IMCC2023，18-23 June 2023

Proton Facilities and Muon Plans in China

The Prospect with Superconducting Linac for High-intensity Muon Beams

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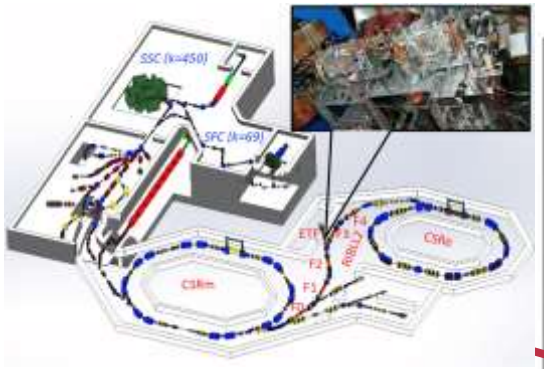
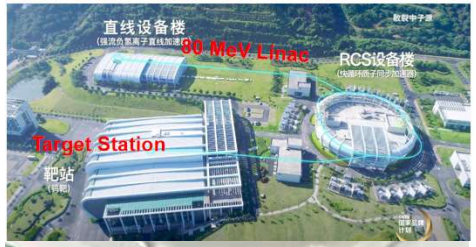
Heavy Ion and Proton Facilities in China



HIRFL/
CAFE



CSNS

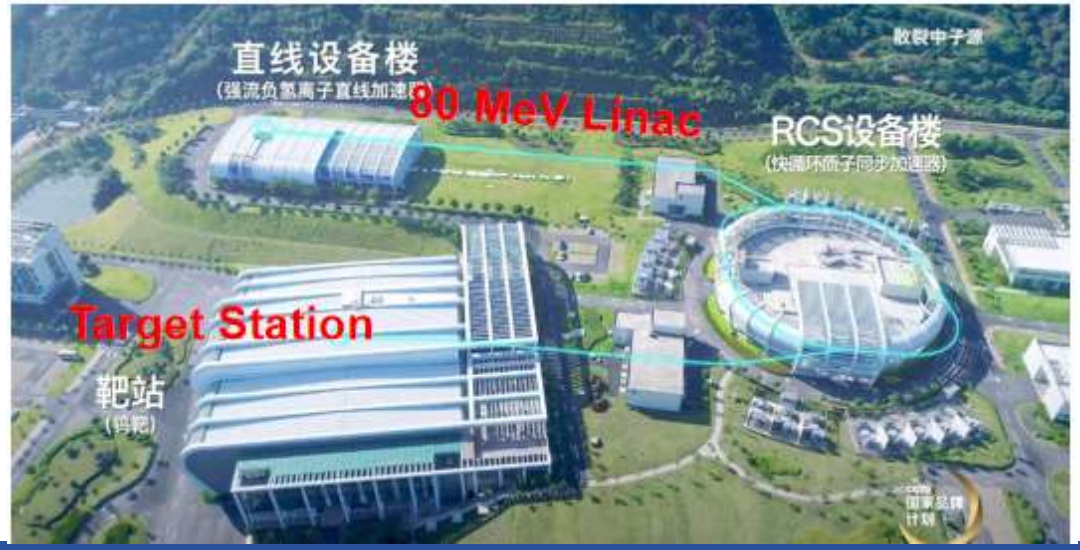
CiADS & HIAF

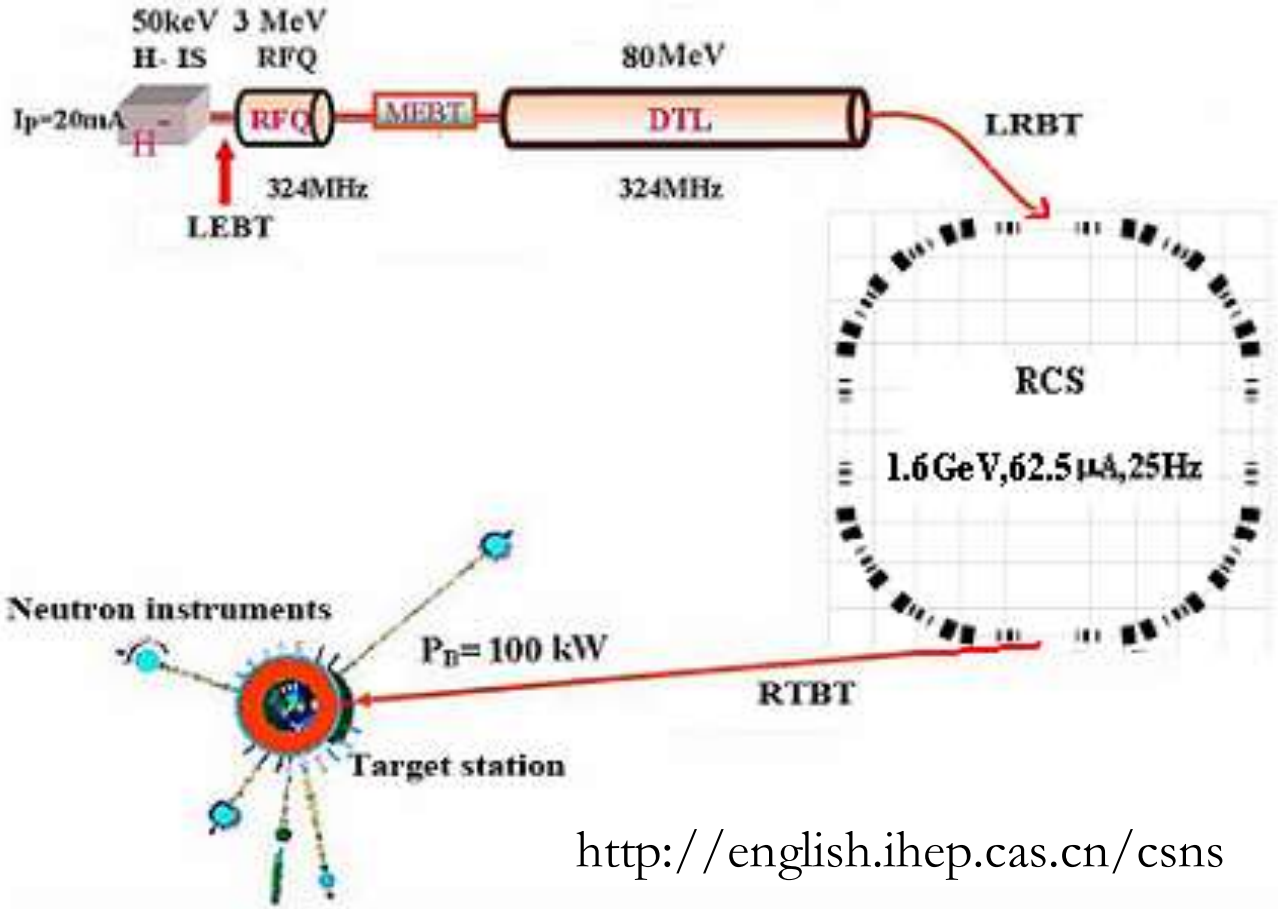
Outlines

- High-intensity Proton Facilities in China
  - CSNS and Project for Muon
  - HIAF and Plan for Muon
  - CiADS and Plan for Muon
- Superconducting Linac demonstration for ADS

Status of CSNS

- **Location：Dongguan City, Guangdong Prov.**
- **CSNS I: Sep. 2011~Mar. 2018**
- **80 MeV Linac + 1.6 GeV RCS**
- **100 kW @ 62.5 μA, 25 Hz**



