029
- 3 MW on target in 2029
- 3 MW in reactor in 2030

Thank you for you attention!