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The CiADS Project: Status and Challenges

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Outline

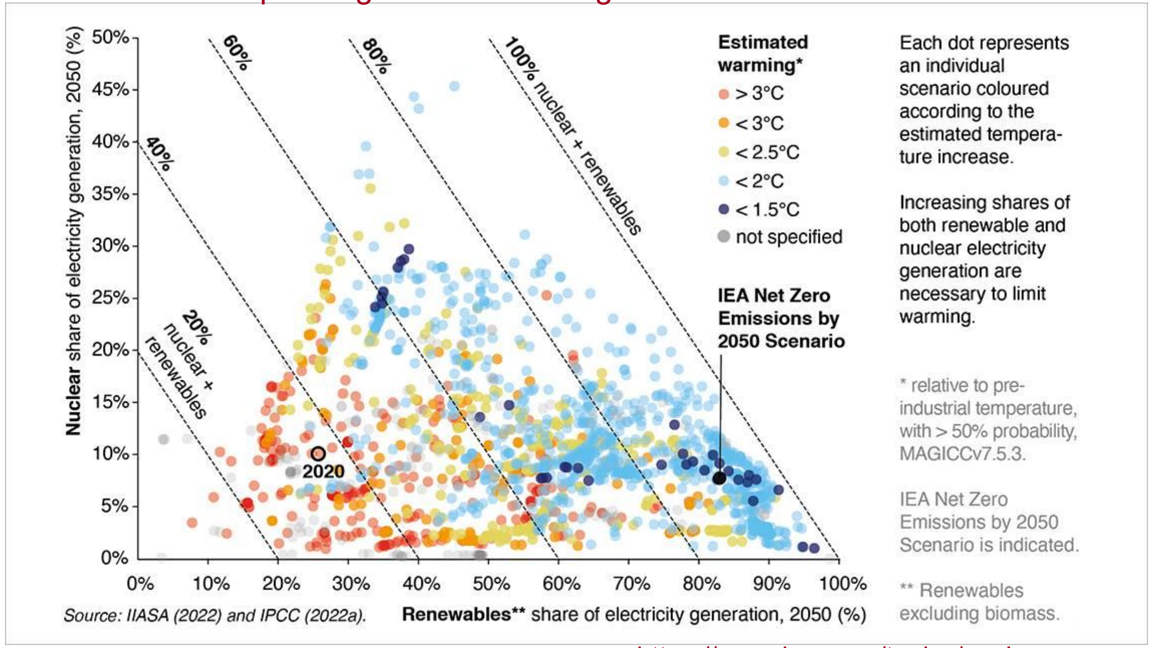
- Backgroud & Brief introduction of CiADS facility
- Challenges and Progress of CiADS linac
- First beam of normal conducting front-end
- Summary and Perspective

Carbon Neutrality and Nuclear Energy

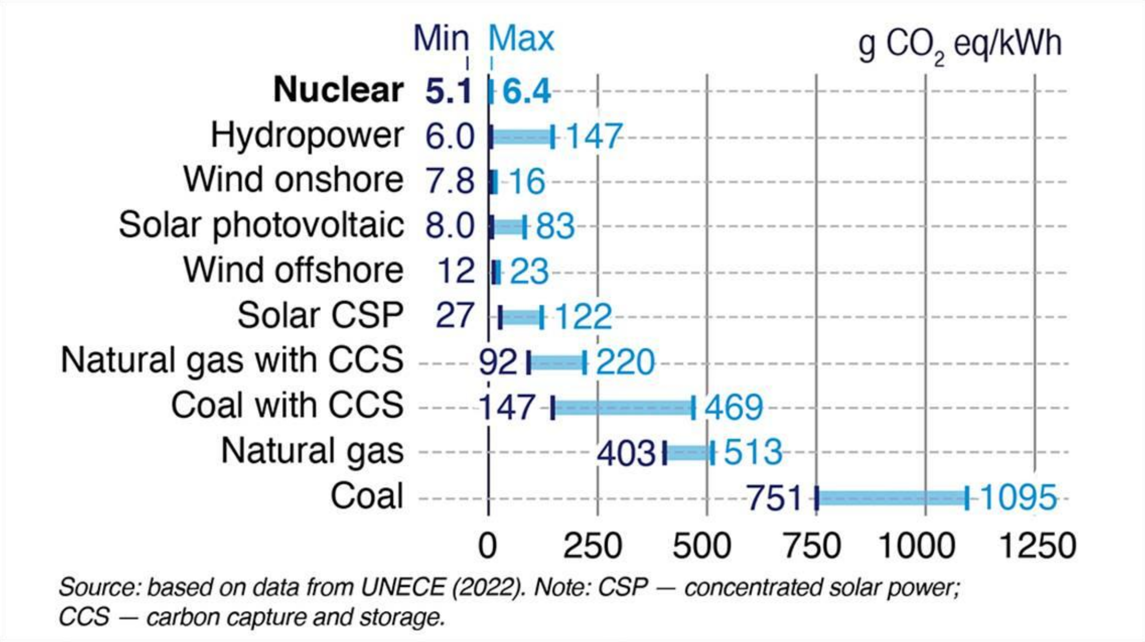
"Holding the increase in the global average temperature to well below 2° C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5° C above pre-industrial levels."

—— ***The Paris Agreement***

Shares of nuclear and renewable energy in the electricity generation mix and corresponding climate warming across IPCC AR6 scenarios.



Greenhouse gas emissions from electricity generation technologies.



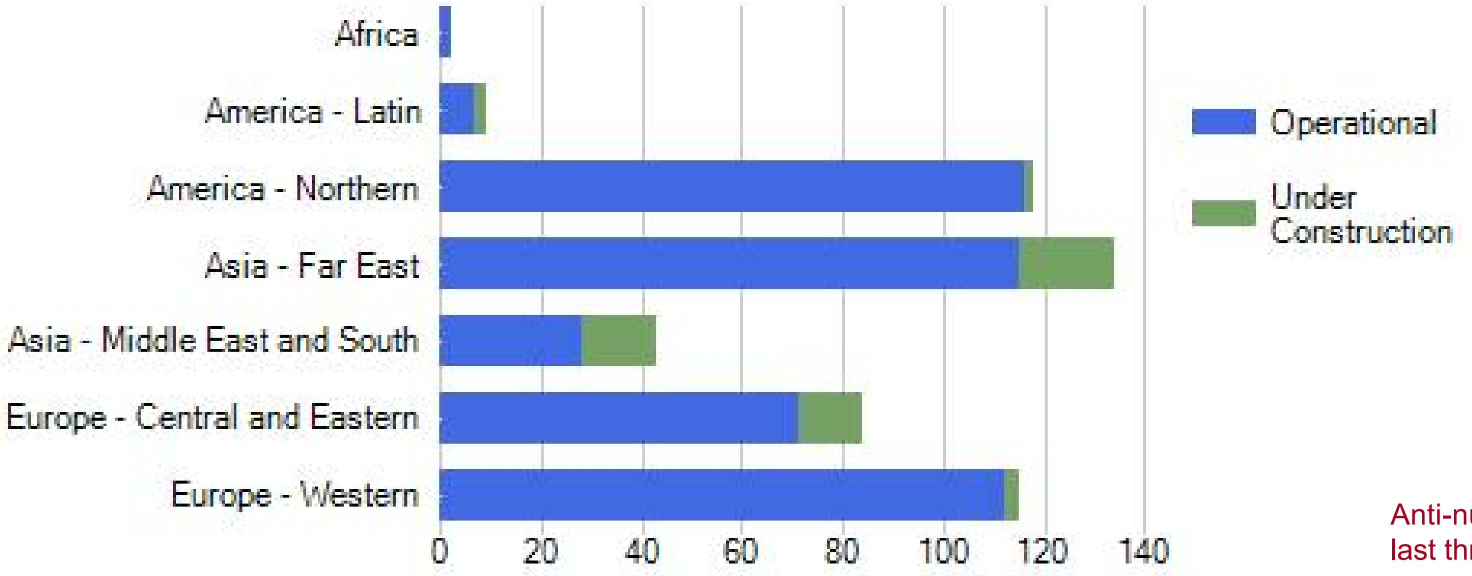
https://www.iaea.org/topics/nuclear-power-and-climate-change/climate-change-and-nuclear-power-2022

- To achieve carbon neutrality in the coming decades, a key to avoiding global warming of more than 1.5℃, investment in the energy sector must be scaled up and directed towards cleaner and more sustainable technologies that support global climate change mitigation and adaptation.
- With one of the lowest carbon footprints, 24/7 availability and the operate flexibly, nuclear power can make an irreplaceable contribution to a stable decarbonized power system and act as a regulator to renewable energy such as solar and wind.

Nuclear Power Making a Comeback

□ Nuclear power is gaining support again after years of decline

- 52 more reactors under construction, 2/3 in Asia.
- ~30 new countries are looking at nuclear energy to meet their power and climate needs.

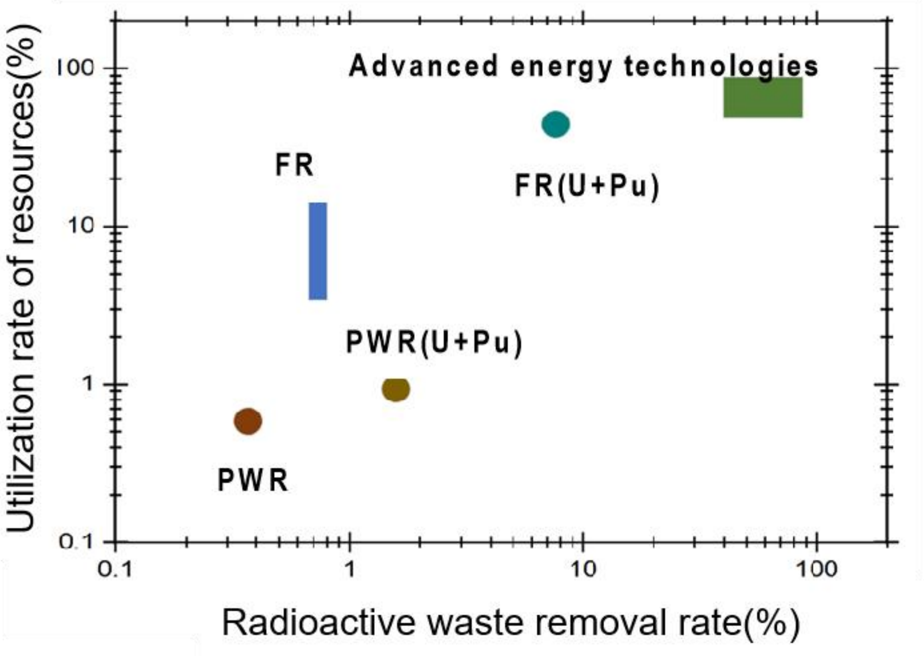


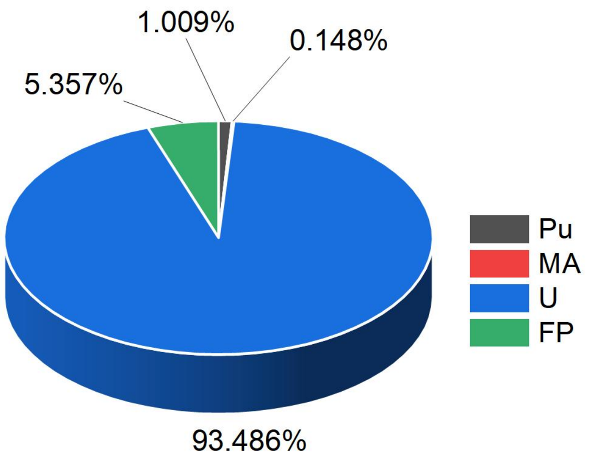
Anti-nuclear movement supporters gather to celebrate the shuttering of Germany's last three nuclear power plants on April 15, 2023 in Munich, Germany.
——*Johannes Simon* | *Getty Images News*

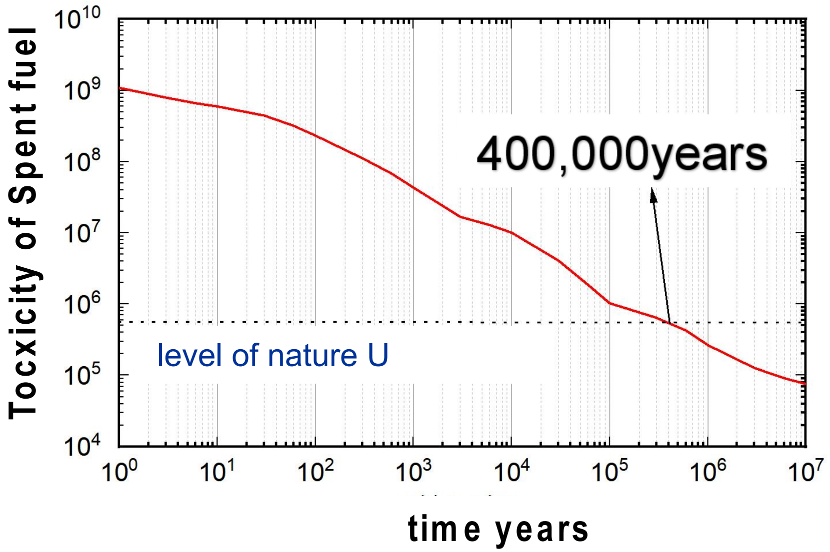
□ Nuclear Energy Makes History as Final COP28 Agreement Calls for Faster Deployment

□ At COP28 by more than 22 countries to advance the aspirational goal of tripling nuclear power capacity by 2050, as well as statements by the IAEA and the nuclear industry.

Issues of Current Nuclear Energy





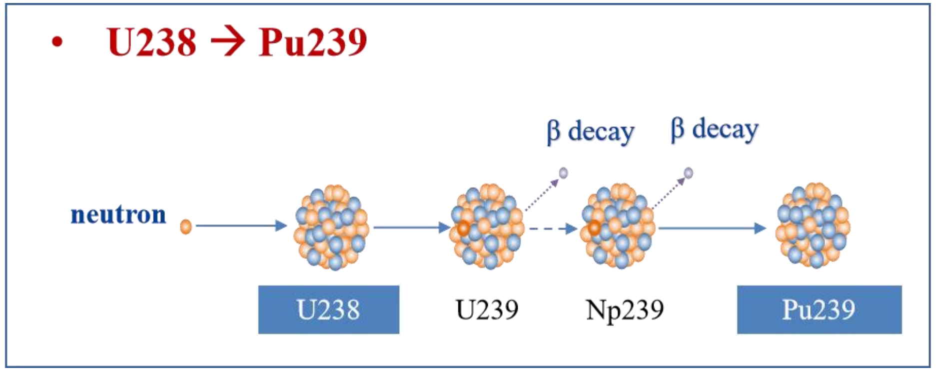


- 8 tons of natural uranium --> 1 ton of nuclear fuel -> only 50 kg is burnup into fission products
  - Reusable fuel (950kg) + depleted uranium (7 tons) has huge untapped potential for energy
- By 2035, UxC estimates that spent fuel emissions will be close to 618,000 tons, according to tripling nuclear power by 2050, that means at least 30,000 tons/y

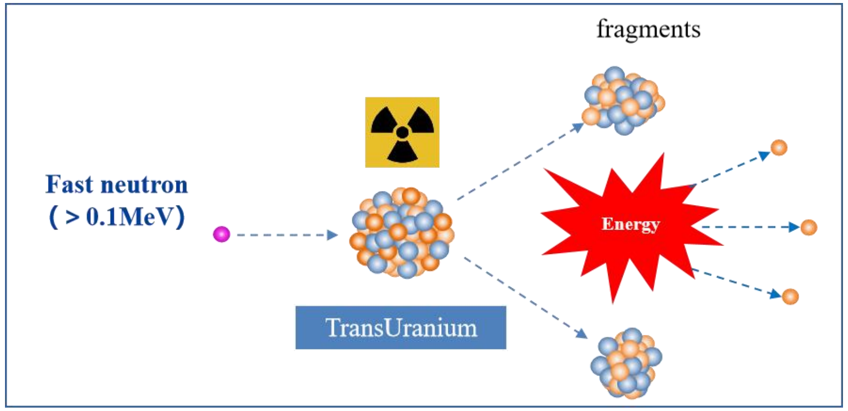
Trend of nuclear fission energy future

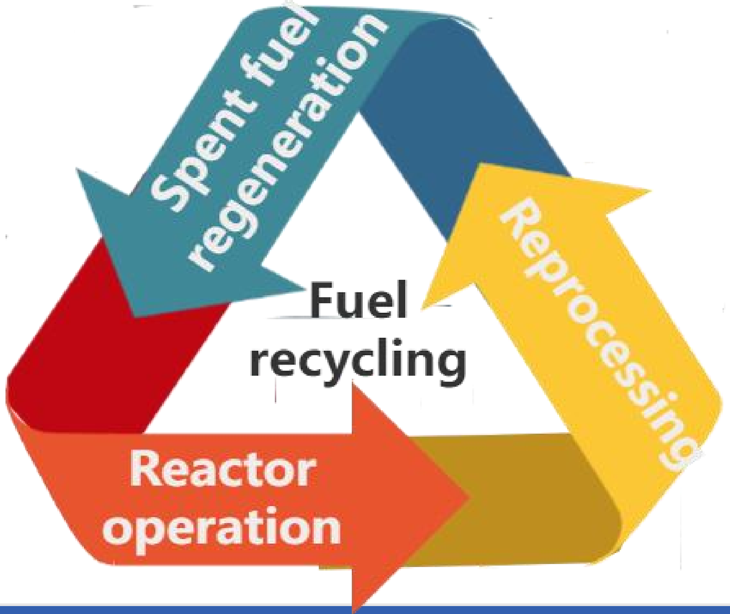
the Next generation nuclear power should be Sustainable