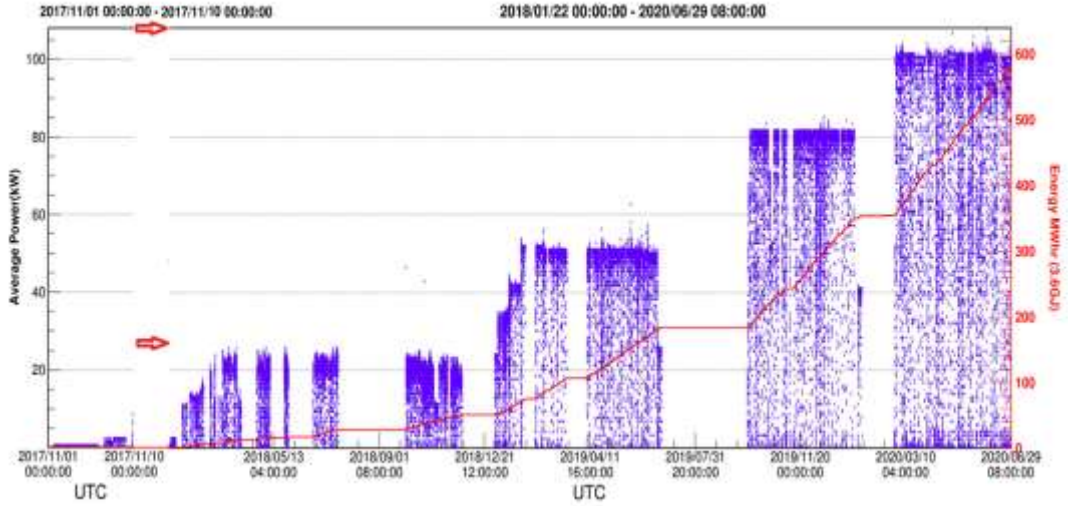


http://english.ihep.cas.cn/csns

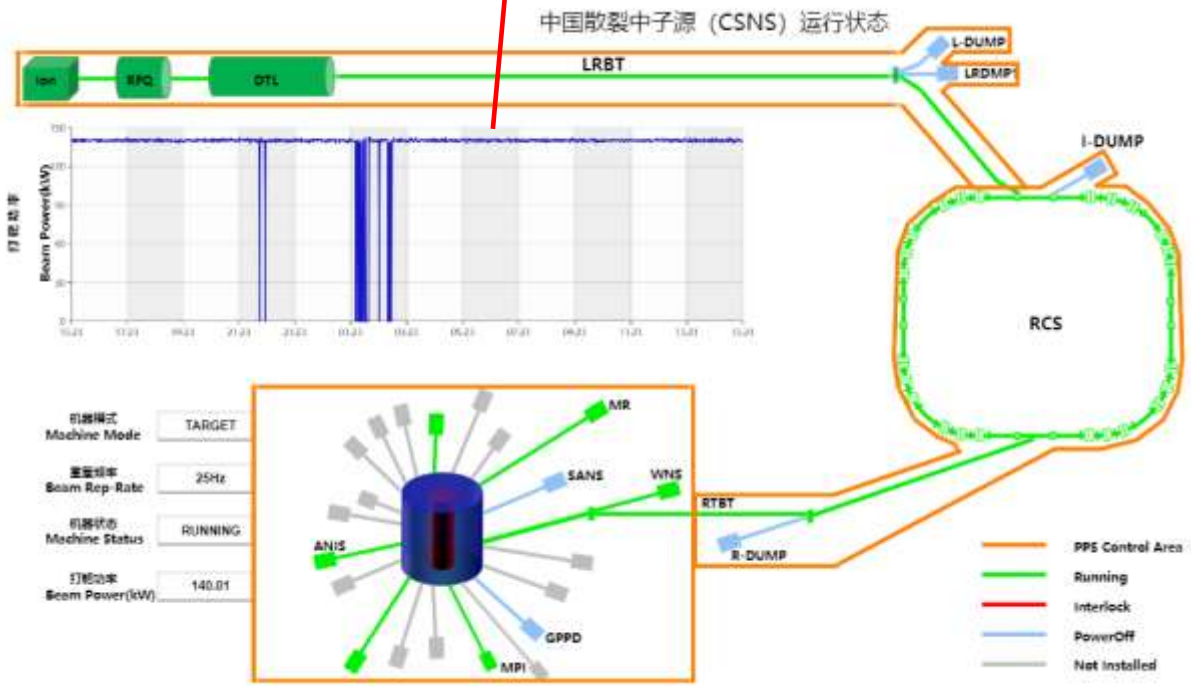
Status of CSNS

- **Beam commissioning started since May 2017.**
- **A series of beam loss optimization work to reduce the uncontrolled beam loss.**
- **Reached the design beam power of 100-kW at the end of February 2020.**

24-hrs. -operation history online: operates at 140-kW stably (June 17, 2023 ~ June 18, 2023)



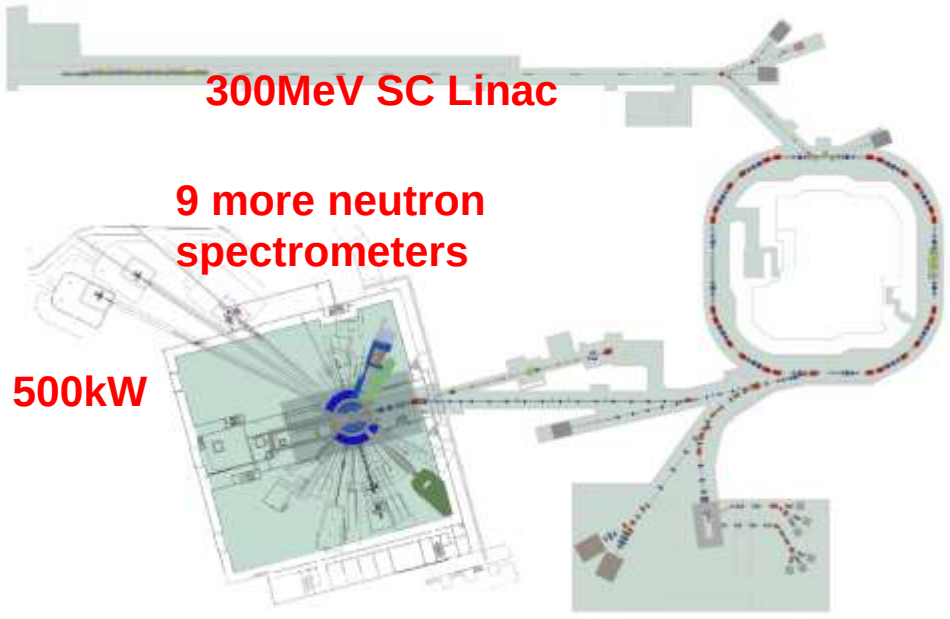
Beam power ramp-up history of CSNS/RCS, where the blue bars correspond to the beam power, while the red line shows the accumulated beam power. Xu S Y, Liu H, Chen J, et al. Achievement of 100-kW beam operation in CSNS/RCS[C]//12th Int. Particle Acc. Conf. 2021: 1869-1871.



https://user.csns.ihep.ac.cn/operating

Status of CSNS II

Parameters	CSNS I	CSNS II
beam power (kW)	100	500
pulse frequency (Hz)	25	25
target number	1	1
averaged current (μA)	62.5	312
beam energy(GeV)	1.6	1.6
RCS injection energy(MeV)	80	300
number of spectrometer	3	20