- Breeding



- Transmutation

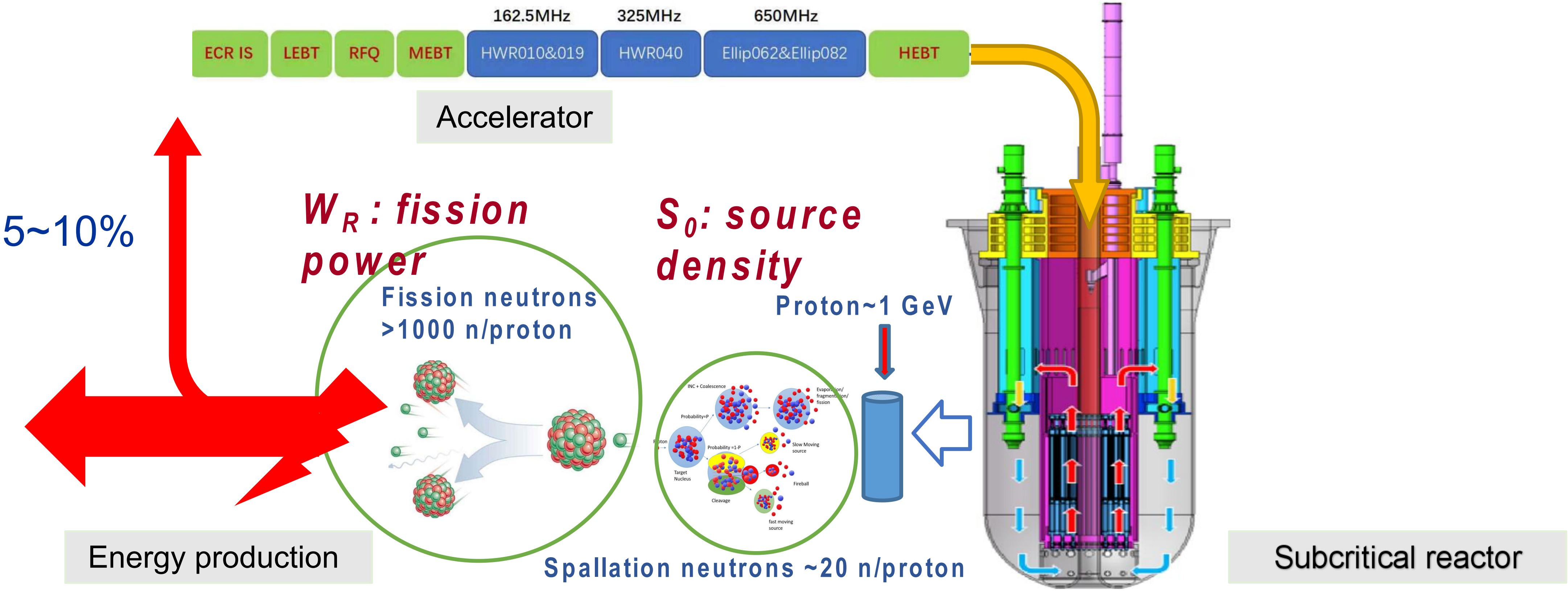




- to increase the amount of nuclear fuel by hundreds times
- to reduce the amount of nuclear waste by tens times
- to shorten the radioactive-lifetime by thousands times

■ Principle of 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.



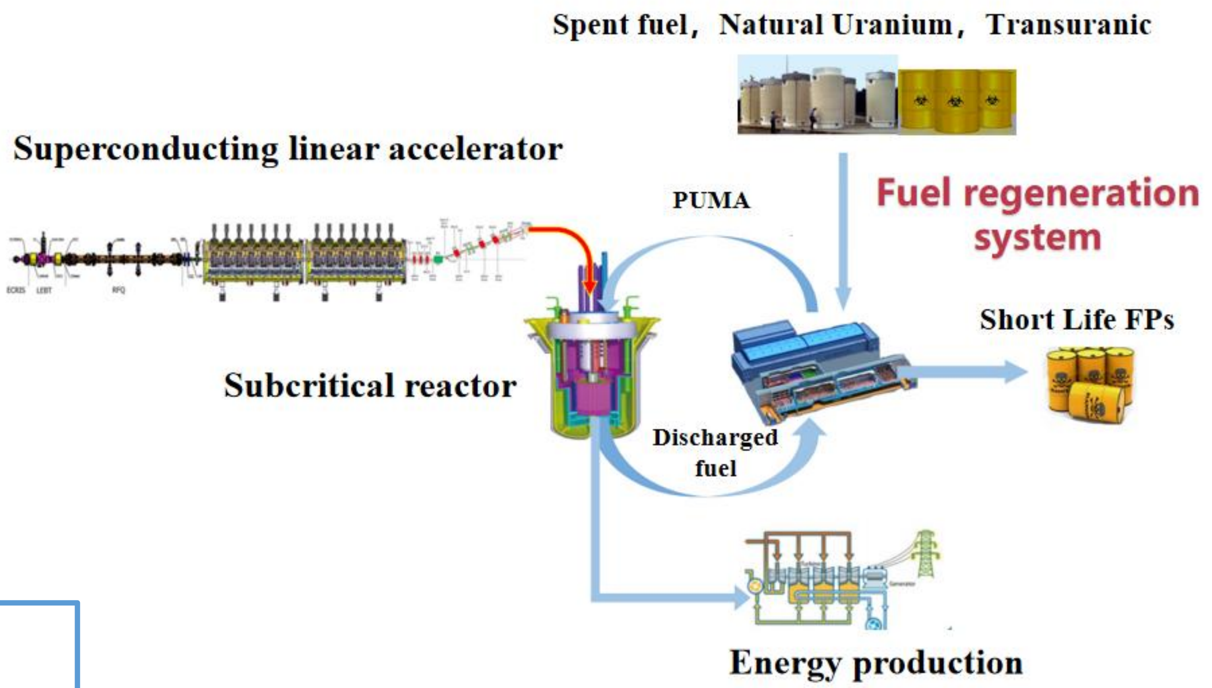
Characteristics of ADANES

"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

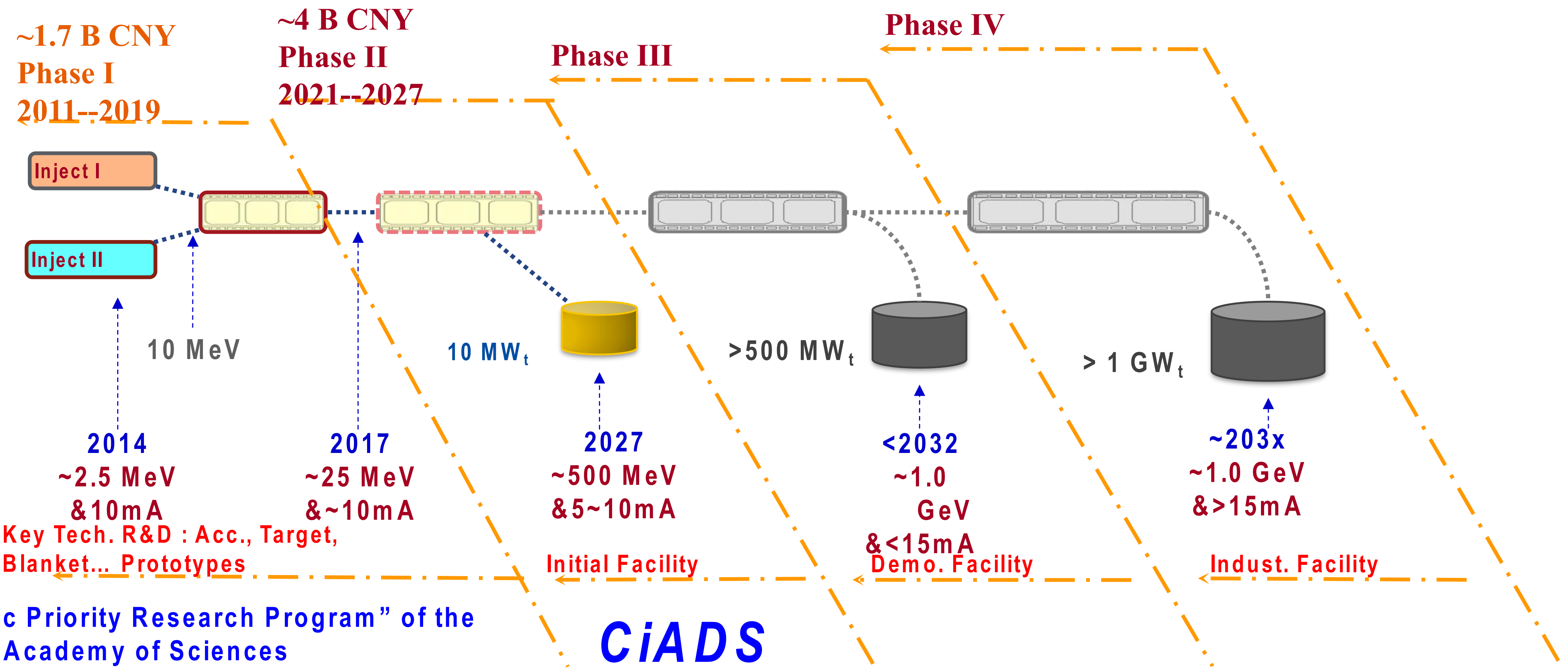


- Complete reprocess of ADANES fuel cycle
- Each time the fission products are removed, and add some spent fuel or depleted uranium

Roadmap of ADANES in China

Accelerator Driven transmutation System is an efficient way.

ADS Roadmap in China



"strategic Priority Research Program" of the Chinese Academy of Sciences

CiADS

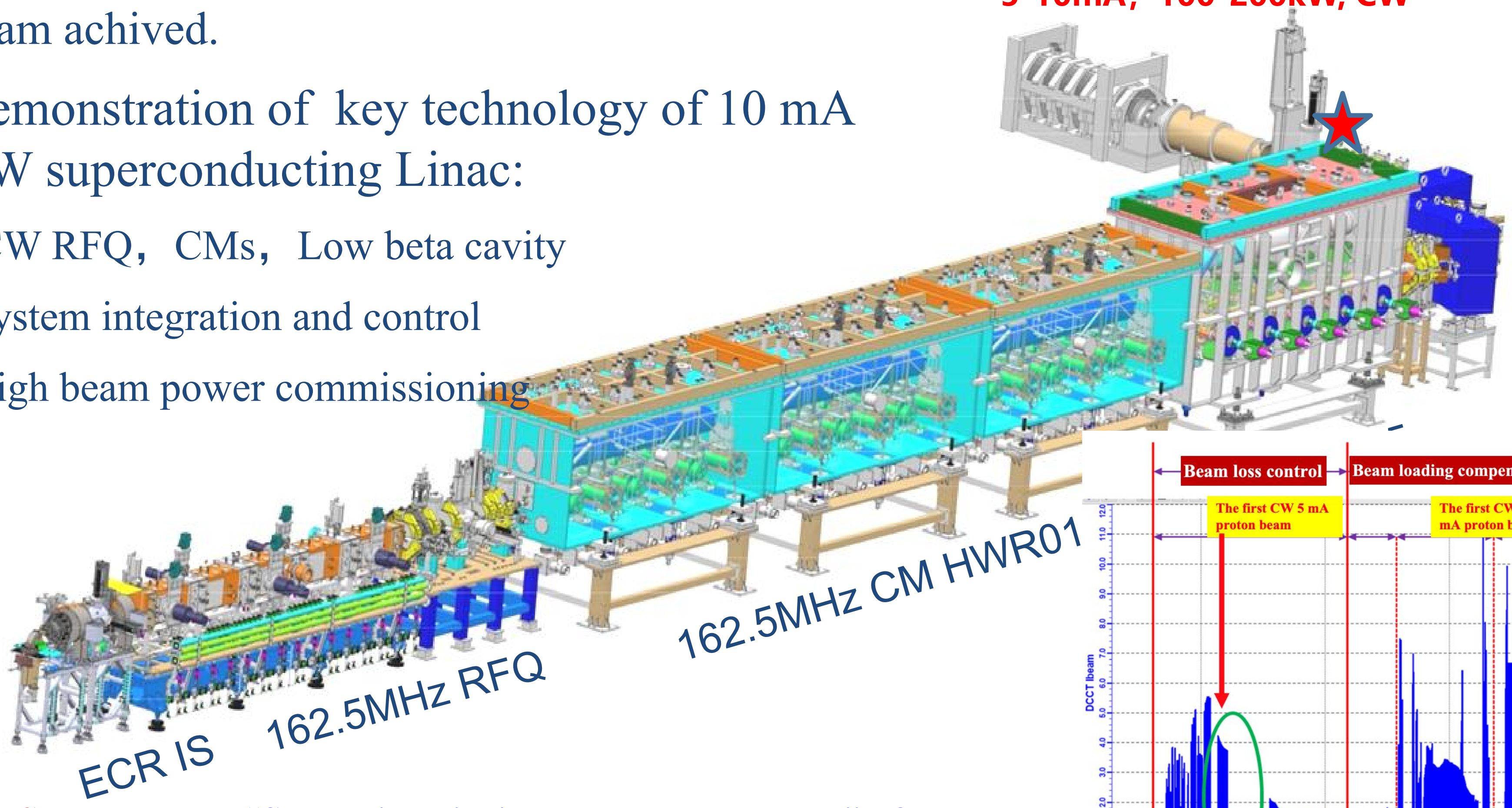
The phase I - CAFe

- CAFe facility was constructed 2011-2021, IMP cooperate with IHEP, 2021,10mA, 20MeV proton beam achived.
- Demonstration of key technology of 10 mA CW superconducting Linac:

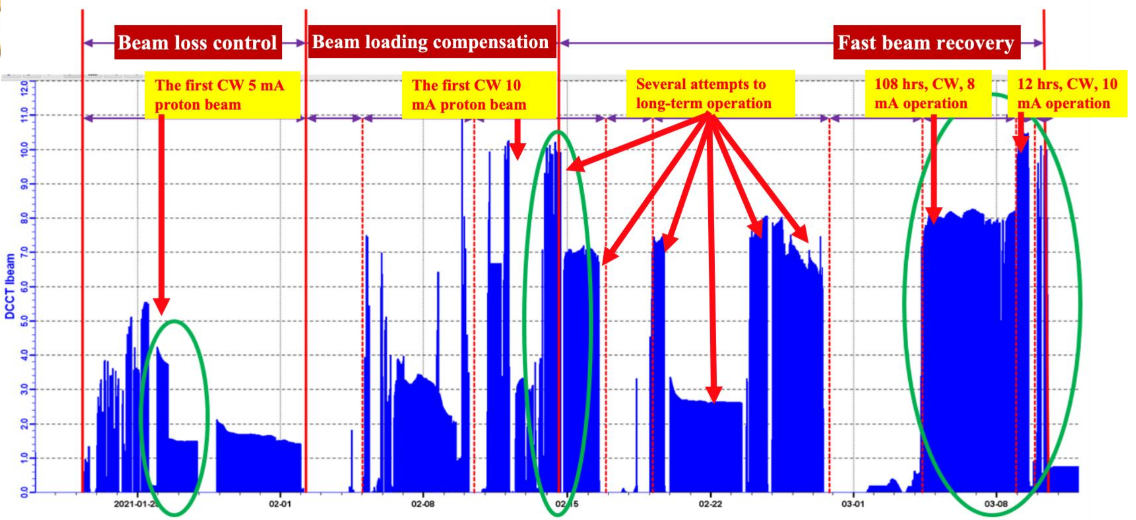
✓ CW RFQ, CMs, Low beta cavity

✓ system integration and control

✓ high beam power commissioning



Ions	P, H_2^+, α
Frequency	162.5 MHz
Current	10 mA
E in RFQ	40 keV
E out RFQ	3.1 MeV
Energy	20/30/40MeV
Temp.	4.5 K

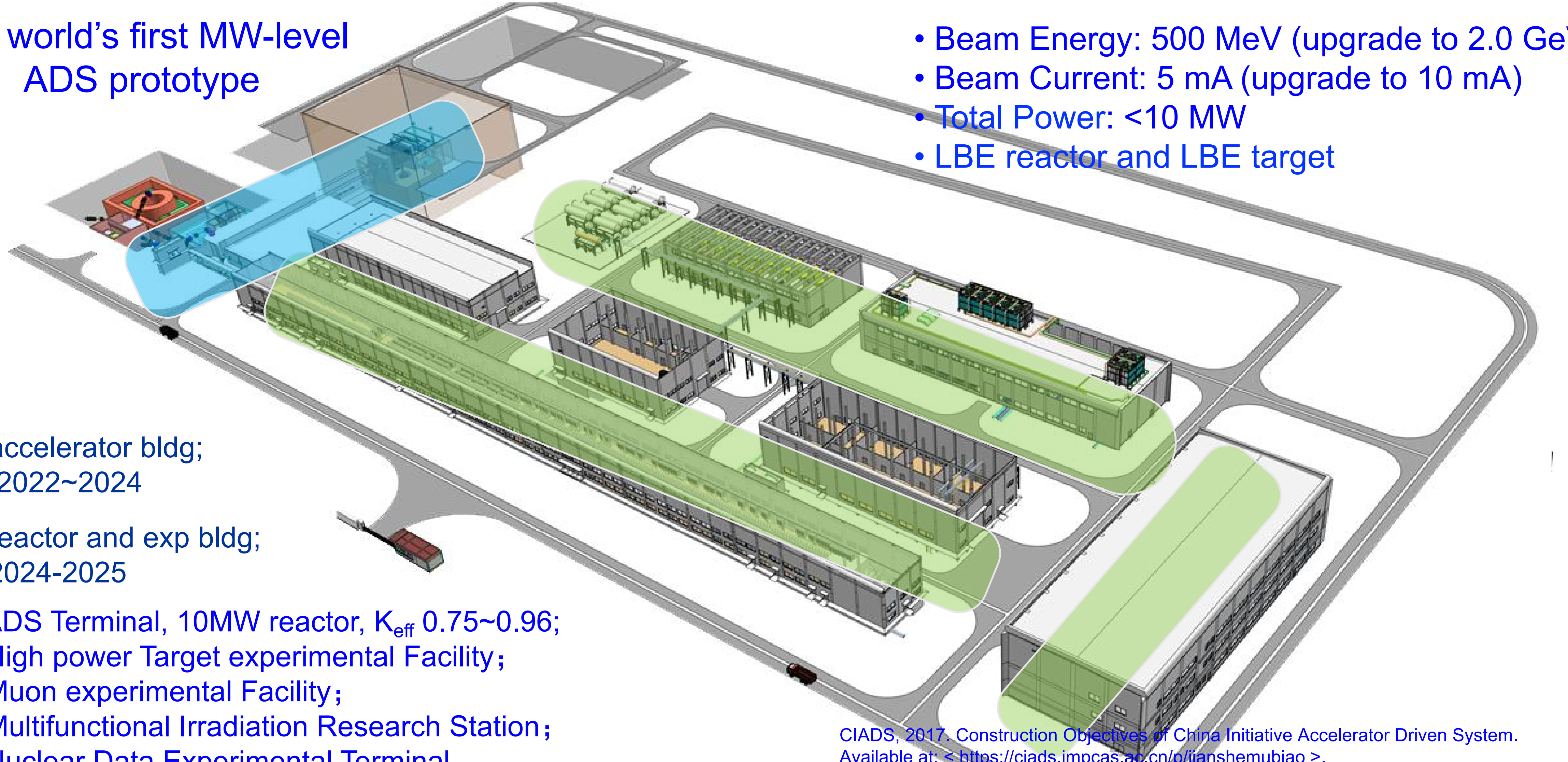


- **Supported by "Strategic Priority Research Program" of the Chinese Academy of Sciences.**

The phase II - CiADS Project

The world's first MW-level ADS prototype

- Beam Energy: 500 MeV (upgrade to 2.0 GeV)
- Beam Current: 5 mA (upgrade to 10 mA)
- Total Power: <10 MW
- LBE reactor and LBE target



accelerator bldg; 2022~2024

reactor and exp bldg; 2024-2025

- T1: ADS Terminal, 10MW reactor, K_{eff} 0.75~0.96;
- T2: High power Target experimental Facility；
- T3: Muon experimental Facility；
- T4: Multifunctional Irradiation Research Station；
- T5: Nuclear Data Experimental Terminal
- T6: ISOL for upgrade

CIADS, 2017. Construction Objectives of China Initiative Accelerator Driven System. Available at: < https://ciads.impcas.ac.cn/p/jianshemubiao >.
Xiao, G.Q., Xu, H.S., Wang, S.C., 2017. HIAF and CiADS National Research Facilities: Progress and prospect. Nucl. Phys. Rev. 34–3, 275–283.

Progress of CiADS Campus

Mile Stones of ADANES/CiADS

2025～2026

Construction Accelerator and Target

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

- ☐ Accelerator Commissioning
- ☐ Target thermal study
- ☐ Beam-target coupling

2026～2027

ADS Coupling pre-Fuel test

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

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

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
- ☐ Power operation study
- ☐ 2.5MW beam realization
- ☐ ADANES design demonstration

2029~2030

ADS/ADANES transmutation research

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

- ☐ 2.5MW target coupling reactor
- ☐ Fuel test in high power density and deep burnup
- ☐ Transmutation demonstration
- ☐ ADANES preliminary design report

Outline

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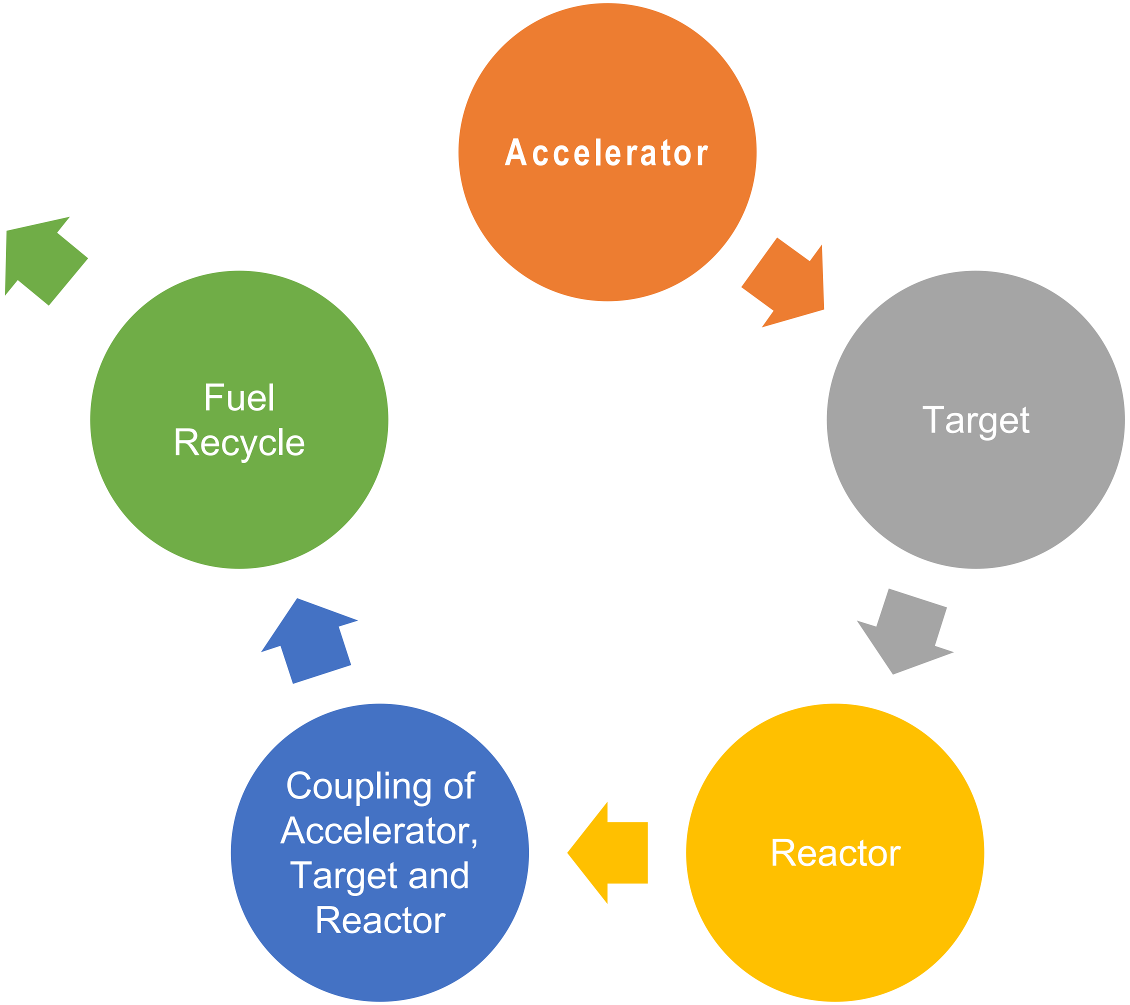
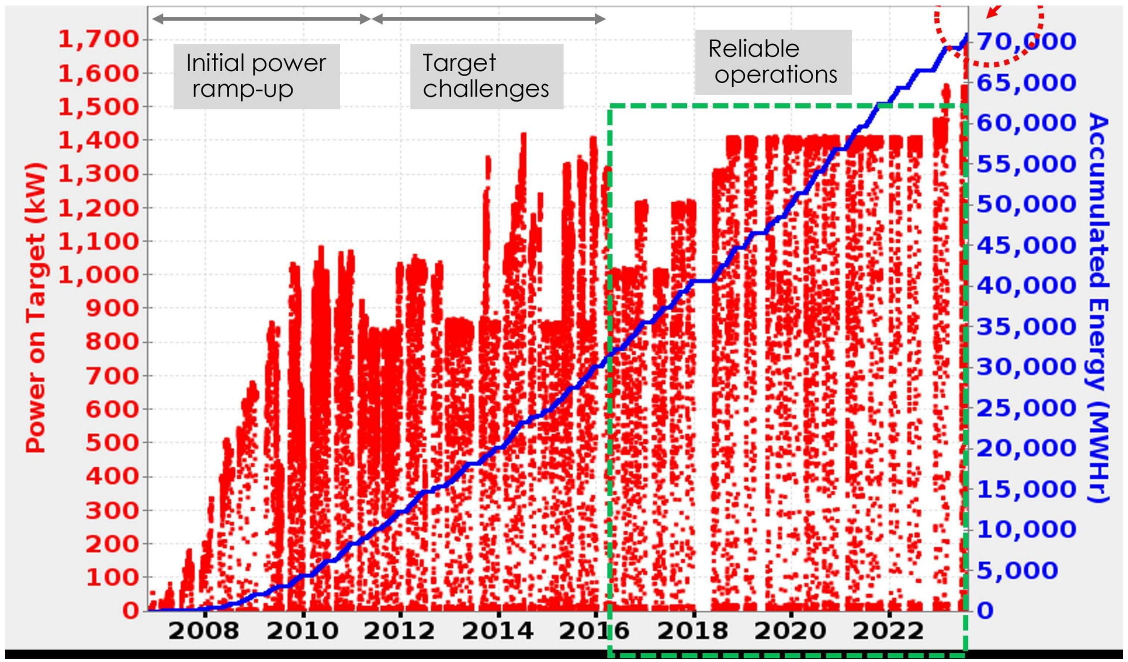
Challenges of ADANES



- **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

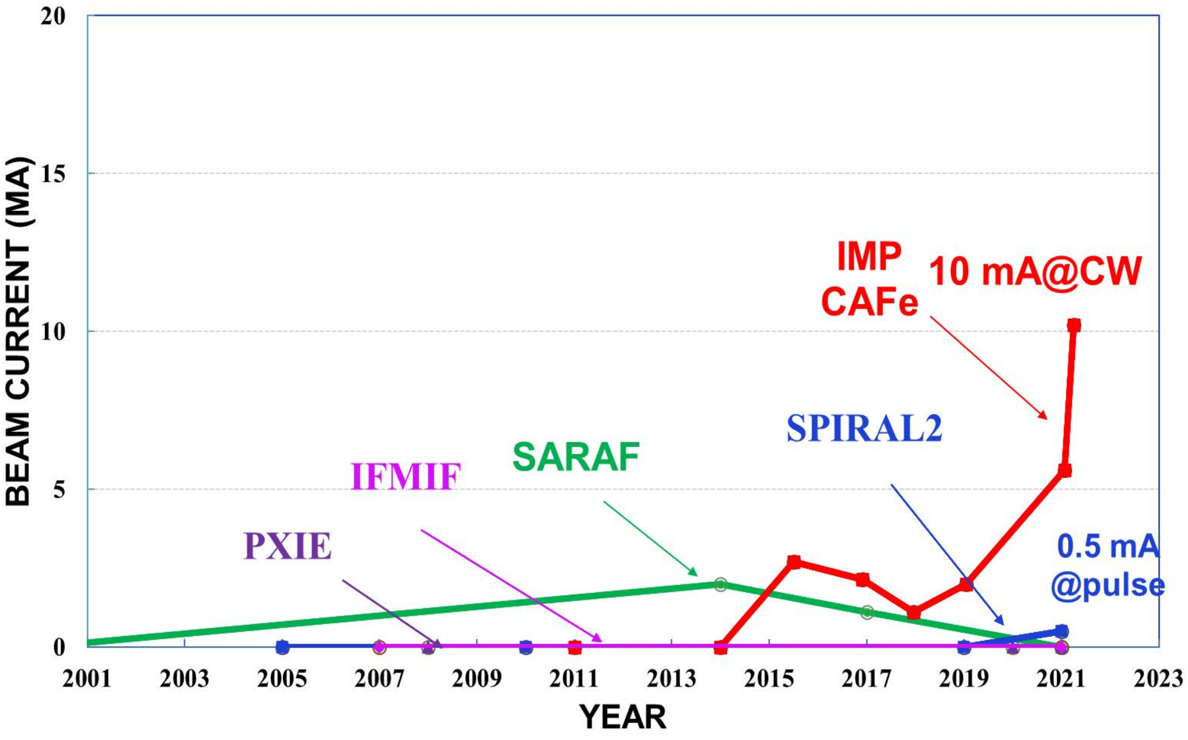
Power and Current Ramping of SC Linacs



I_{ave}=1.3~1.4 mA

Spallation Neutron Source Ramping power to 1.7 MW from 2008 to 2023

A. Aleksandrov, Warm and cold SNS LINAC commissioning, HB 2023



10 mA CW proton beam was realized at CAFe (IMP) in 2021

Zhijun Wang, IPAC 2023, WEOGB2

10 mA CW proton beam has been achieved in sc-linac firstly in the world

Major Challenges of ADS Accelerators

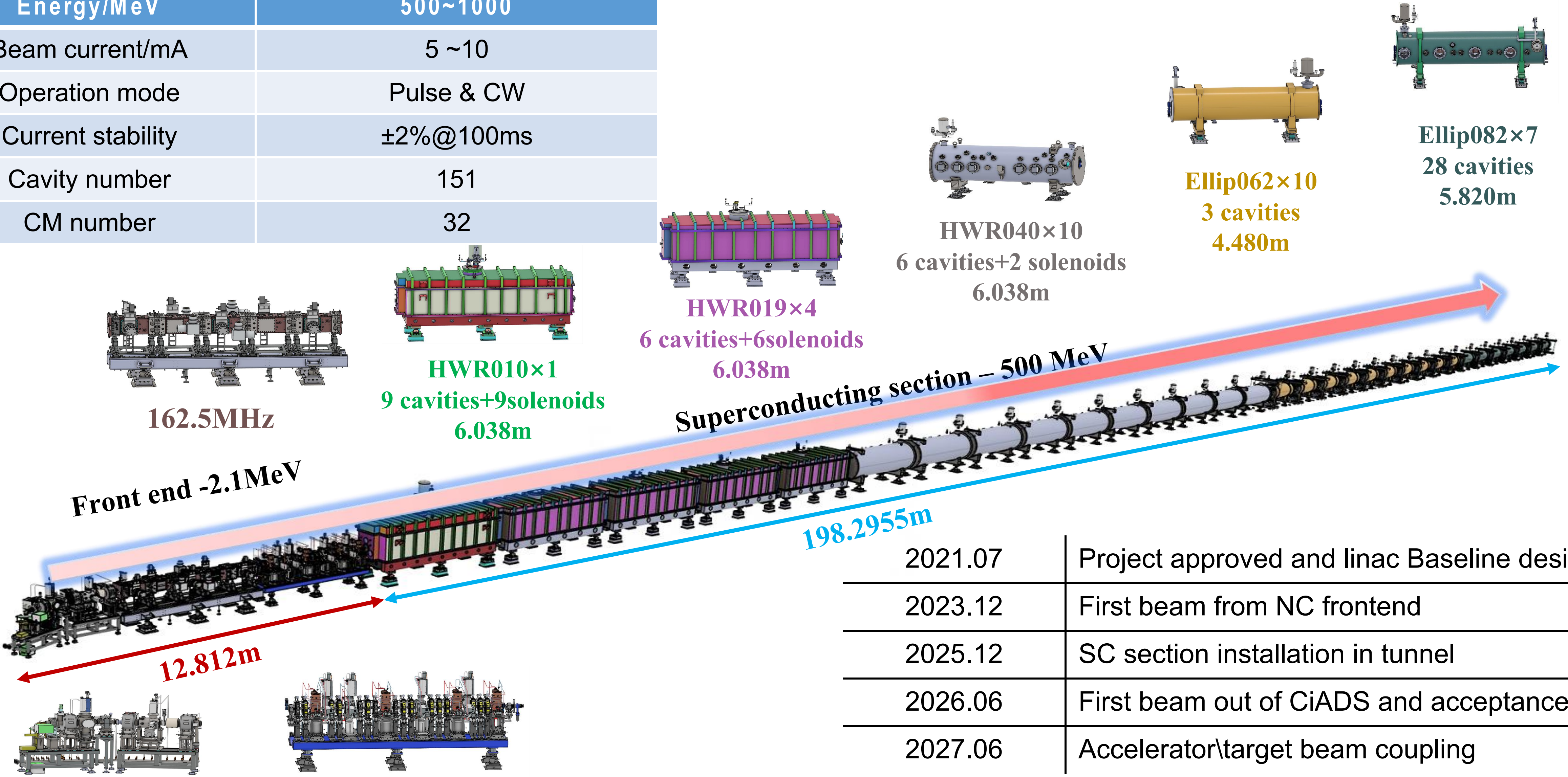
For an industrial scale ADS, beam trip requirements are strict and time related.