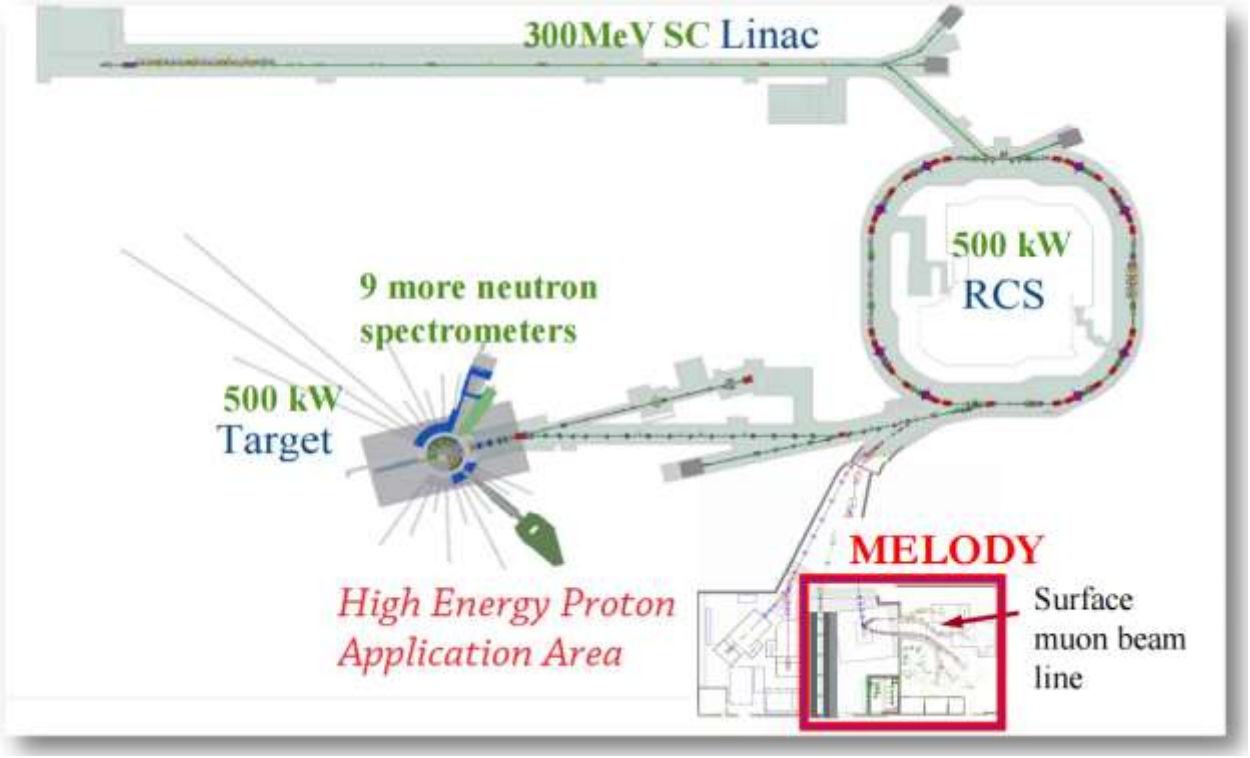


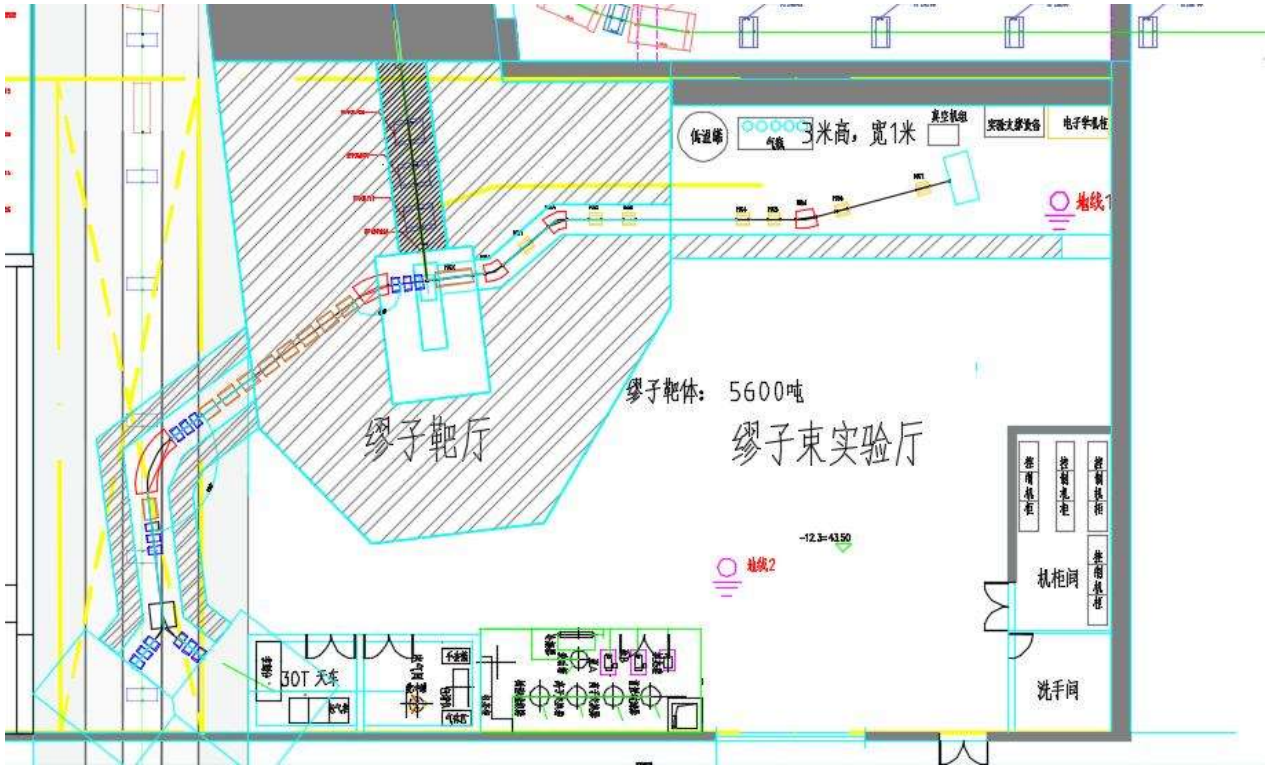
- Linac: 80 MeV to 300 MeV SC
- RCS Beam Power: 100 kW to 500 kW
- Spectrometers: 3 to 20
- Review of the Linac Design has been performed on March 22, 2021.
- Project has been approved on Jan. 11, 2023.

Muon Source Project at CSNS

- MELODY Project @ CSNS II (Muon station for science technology and industry)
  - Protons: 1.6 GeV, 1 Hz (up to 5Hz), 130ns double pulses
  - Muon beamlines: one surface muon and one decay muon beam
  - Spectrometers: 1 μSR spectrometer and more…

Courtesy Bao, Yu

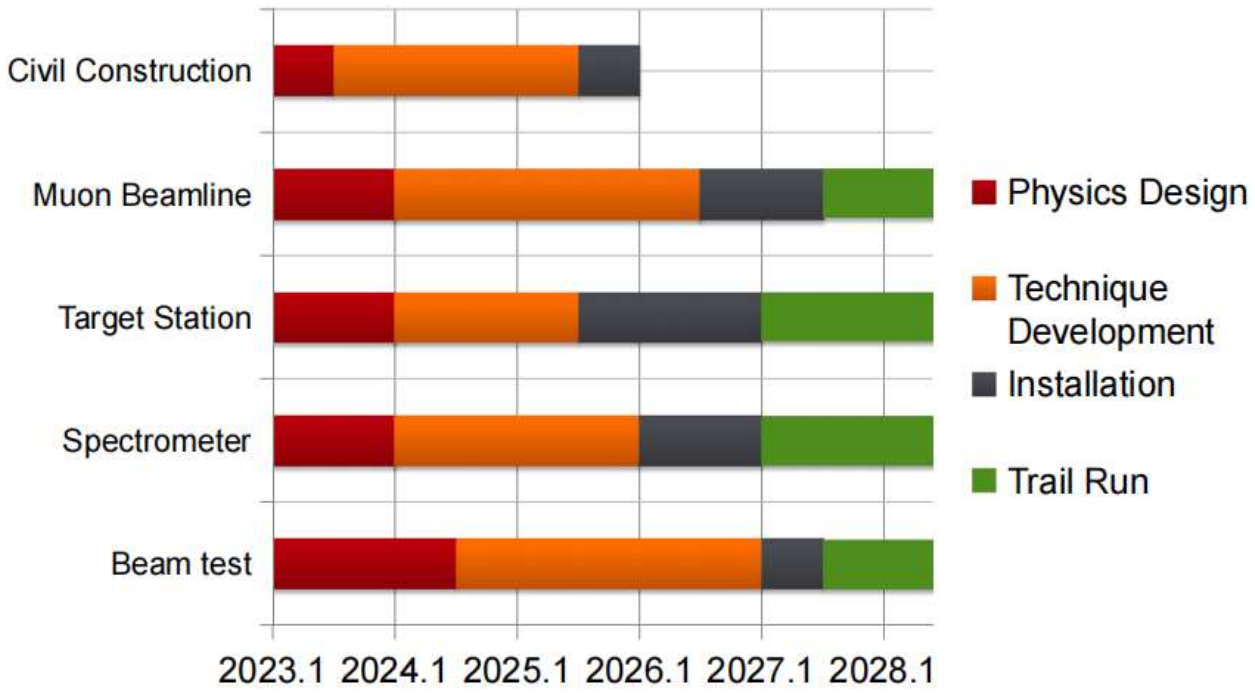




Muon Source Project at CSNS

- Feasibility Study has been approved by National Development and Reform Commission
- First Geosurvey has been carried out at the muon hall