Beam Trip duration (s)	Industrial Scale Transmutation（num/year）	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>5 min	<50	System availability
Availability	>80%	

H. Aït Abderrahim et al, Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production. 2010. https://doi.org/10.2172/1847382

the superconducting lianc for CiADS

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



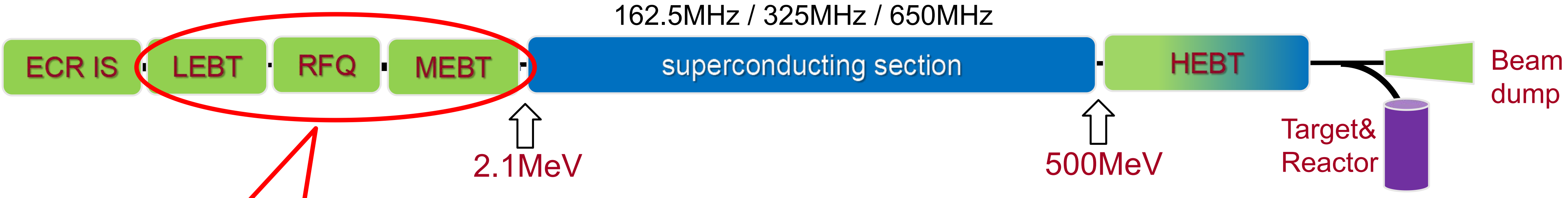
2021.07	Project approved and linac Baseline design
2023.12	First beam from NC frontend
2025.12	SC section installation in tunnel
2026.06	First beam out of CiADS and acceptance
2027.06	Accelerator\target beam coupling

Challenge of SC-Linac for CiADS

- Beam loss control for high beam power
- Fault recovery scheme for high aviability
- Beam uniformity on the target
- Intelligent beam operation
- High stable Cavities
- High efficiency HP rf system
- High accuracy CM system
- ……..

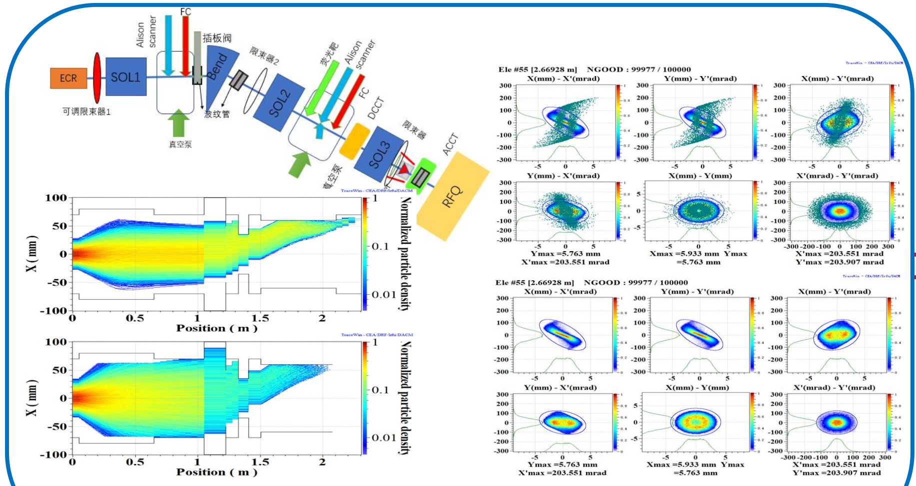
Beam loss control

Beam physics design

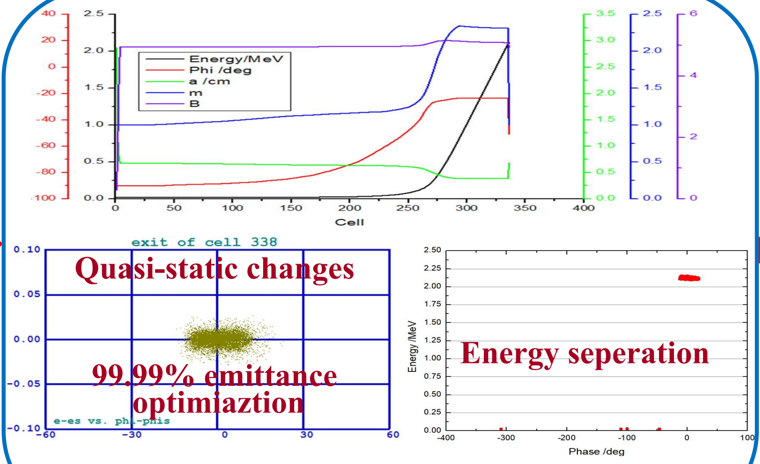


Beam quality operation

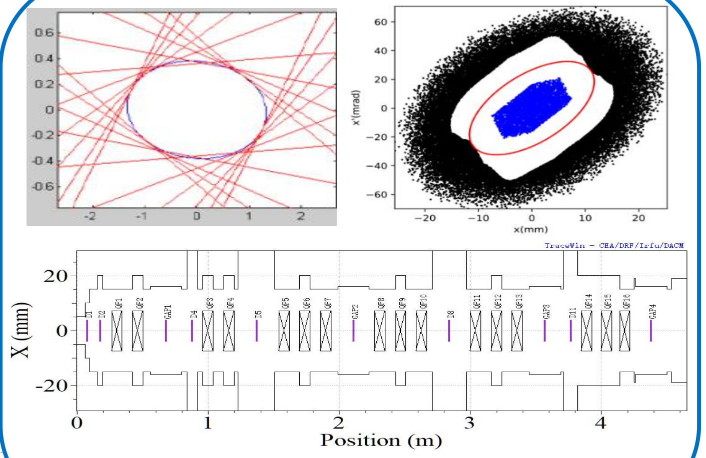
- **LEBT :** Transverse beam quality control- Bend structure + beam scraping
- **RFQ :** Longitudinal beam quality control- Full particle optimization
- **MEBT:** Beam halo control- Full space scraping



LEBT



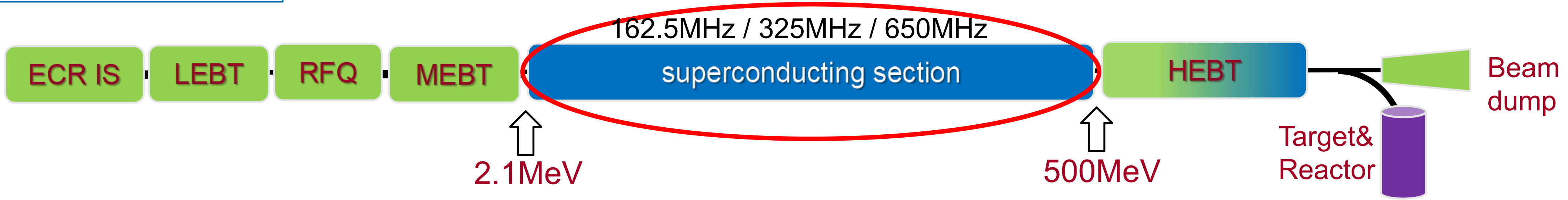
RFQ



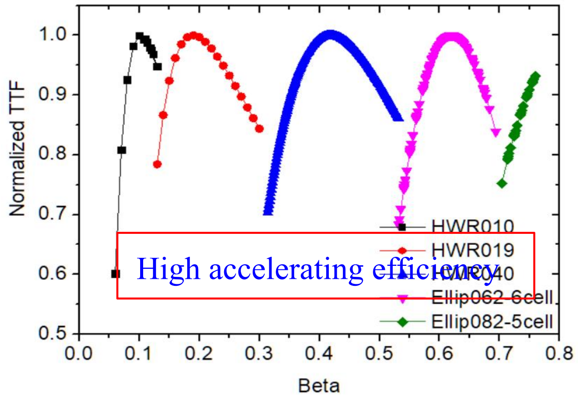
MEBT

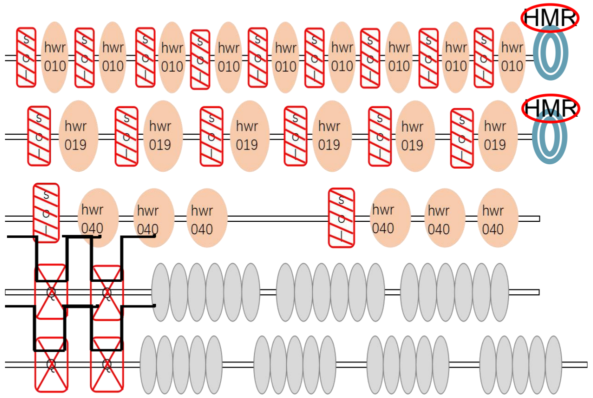
Beam loss control

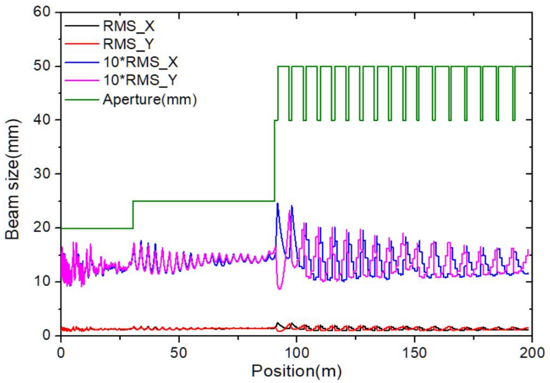
Beam physics design

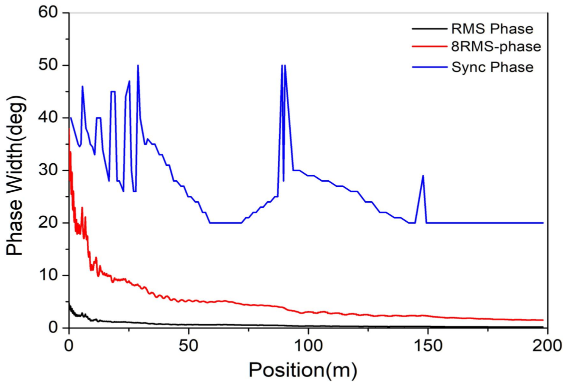


- **High accelerating efficiency**
- **Low beam loss control**
  - ✓ **Lattice optimization** compact qusi-periodic structure and periodic lattice
  - ✓ **Beam matching** for mitigating halo formation and beam emittance growth
  - ✓ **Beam halo collimation** to reduce the probability of beam loss on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



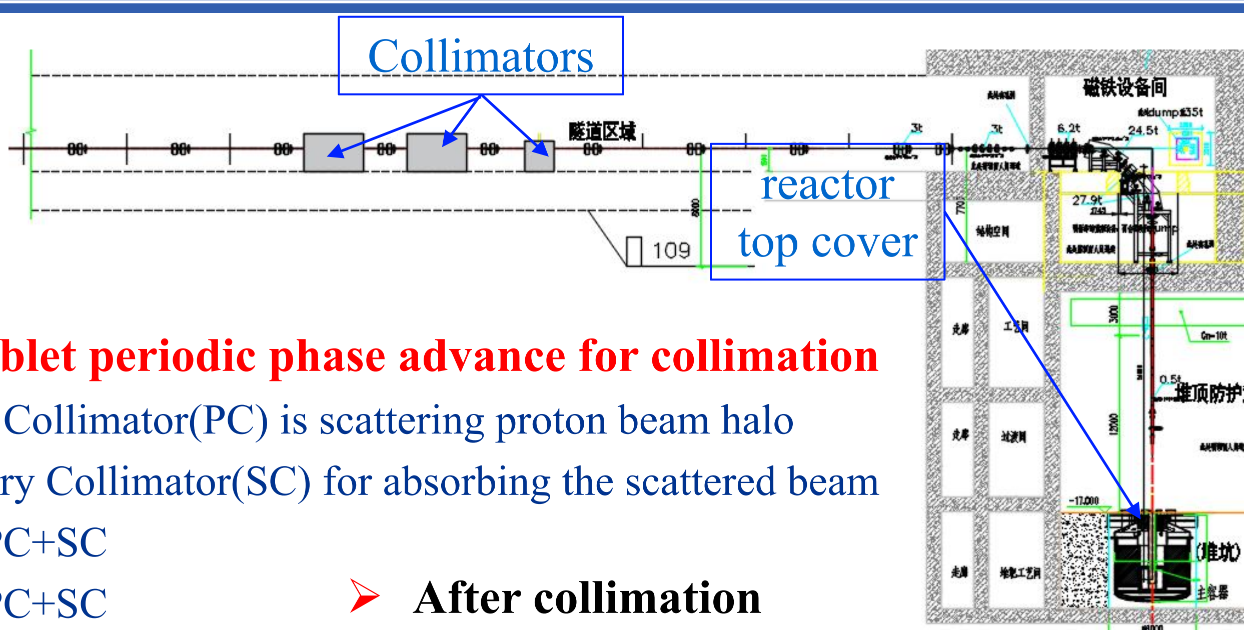






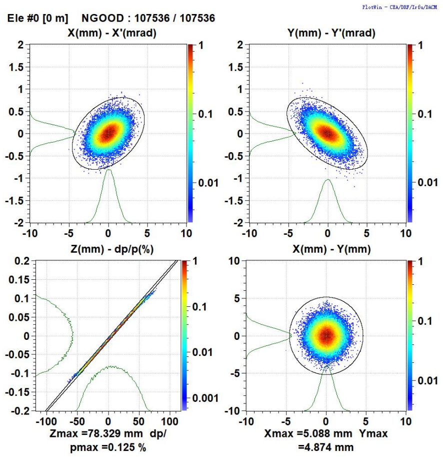
Beam collimation for power loss control

- **2.5 MW proton beam power (500 MeV@5 mA)**
- **Beam with halo lead to downstream beam loss**
  - Halo outside of 5σ is 0.4%, i.e. 10 kW
  - too high radiation maintenance and equipment

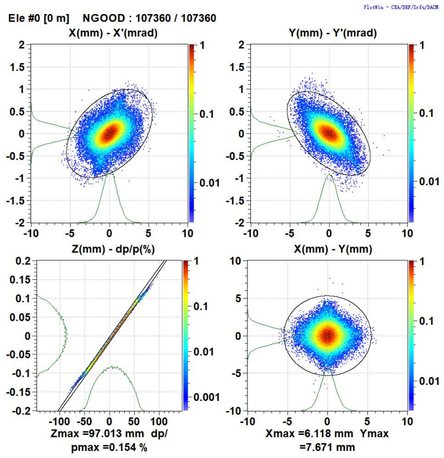


- **3*60° doublet periodic phase advance for collimation**
  - Primary Collimator(PC) is scattering proton beam halo
  - Secondary Collimator(SC) for absorbing the scattered beam
  - Col-1: PC+SC
  - Col-2: PC+SC
  - Col-3: SC

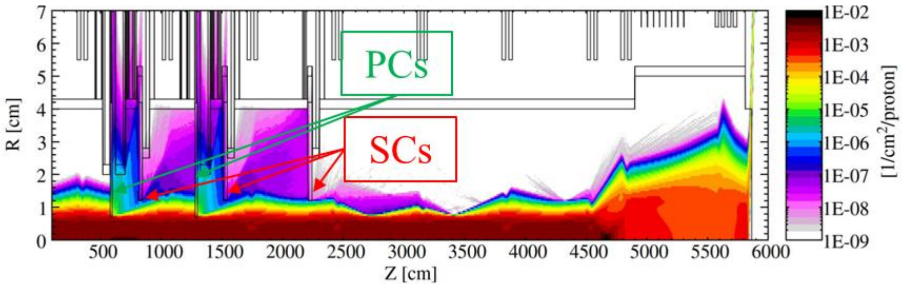
- **After collimation**
  - Beam halo becomes small and clean
  - Beam loss rate <10 W/m before the target

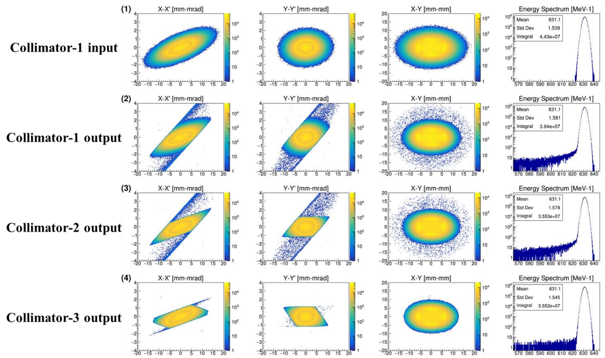


Matched beam



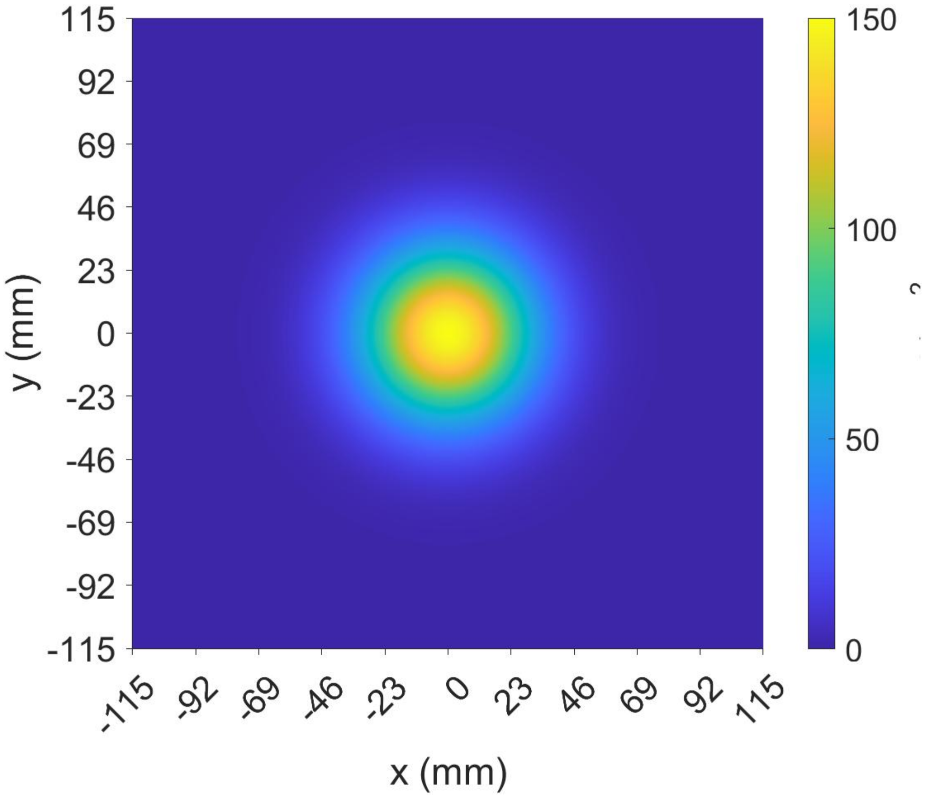
Mismatched beam





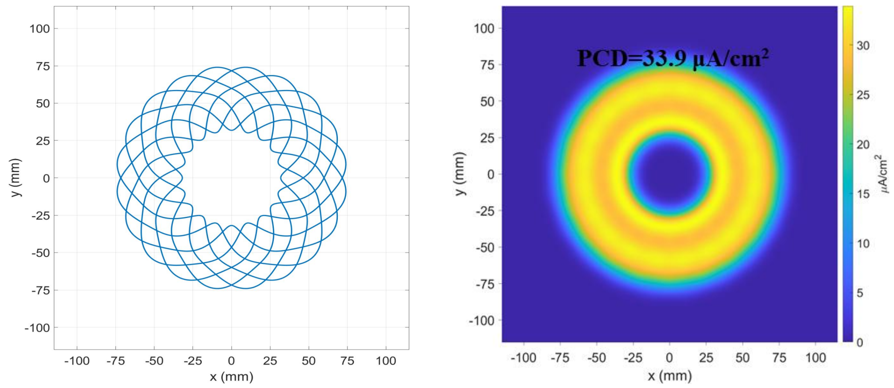
Beam uniformity on the target

- **5 mA beam within D=230 mm vacuum tube**
  - For extended Gaussian distribution with σ=23 mm, PCD=150 μA/cm²>>35 μA/cm² limitation considering target window DPA.

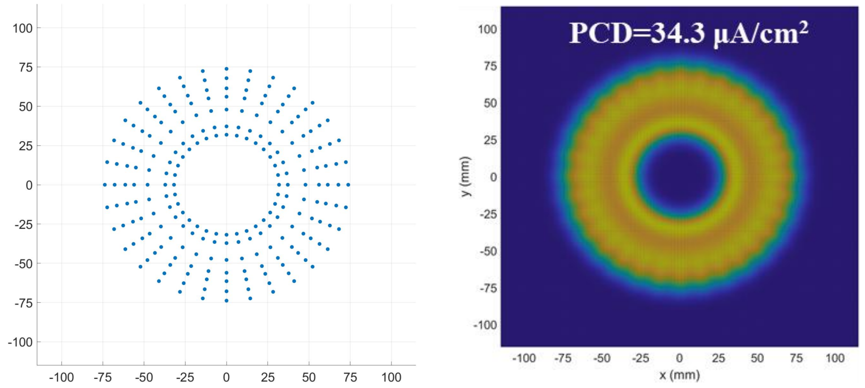


Gaussian distributed beam

- **Beam uniformity by Multi order Sine wave scanning**
  - Fourier harmonic superposition based on scan magnets
  - Fourier harmonic superposition based on RF cavities



Scan magnets uniformity



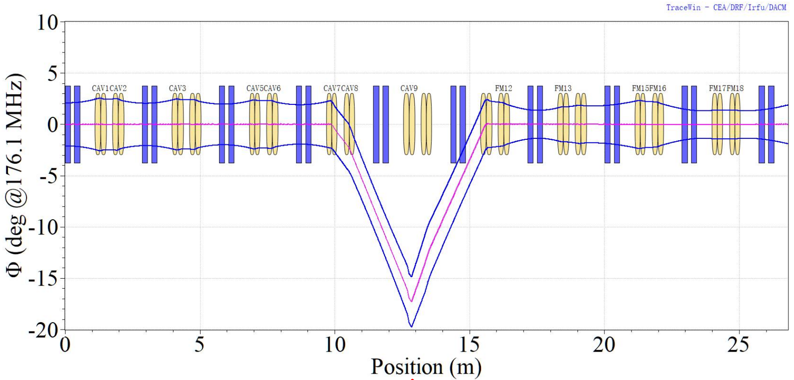
RF cavities uniformity

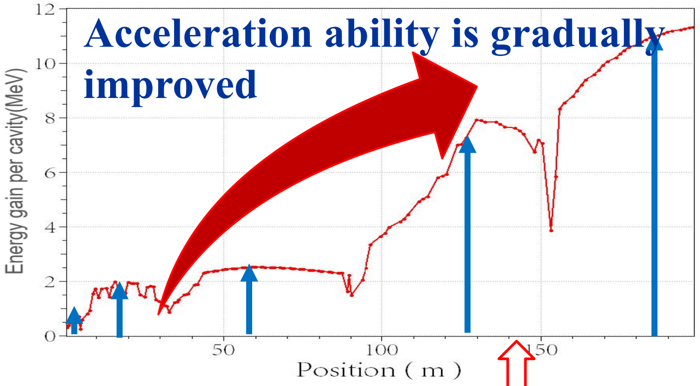
- **After scanning uniformity: PCD＜35 μA/cm²**

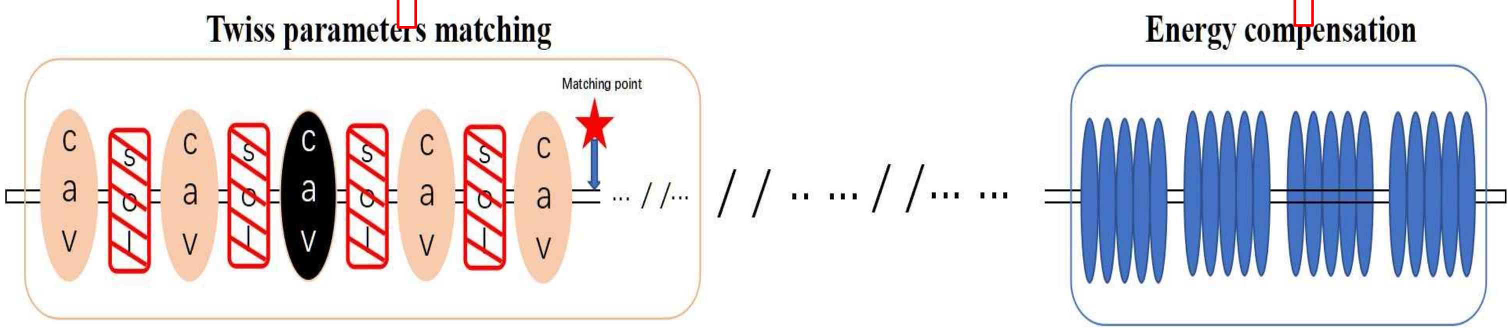
Fault recovery scheme

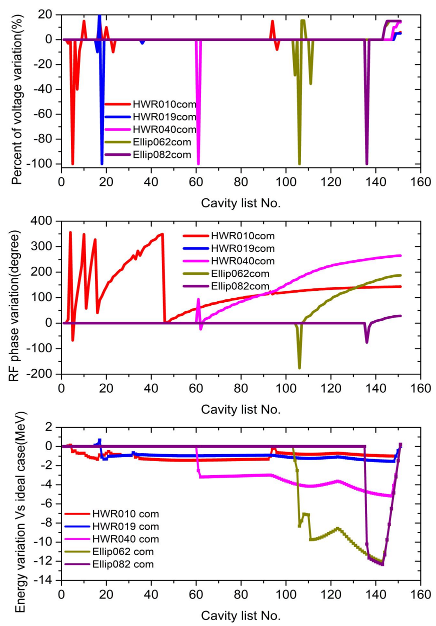
Besam Rematch to avoid beam loss at the location where the failure occurred by adjusting the neighboring cavities and magnets of the failure cavity

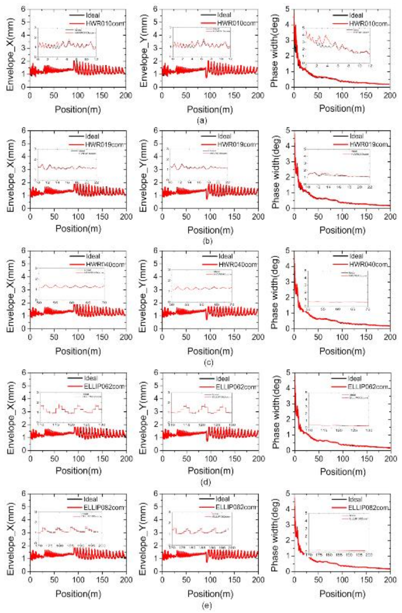
Energy compensation by cavities in the higher energy part because of the larger acceleration capability of the high beta cavity

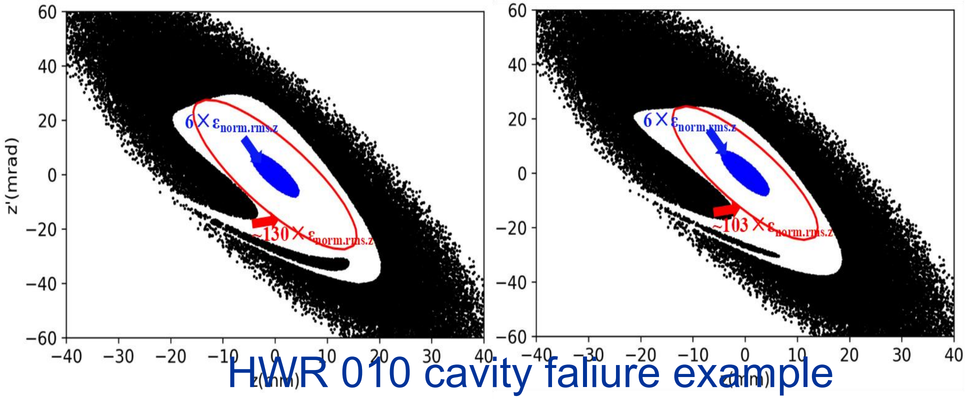












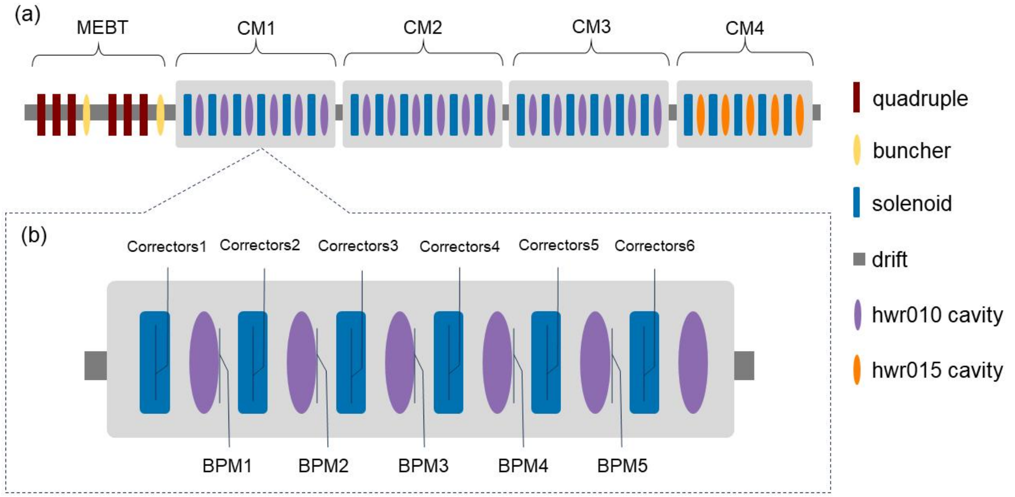
HWR 010 cavity faliure example

hybrid compensation scheme: large longitudinal acceletance, applied at low energy

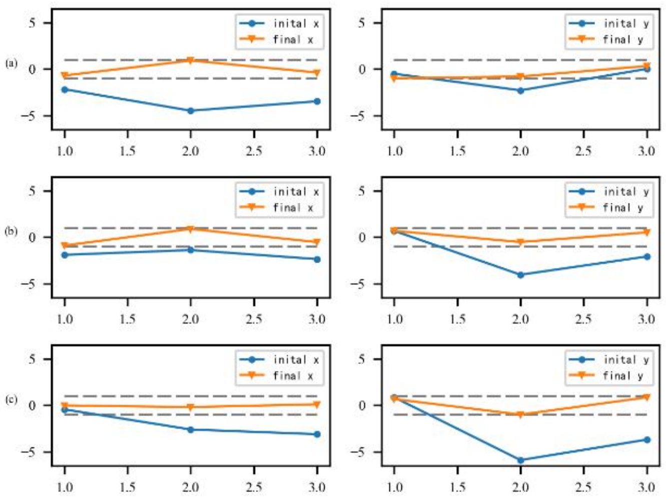
Beam tuning with ML

First task with AI:

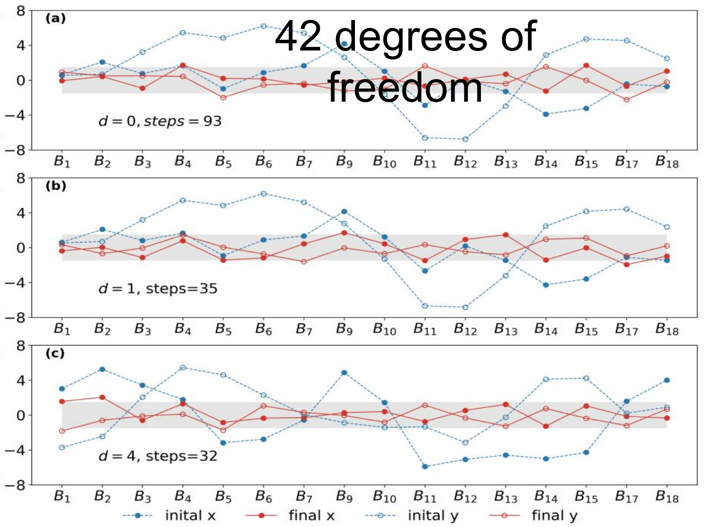
- Orbit correction in MEBT section with reinforcement learning (RL). --- linear
- Orbit correction in superconducting section with RL. --- non-linear



Structure of the SC in CAFe II



Orbit correction in the MEBT



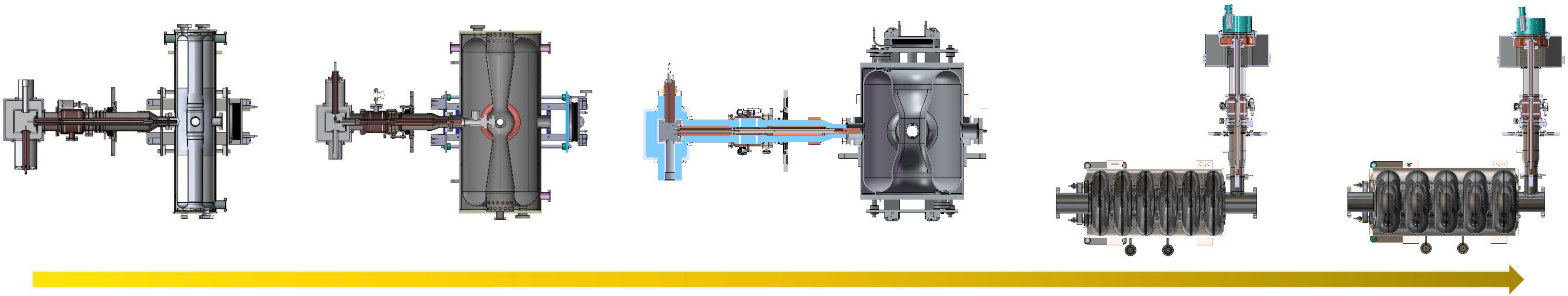
Orbit correction in the SC

Results:

- ✓ **Seamless transition from simulation to reality**, adaptable to various mass-to-charge ratios and lattice configurations.
- ✓ **Regularly used in CAFe II's commissioning process**, reducing tuning time to 3 minutes—1/10 of the time required for manual tuning.
- ✓ **Simultaneously controls 42 magnets** to optimize 36 BPMs along the beamline.

More tuning task is under developed based on ML for CiADS linac tuning

High stability of SRF cavities

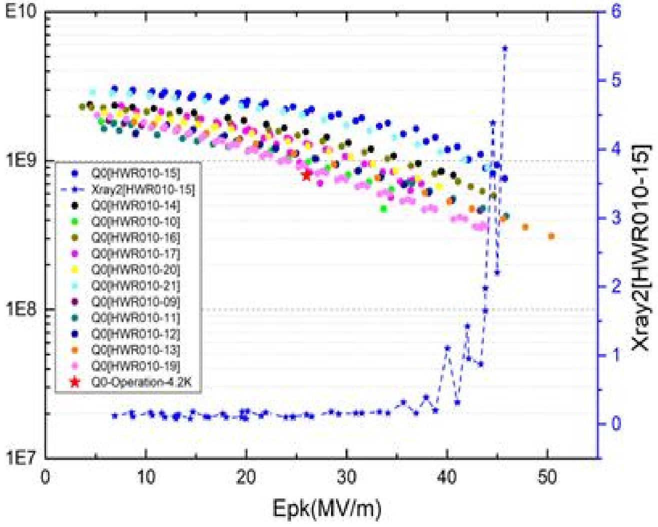


- Total 151 superconducting cavities with five cavity types for the CiADS linac
  - HWR010(9)/HWR019(24)/HWR040(60) & Elliptical062(30)/Elliptical082(28)
  - Similar power coupler and tuner used to decrease the development of prototype time
- The baseline Bulk niobium cavities show promising result
  - Prototype meets the requirement of operation at 2K
- Cu/Nb Composite Cavity (Thin bulk niobium cavity backed up by copper/Aluminum shell) as an alternative choice for 4.2K operation
  - Thermal stability: Thermal breakdown due to defects, field emission and multipacting electrons etc
  - Mechanical stability: Helium pressure fluctuation detuning(df/dp), Lorentz force detuning(LFD) , environmental vibration etc

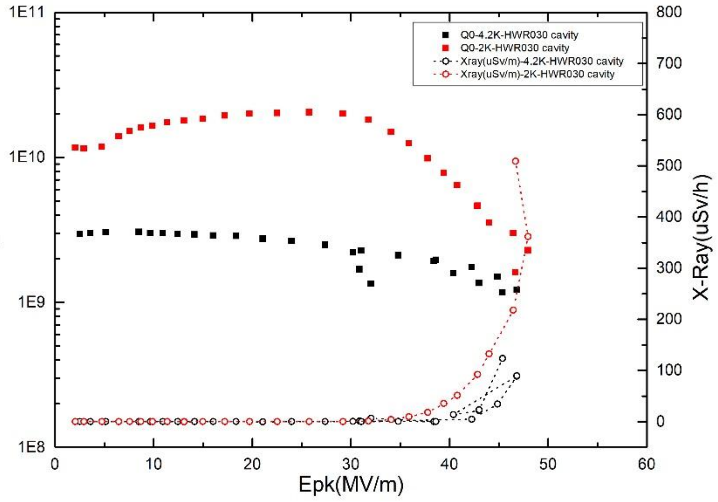
Bulk Niobium SC Cavities

- **Bulk niobium cavities have entered batch manufacturing stage**

1) All the HWR010 cavities has been fabricated， ready for hotizontal testing in CM
2) The HWR019 cavity is in mass production
3) The prototype of 325MHz HWR shows the vertical testing result achieving the nominal specification
4) The elliptical prototype has been manufactured, prepared for VT



HWR010 test result at 4.2K



Prototype of medium beta HWR 040 and test result

Prototype of elliptical cavity

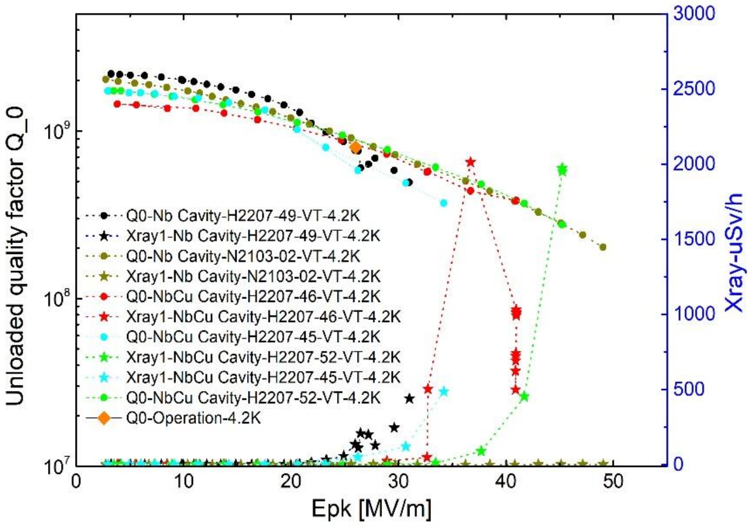
Nb/Cu Composite SC Cavities

- **Preliminary cryogenic results indicate mechanical stability**

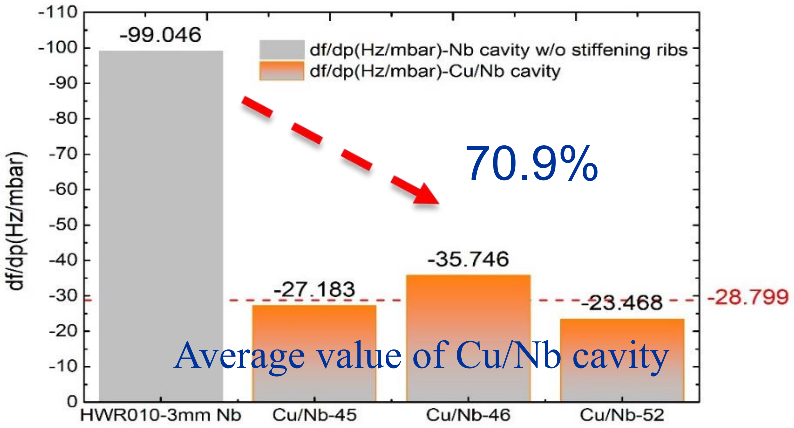
1) Cu/Nb structure: 1mm Nb+5 mm Cu ;
2) Surface treatment: 30 μm BCP, 380℃/2.5 hours heat treatment for stress relief of copper, 30 μm BCP, HPR, 120 ℃ /48 hours in clean room;
3) Slow cooling at T_c crossing of niobium adopted, ambient magnetic field < 10 mG;
4) Q_0 vs. E_{pk} at 4.2K meets the operation requirement;
5) Df/dp improved by 70.9% ;
6) LFD coeff. improved by 76.8%.

HWR010 Cu/Nb cavity on vertical test stand

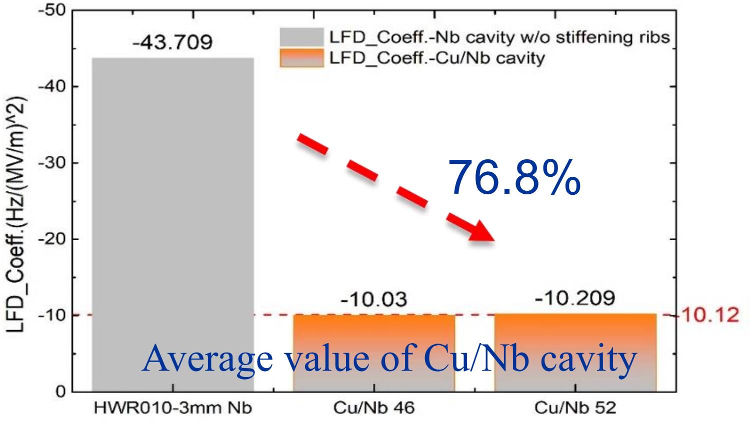
The assembled HWR040 CuNb cavity in clean room



Q_0 vs. E_{pk} at 4.2 K



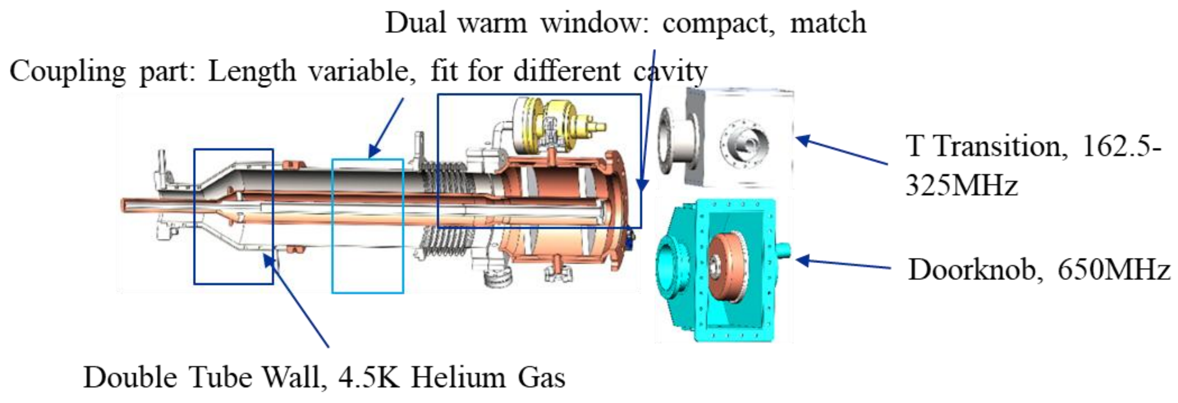
df/dp comparison between Nb cavity w/o stiffening ribs and Cu/Nb cavity



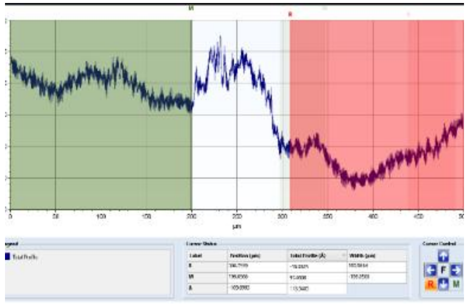
LFD coeff. Comparison between Nb cavity w/o stiffening ribs and Cu/Nb cavity

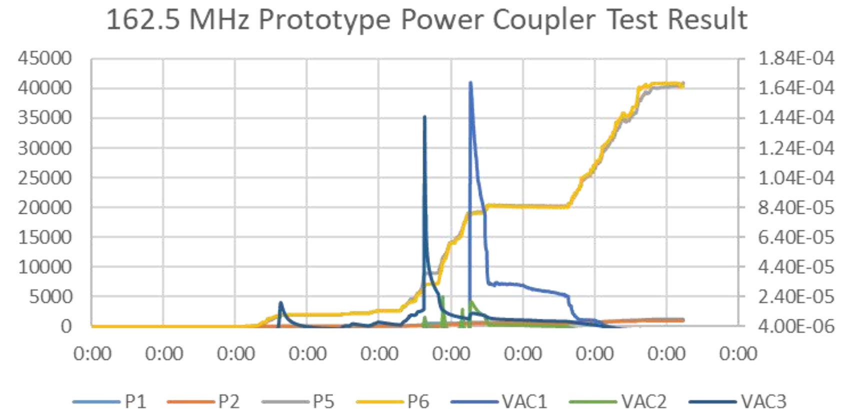
Power Coupler

- Various types of resonator， Wide frequency range
- High reliability requirement



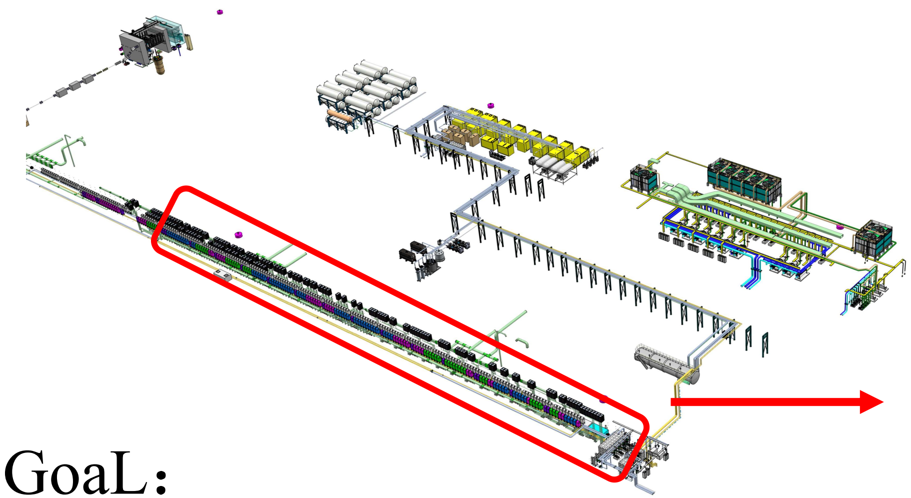
- **The same dual-warm-window and double Tube wall**
- **Coupling part and outer conductor part are adjusted for different cavity**





- **Dual warm window coupler**
  - meets the requirement, > 40kW CW @ standing wave mode
  - Two families of coupler manufactured, good reproducibility