Courtesy Bao, Yu

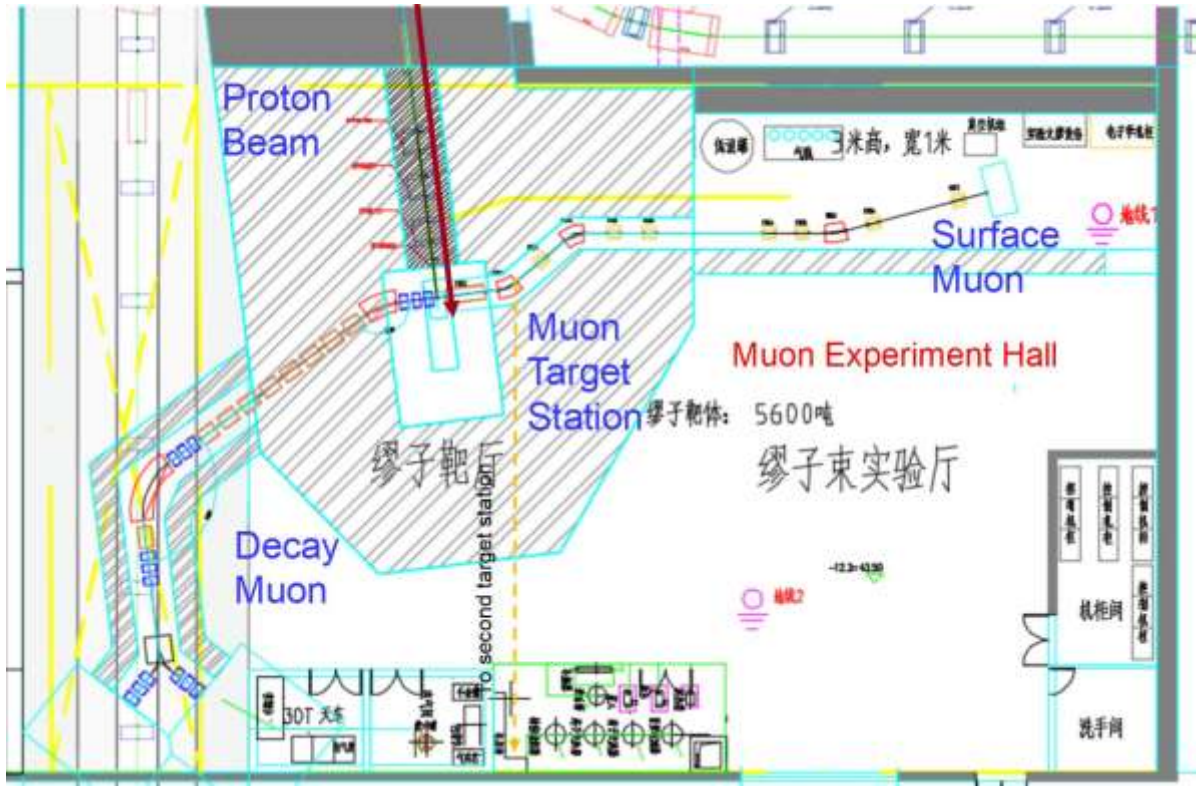


Muon Source Proposals at CSNS

Prospect with MELODY II

Courtesy Bao, Yu

- Pion/Decay muon beam： up to 300MeV, up to 10^7 /s
- Higher repetition rate
- Pulse slicer: Short pulse
- More terminals： various spectrometers, low energy muons, μ^- applications, μ imaging, muonic X-ray, technique development



	MELODY I	MELODY II
Proton Power（kW）	20	Up to 100
Pulse width (ns)	130	down to 10ns
Surface muon intensity（/s）	10^5	$5*10^5$
Polarization（%）	>90	>90
Positron（%）	<1%	<1%
Repetition（Hz）	1	Up to 5
Terminals	1	2-6
Decay muon energy（MeV/c）	NA	Up to 120
Full Beam Spot（mm）	30	30

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HIAF & CiADS

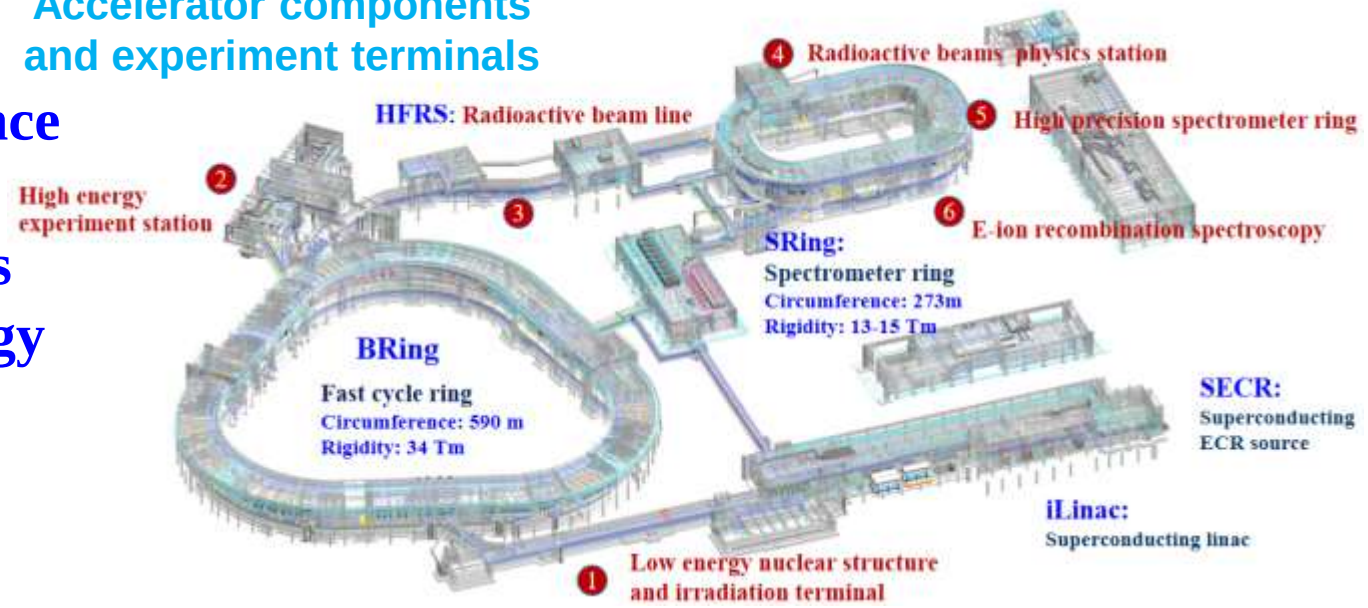
HIAF Project

- To explore the limit of nuclear existence
- To study exotic nuclear structure
- Understand the origin of the elements
- To study the properties of High Energy and Density Matter

……

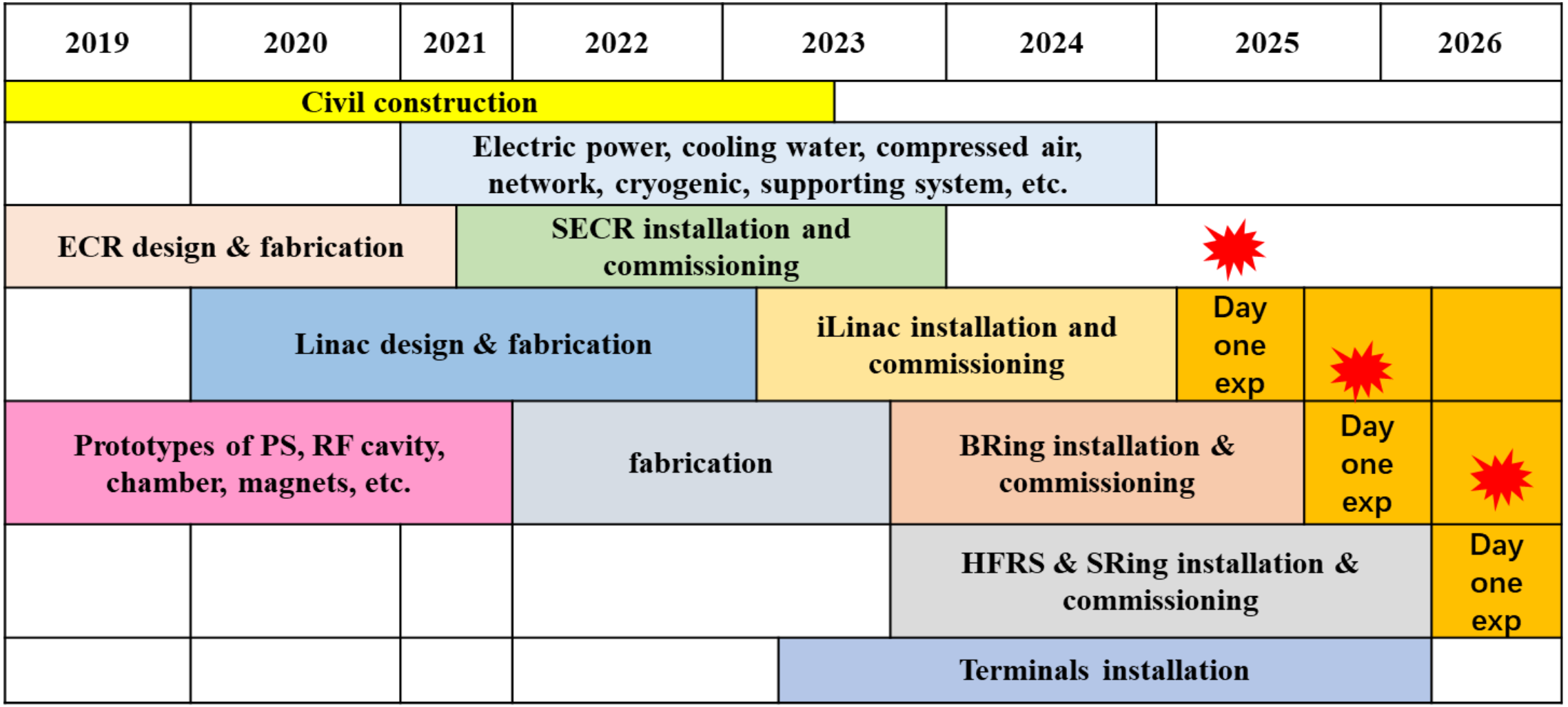
Courtesy Yang, Jiancheng

Accelerator components and experiment terminals



	iLinac	BRing		SRing	
Length / circumference (m)	114	569		277	
Final energy of U (MeV/u)	17 (U^{35+})/150	835 (U^{35+})	9300 (p)	800 (U^{92+})	3500 (p)
Max. magnetic rigidity (Tm)	---	34		15	
Max. beam intensity of U (ppp)	**28 pμA**	**2×10^{11}**	**$(1\text{-}3)\times10^{13}$**	**$(0.5\text{-}1)\times10^{12}$**	**$(1\text{-}3)\times10^{13}$**
Operation mode	CW or pulse	Fast ramping (12T/s, 3Hz)		DC, deceleration	
Emittance or Acceptance (H/V, π·mm·mrad, dp/p)	5 / 5	200/100, 0.5%		40/40, 1.5% (normal mode)	

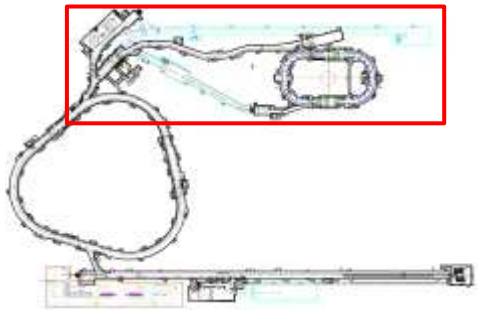
Schedule of HIAF



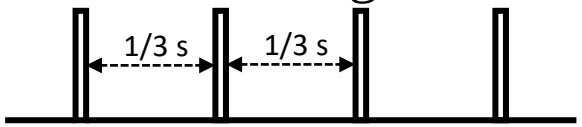
Muon Source plan at HIAF

❑ Muon generation

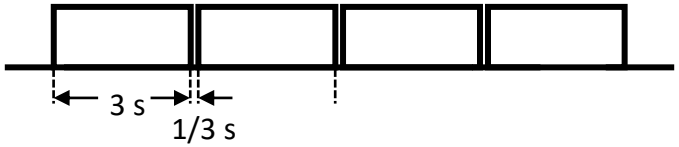
- HIAF can provide high-intensity proton/ion to drive the surface/decay muon source
- The fast/slow extraction mode of BRing can provide pulse/continuous beam for various experimental requirement.