High power RF system



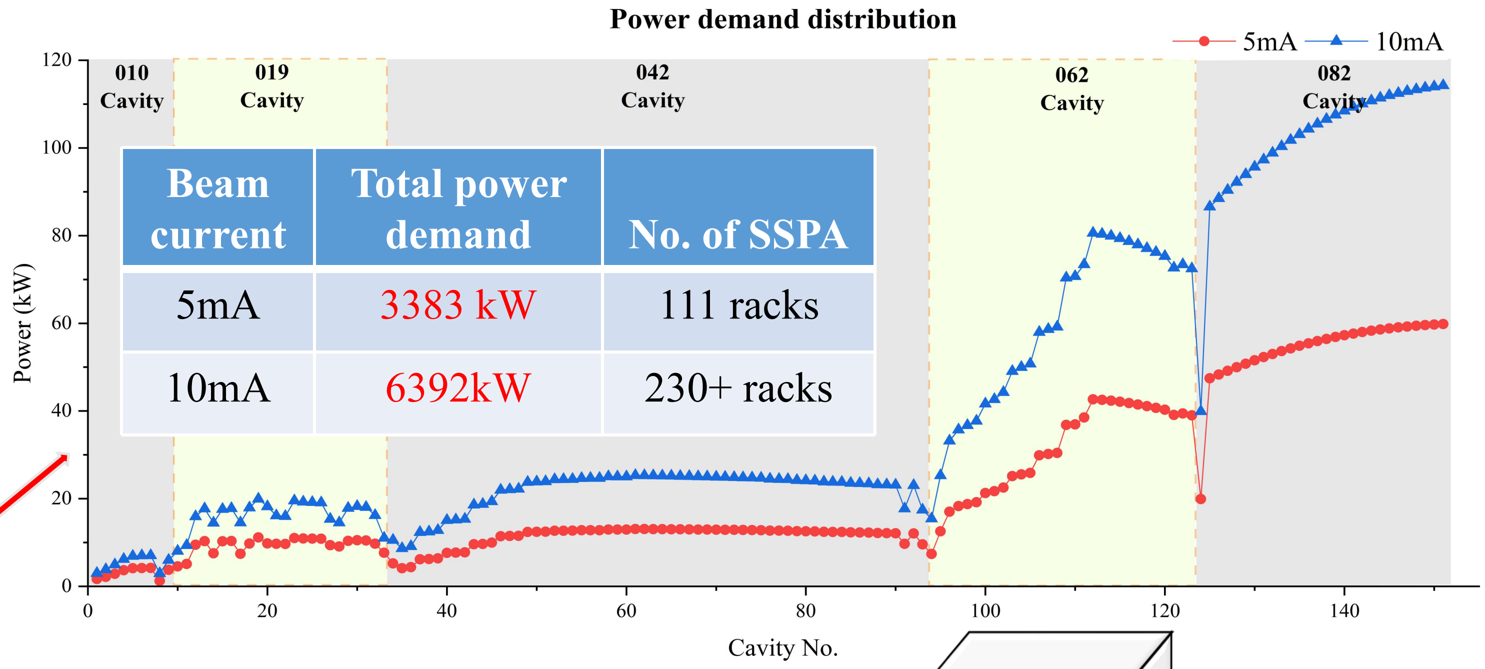
SSPA Layout Diagram

GoaL：

High utility of beam/RF power

High stability of complex RF system

High efficiency of amplifier



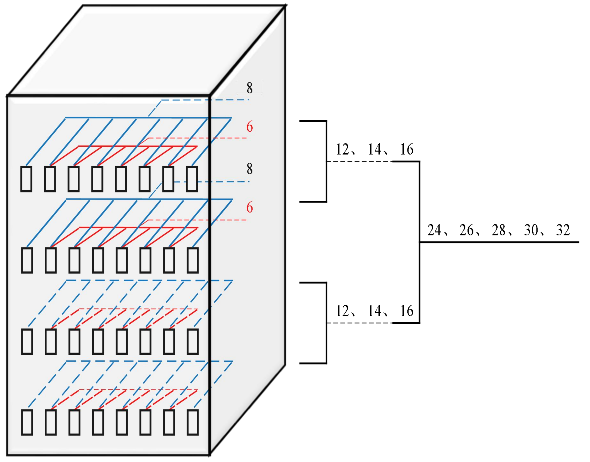
Beam current	Total power demand	No. of SSPA
5mA	3383 kW	111 racks
10mA	6392kW	230+ racks

Design of Flexible Output for Optimal $P_{beam}/P_{amplifier}$

Output Mode	1	2	3	4	5	6	7	8	9	10
RF output	6	8	6+6	6+8	8+8	6+6+6+6	6+6+8+8	6+6+6+8	6+8+8+8	8+8+8+8
Power（kW）	6	8	12	14	16	24	28	26	30	32

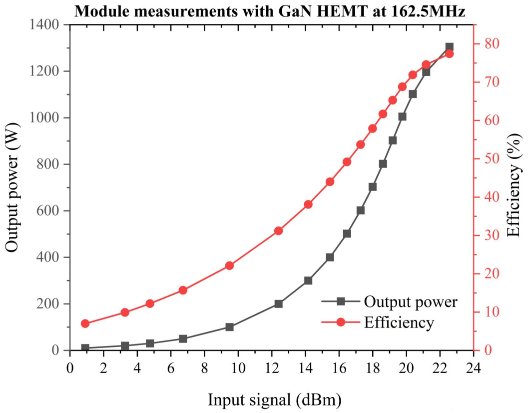
unbalance combiner

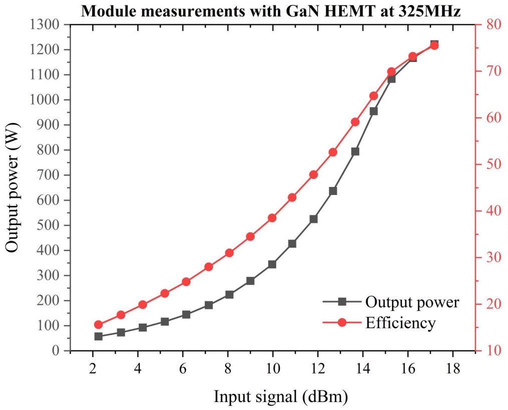
One cavity to four cavities

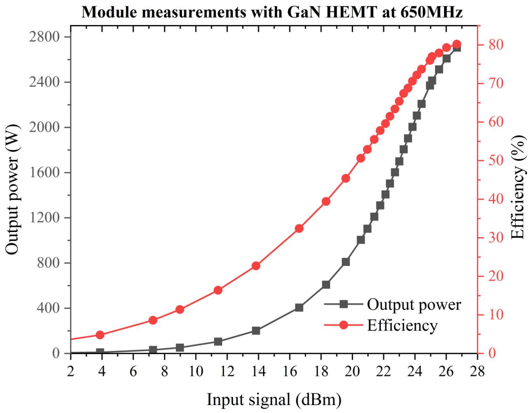


162.5MHz rack output design

High power RF system





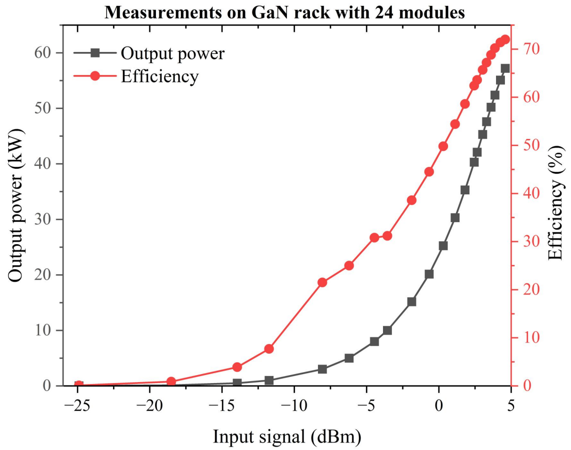


Measurements of P-band GaN module.

Measurements of 60 kW GaN rack with dummy load.

Frequency	LDMOS(with circulator)		GaN(with circulator)	
	power	efficiency	power	efficiency
162.5MHz	1100W	71%	1200W	73%
325MHz	1100W	65%	1200W	74%
650MHz	1800W	60%	2700W	76%

Comparison with LDMOS PA pallet.



Over 15% efficiency promotion of GaN SSPA

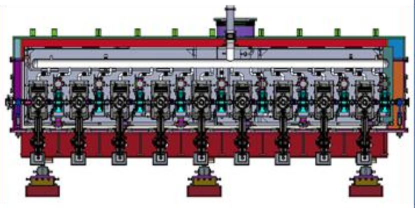
All P-band SSPA based on GaN(Gallium Nitride) have been developed in IMP successfully.

GaN HEMT (High Electron Mobility Transistor) have excellent performance at 650MHz.

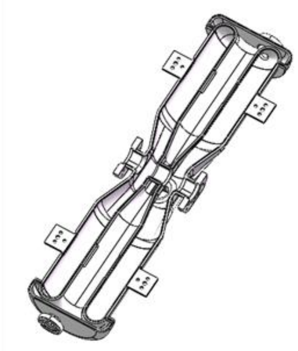
* <Research on the Newest GaN-Based Solid-State Power Amplifier for CiADS Project>， Nucl. Instrum. Methods Phys. Res. A1055, 168403(2023)

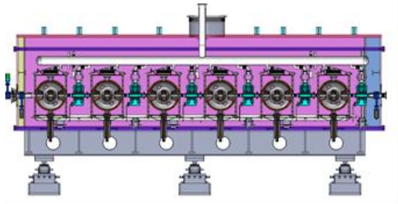
Overview of Cryomodules

- There are 5 families of cryomodule, rectangle for HWR010 and HWR019 and elliptical for others
- bottom-supported scheme
- Cold mass alignment less than±0.5mm

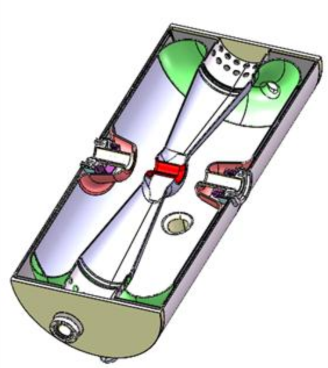


CM010
HWR cavity, beta= 0.10

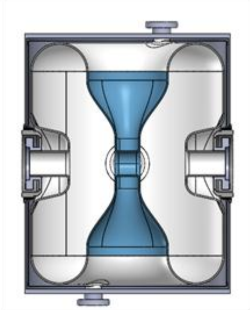


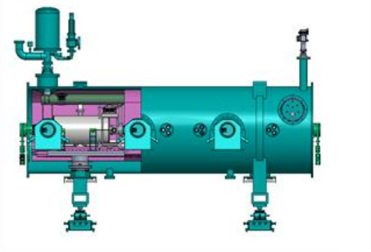


CM019
HWR cavity, beta= 0.19

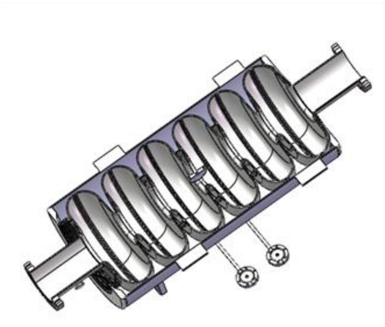


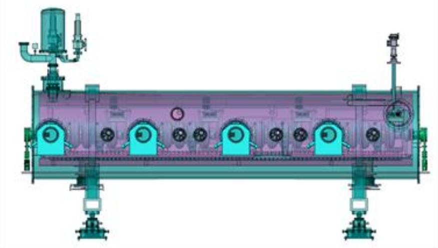
CM040
HWR cavity, beta= 0.40



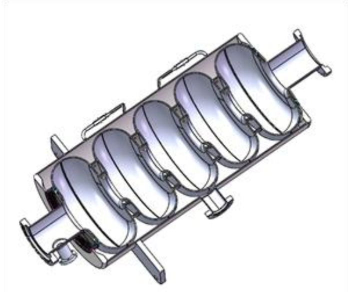


CM062
Elliptical cavity, beta= 0.62



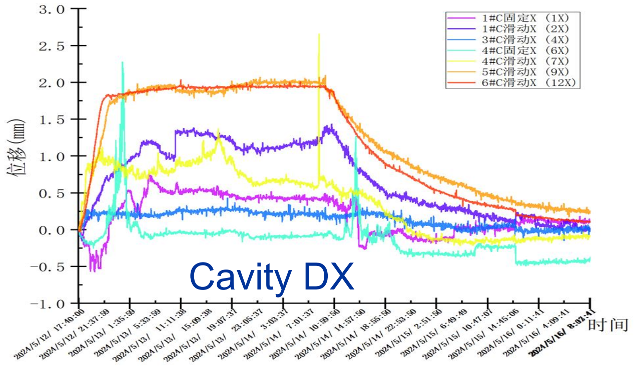


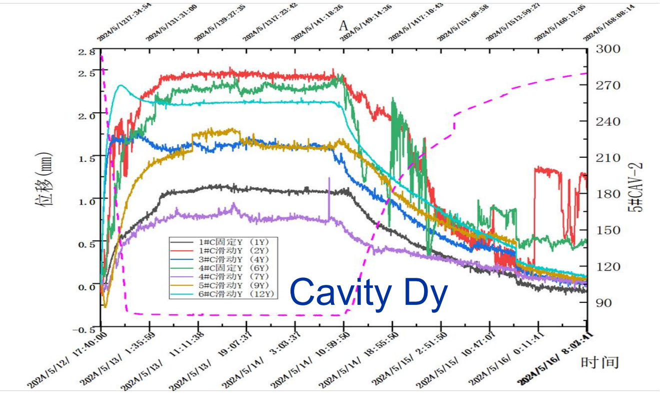
CM082
Ellipticalcavity, beta= 0.82

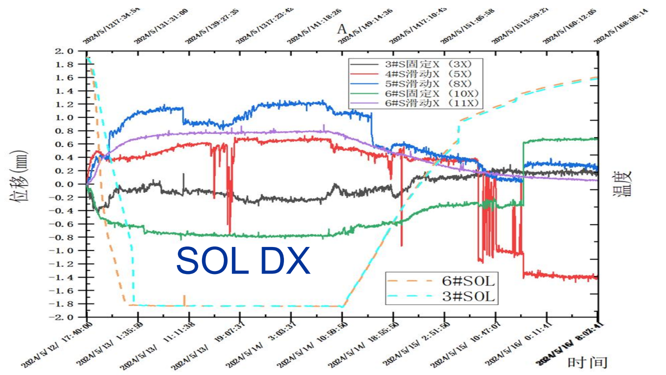


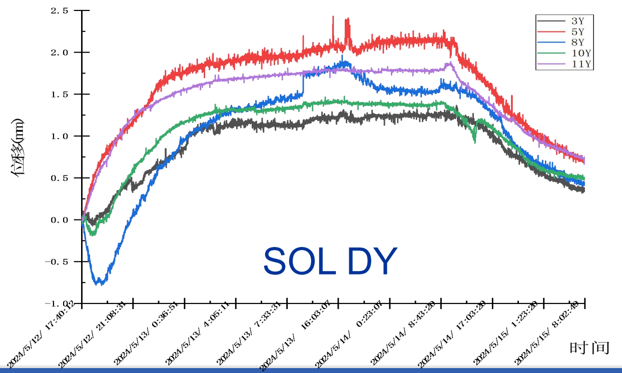
Cryomodules

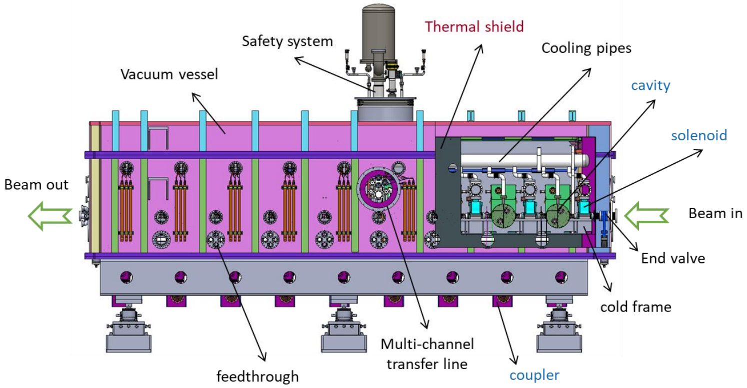
- **HWR Cryomodule used the baseplate support scheme,**
- **The uncertainty of cold mass alignment is from manufacture , the vacuum deformation and mainly cold contraction**
- **The cavity and solenoid contraction in LN_2 temperature was monitored by WPM， the cold contraction agrees well with simulation and is consistent after cooling cycle**









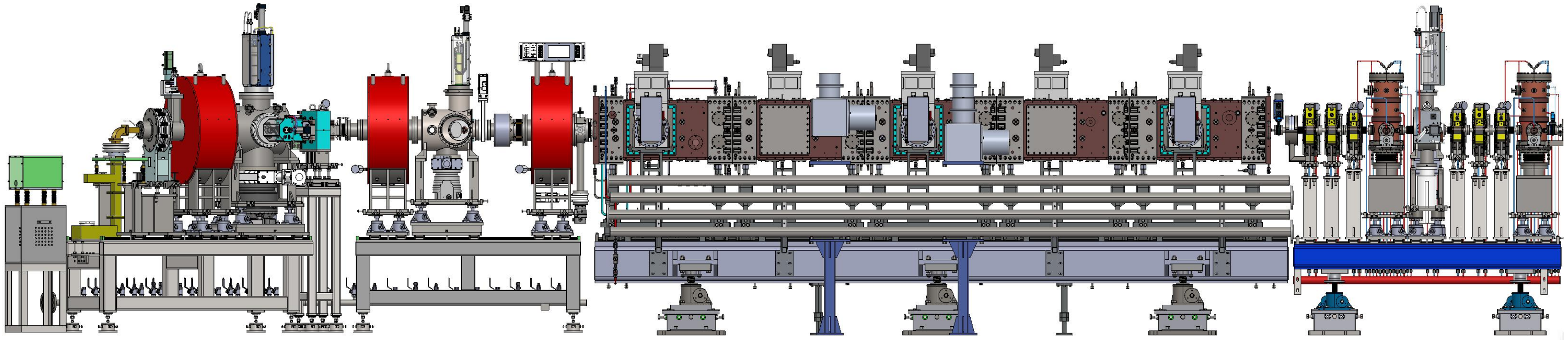


Outline

- Backgroud & Brief introduction of CiADS facility
- Challenges and Progress of CiADS linac
- First beam of normal conducting front-end
- Summary and Perspective