Fast extraction: High-intensity pulsed pion

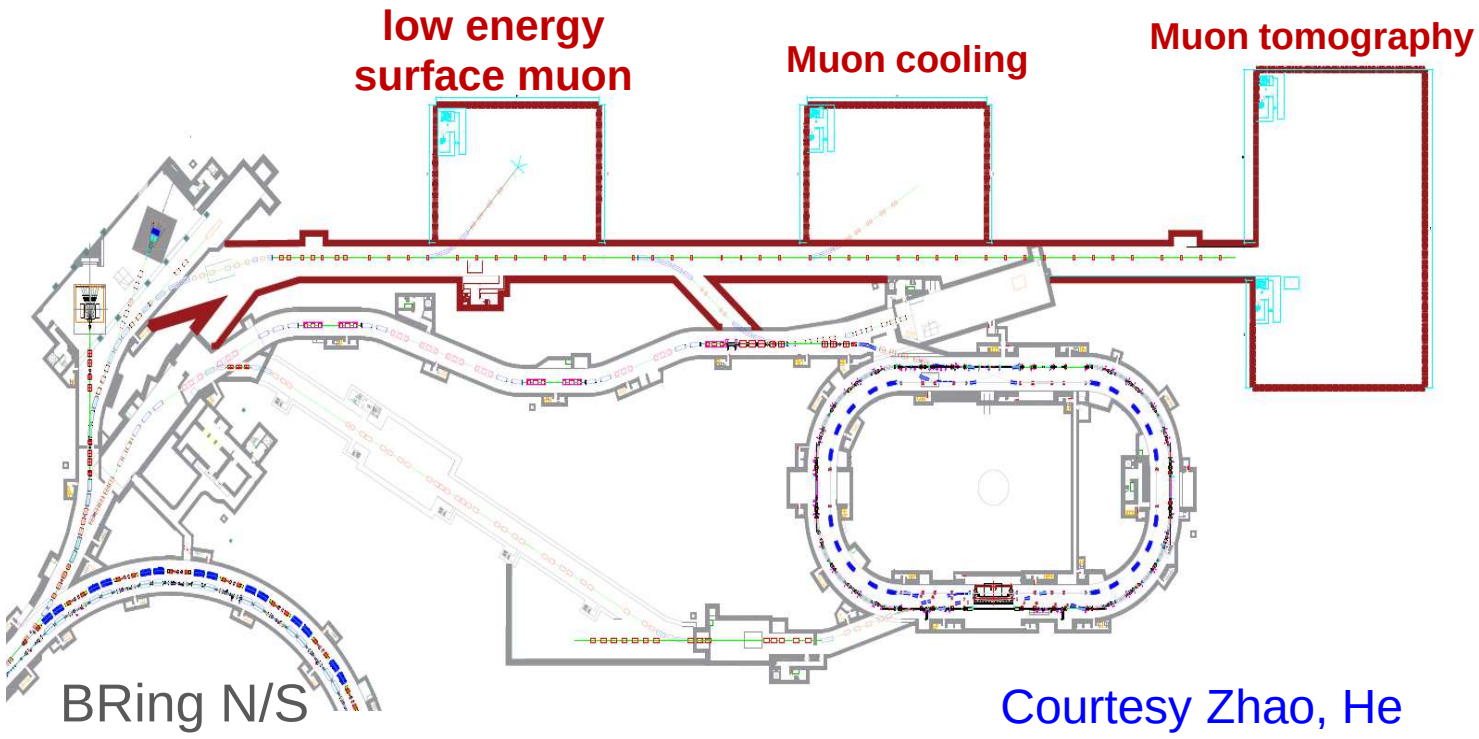


Slow extraction: Quasi-continuous pion



Decay μ: tomography, ionization cooling

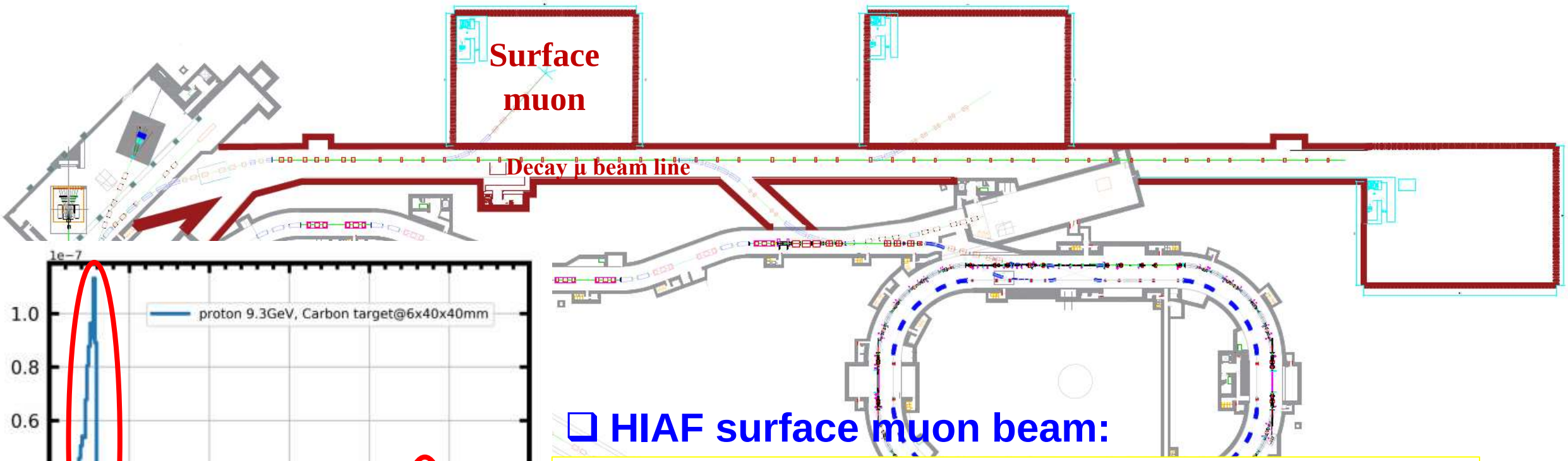
Surface μ : μSR



Courtesy Zhao, He

Muon Source plan at HIAF

Proton 9300MeV, 5×10^{13} ppp, 3 Hz



❑ HIAF surface muon beam:

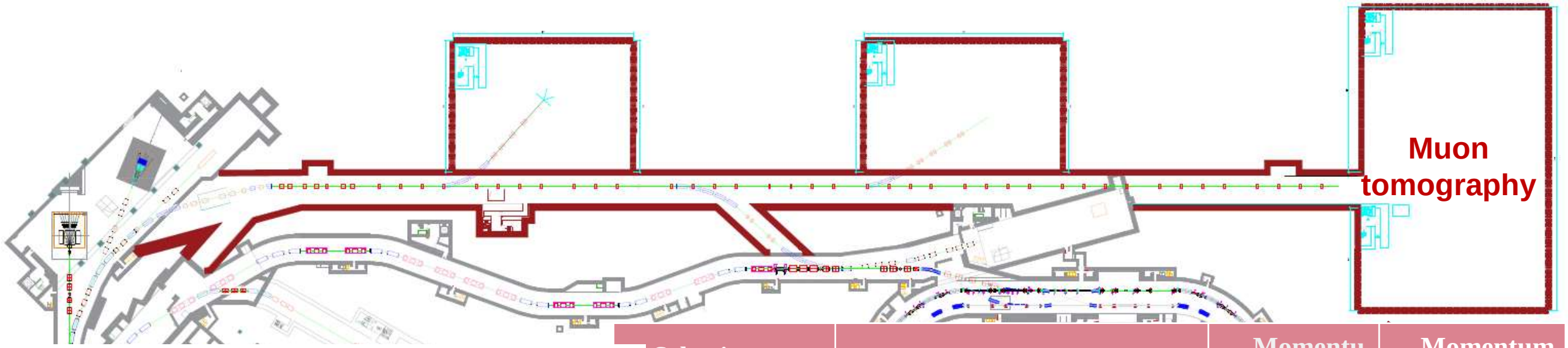
- ~30 MeV/c surface muon (pion DAR), intensity of 1.7×10^{7} μ^{+}/s, pulse width of ~150 ns, 3Hz.
- ~240 MeV/c surface muon (kaon DAR), pulse width of ~100ns.

Courtesy Chen, Liangwen & Zhao, He

Muon Source plan at HIAF

Courtesy Zhao, He

4.26GeV/u $^{36}Ar^{18+}$+ C(22.53g/cm^2) Intensity: 1e+11 ppp



- **High-energy muon beam for muon tomography**
  - Momentum 0.99~3.9 GeV/c
  - Intensity ~ $10^3/(cm^2 \cdot s)$

Selection omentum eV/c)	Muon rate		Momentum	Momentum spread (σ)
	(ppp)	(ppp/cm^2)	GeV/c	MeV/c
1	2.99e+5	9.52e+2	0.99	21.69
2	2.01e+6	6.38e+3	1.96	43.87
3	1.9e+6	6.04e+3	2.90	85.9
4	3.35e+5	1.07e+3	3.90	87.42

Courtesy Chen, Liangwen & Zhao, He

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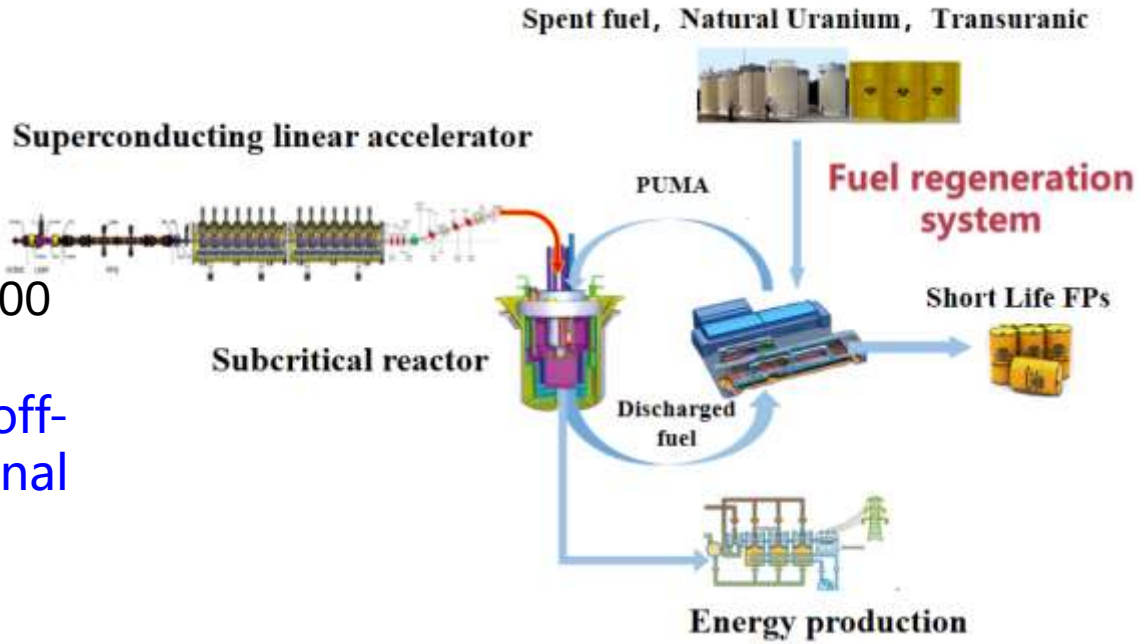
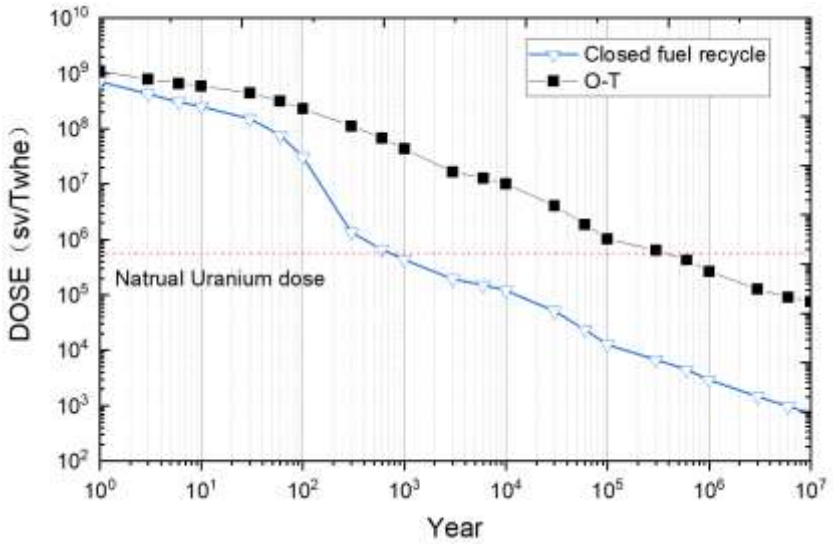
Sustainability of Nuclear Power

- Spent fuel: reusable fuel + fission products (waste), extremely difficult to partition
- ~11,300 tons of spent fuel unloaded annually
- By 2035, spent fuel emissions will be close to 618,000

Until now, all spent fuels are stored on-site or off-site in engineered storage facilities, pending final decisions on its disposition



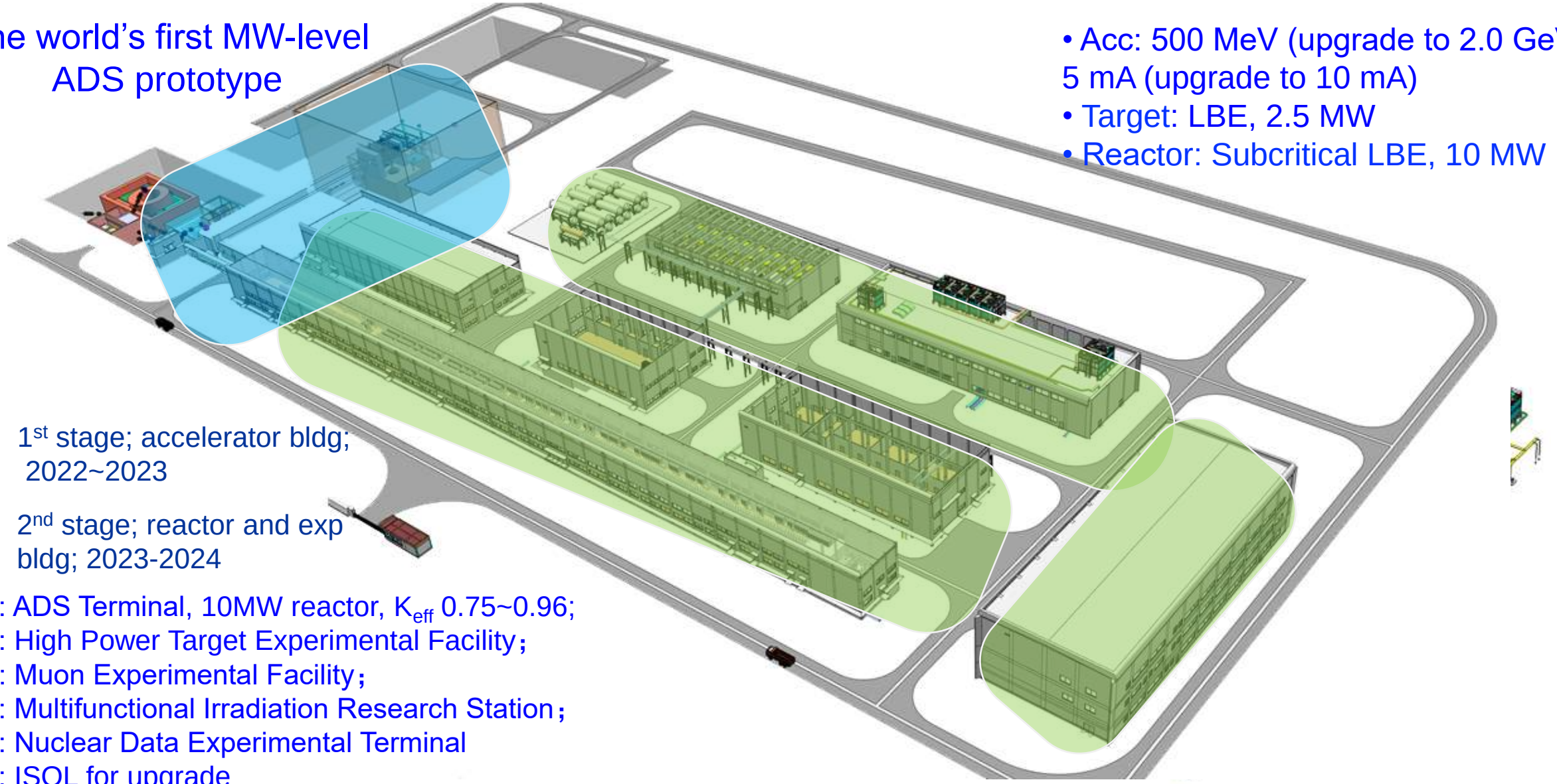


- **Environment-friendly innovative closed fuel cycle**
  - Natural resources preservation
  - Burn the spent fuel storage from current reactors
  - Fully utilize nuclear energy resources > 95%
  - Waste minimization < 400 years

CiADS Project

The world's first MW-level ADS prototype

- Acc: 500 MeV (upgrade to 2.0 GeV), 5 mA (upgrade to 10 mA)
- Target: LBE, 2.5 MW
- Reactor: Subcritical LBE, 10 MW



1st stage; accelerator bldg; 2022~2023

2nd stage; reactor and exp bldg; 2023-2024

- 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

Superconducting Linac

- Parameters of CiADS linac

particle	proton	
Energy	500	MeV
current	5/10	mA
Beam power	2.5	MW
RF freq	162.5/325/650	MHz
Epeak	26/28/29/29/29	MV/m
Num of CM	32	-
Num of cavity	151	-

The overview design consideration :

- RAMI - oriented
  - Redundancy design
  - Modular design
  - Fault-compensation scheme
  - Beam loss control
- Economy
  - High utility efficiency of Key components (cavity and SSA)
  - Well developed technology at IMP
  - More focus on the system integration and optimization (LLRF,ICS)
- Upgradeability
  - Energy ~2 GeV
  - Current ~ 10 mA

CiADS Research Plan (2025 ~ 2030)

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

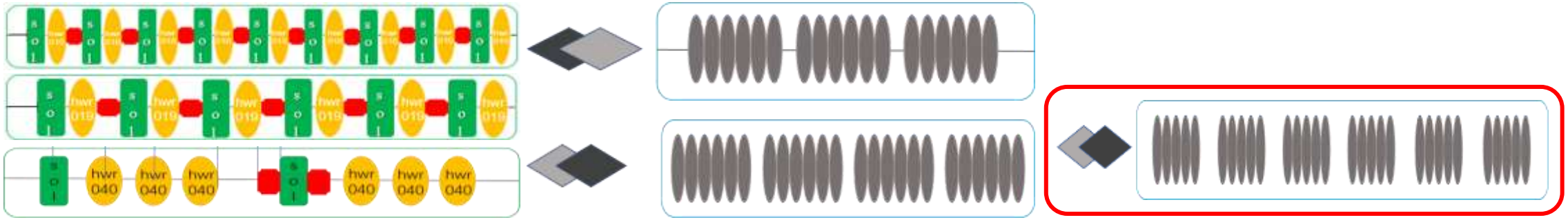
ADS/ADANES transmutation research

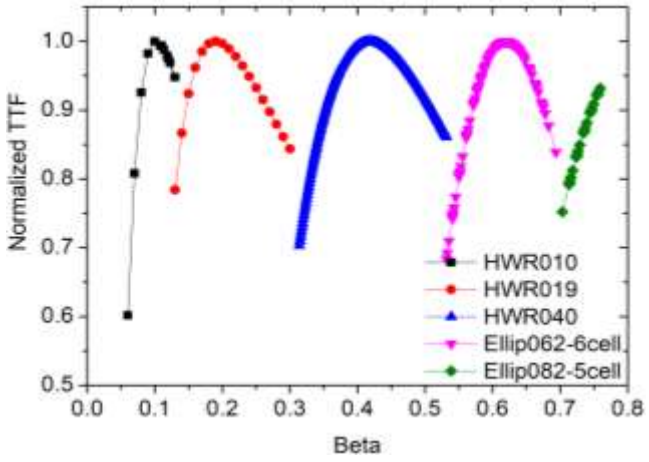
- Accelerator ~2.5MW
- Target ~2.5MW
- K_{eff}~0.75
- Reactor ~7.5MW