Normal temperature front end setup

NT.front end section layout



Beam parameters

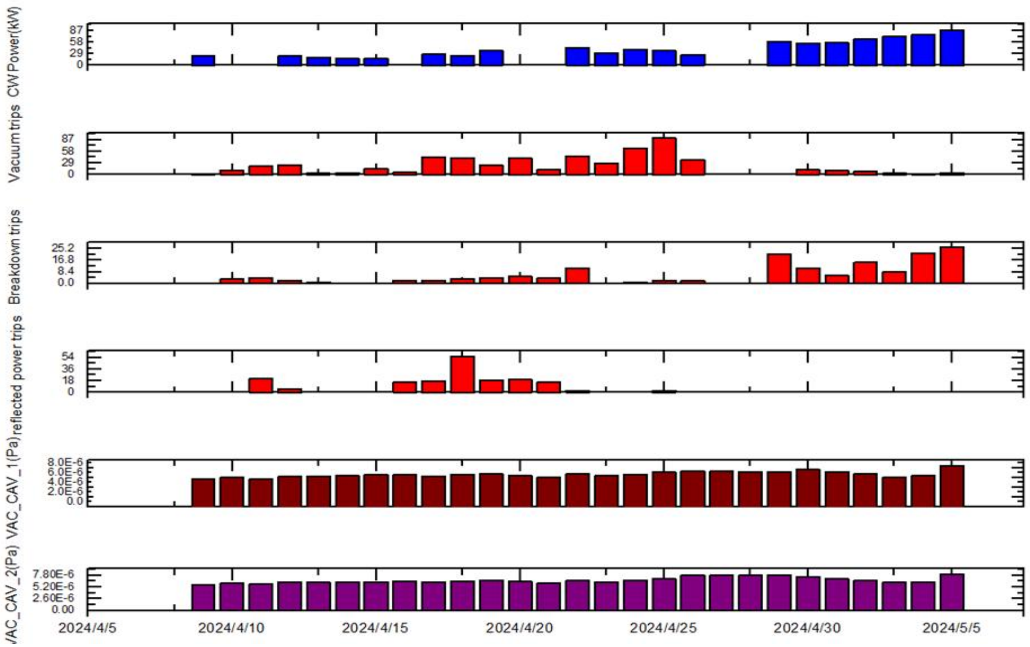
Parameters	data	unit
Particle	H^+	-
Energy	2.1	MeV
Current	5	mA
Frequence	162.5	MHz
Opration mode	Pulse/CW	-

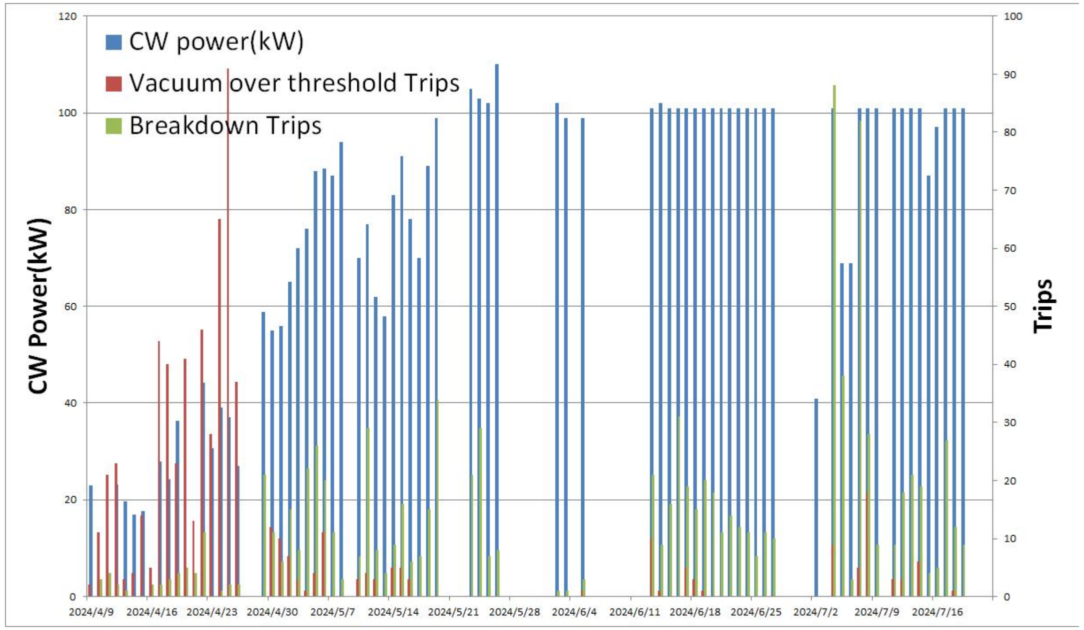
- **Construction during 2022.10-2024.5**
- **Goal: to demonstrate 5 mA beam of front-end Linac for CiADS.**
- **First beam at 2023, test-MEBT update and systematic commissioning at 2024**

RFQ system conditioning

Conditioning scheme

- 20μs-short pulse conditioning MP in power coupler ~8 hours
- Frequency sweep conditioning vacuum burst at pulse and CW power ~127 hours
- RF power ramping to ～100 kW at CW ~182 hours

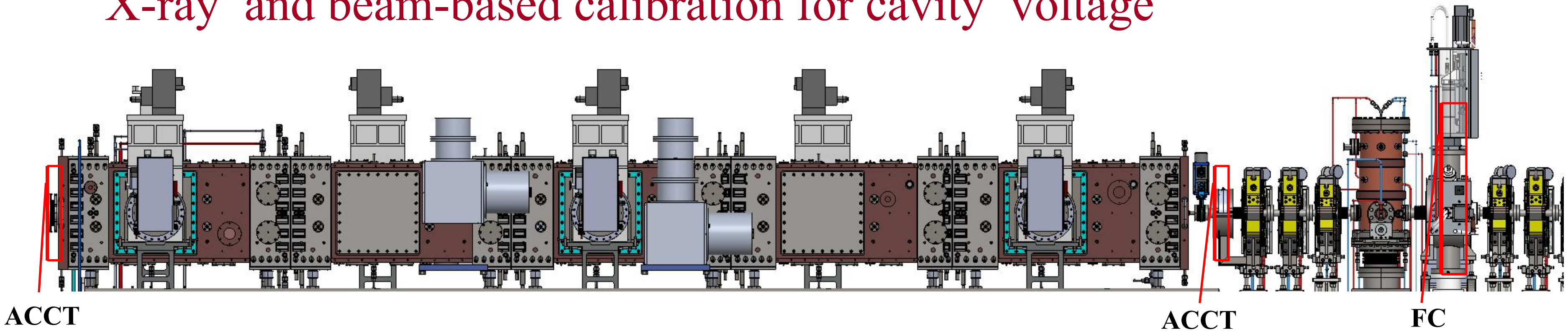


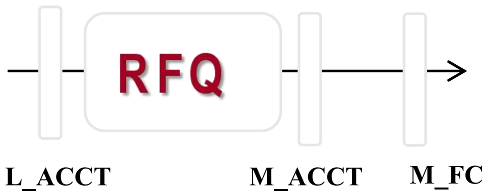


Stable operation 7 days at 101 kW without downtime.
The number of arc trips per day less than 20 and recovery automatically.

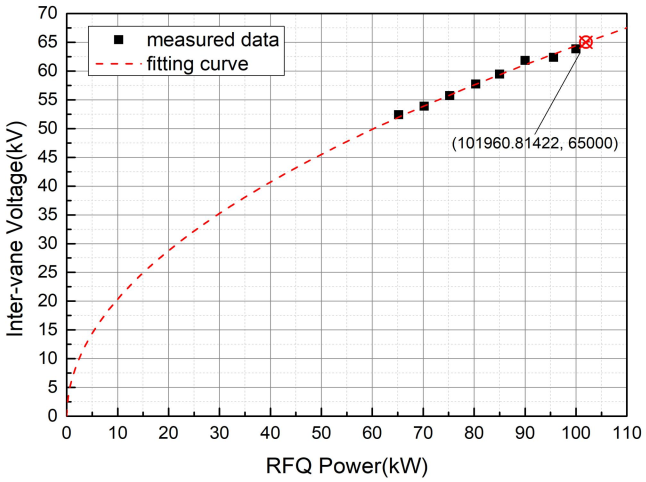
Beam transmission of RFQ

X-ray and beam-based calibration for cavity voltage

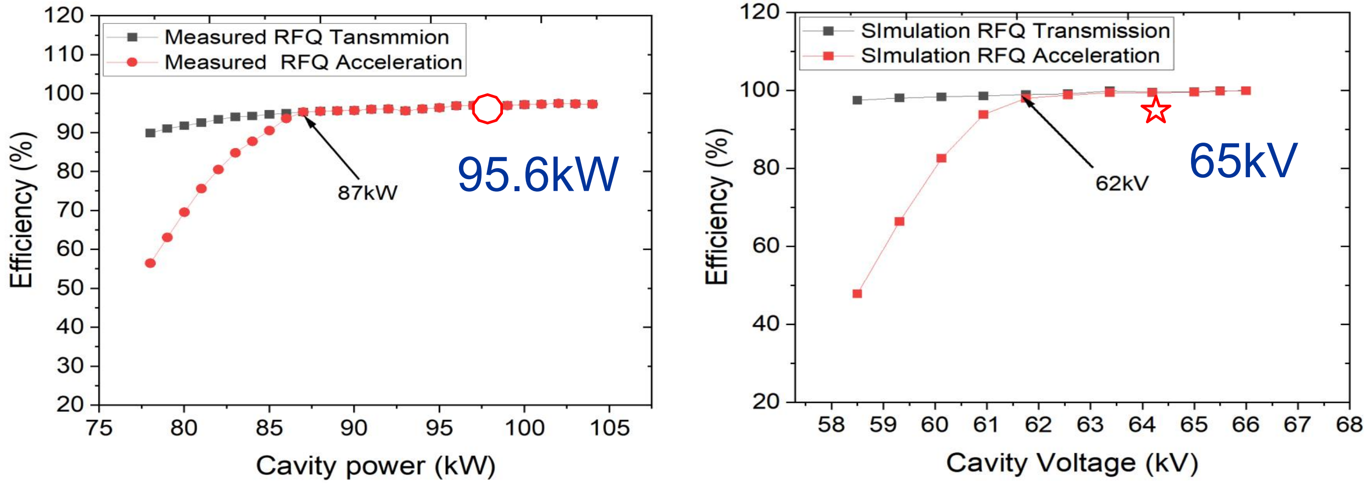




Transmission= M_ACCT / L_ACCT
Acc. efficiency=M_FC / L_ACCT



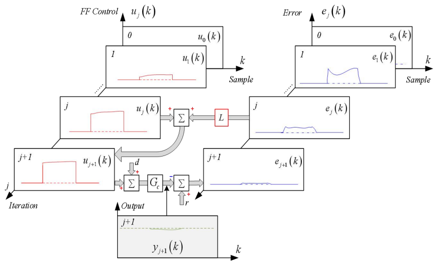
X-ray measurement of inter-vane voltage of RFQ



Measured beam transmission V.S. voltage of RFQ

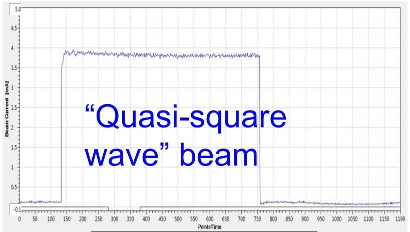
The calibration results of the X ray method and beam transmission are relatively consistent（5%）.
The RFQ design cavity voltage of 65 kV with transmission ~98%.

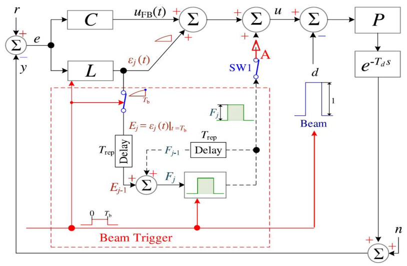
Beam energy measurement



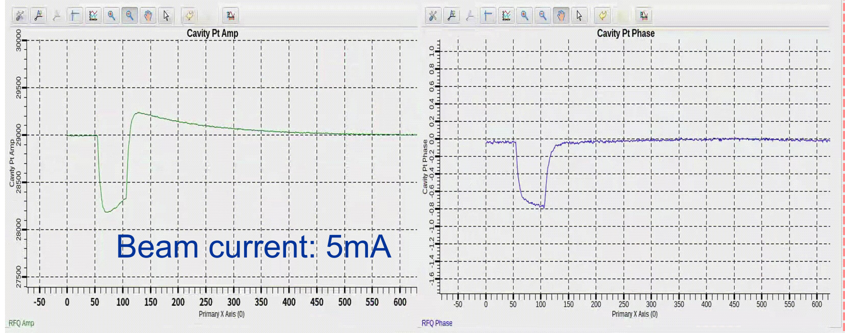
$$u_{j+1}(k) = u_j(k) + Le_j(k)$$

The main ILC algrithm is usually implemented outside FPGA

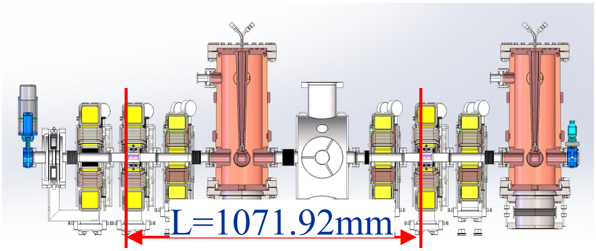


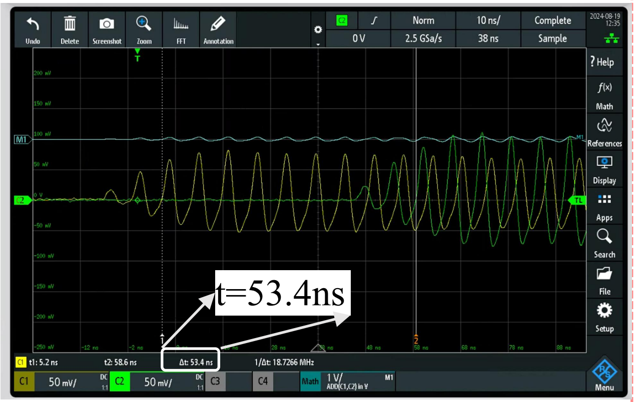


Pulsed-beam is considered as quasi-rectagular, FF could be a rectangular pulse (i.e. constant value)



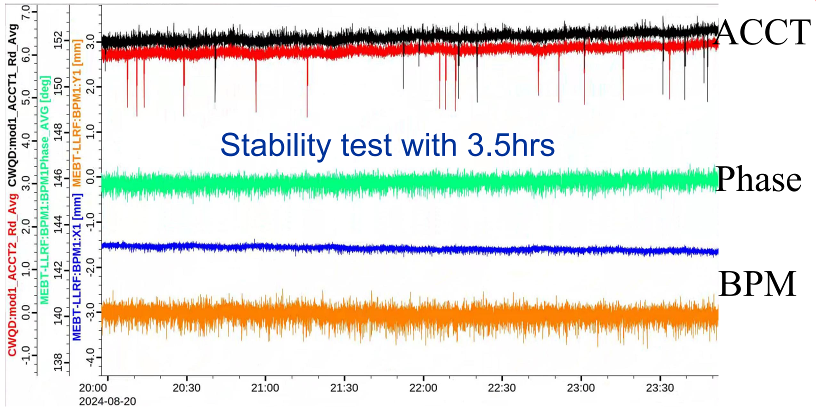
RFQ forward feedback compensation





$$v = \frac{L}{t} \quad \gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} \quad W = (\gamma - 1)E_0$$

W~2.110±0.004MeV, is consistent with the simulated value (2.115MeV)



Mean Data: X~-1.58mm Y~-3.05mm Pha: 145.84deg
Standard Deviation: X~0.044mm Y~0.090mm Pha: 0.166deg

The beam energy out of RFQ cavity is consistent with simulated

the operation stability is monitored by BPM position and phase.

Summary and Perspective

- The CiADS linac is challenging for the high power, CW operation, high reliability
- The key technology has all been demonstrated and project is progressing well
- First beam exacted from normal conducting front-end and CW beam will be accelerated soon.

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Thanks for your attention！