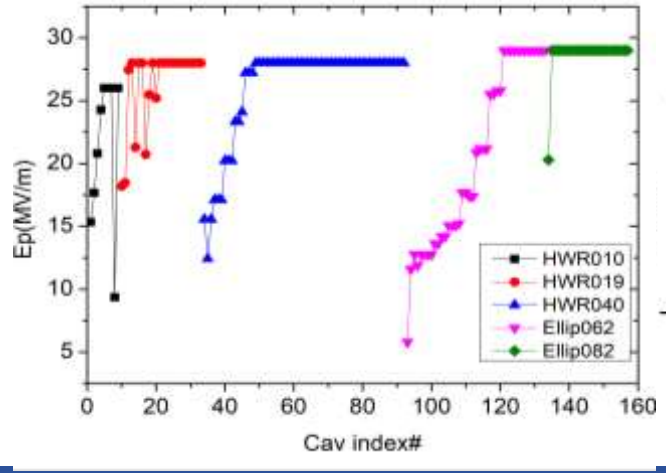
- **High power target demonstration**
- ADS operation with high power
- **Transmutation demonstration**
- Test fuels with deep burnup
- Fuel test with high power density
- ADANES preliminary design report

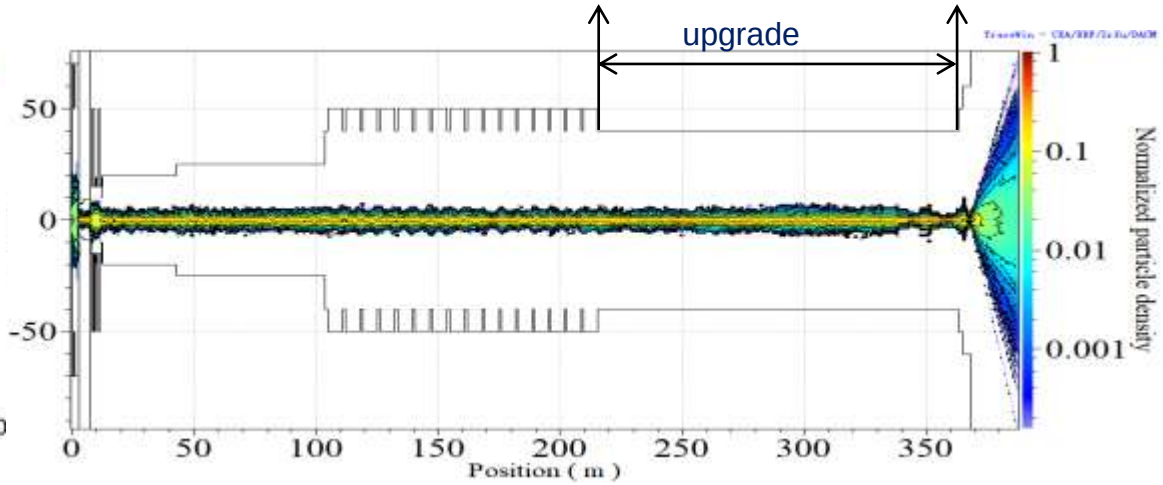
Upgrade of Superconducting Linac

RFQ	HWR010 1CM	HWR019 4CM	Spoke042 10CM	Ellip062 10CM	Ellip082 7CM	Ellip093 nCM
	9cavity 162.5MHz	24cavity 162.5MHz	60cavity 325MHz	30cavity 650MHz	28cavity 650MHz	Upgrade in future
2.1MeV	7MeV	45MeV	175MeV	375MeV	500MeV	2GeV





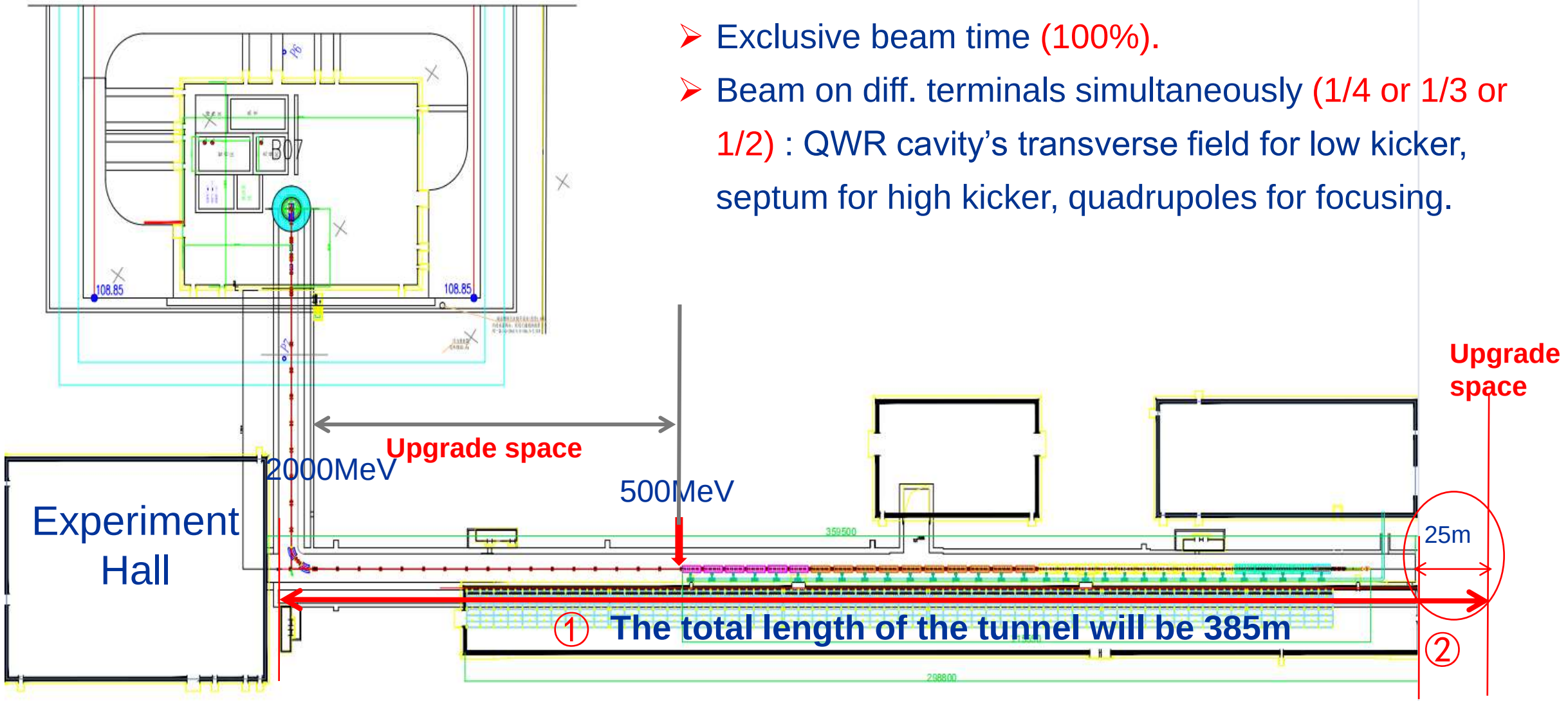




Muon Source plan at CiADS

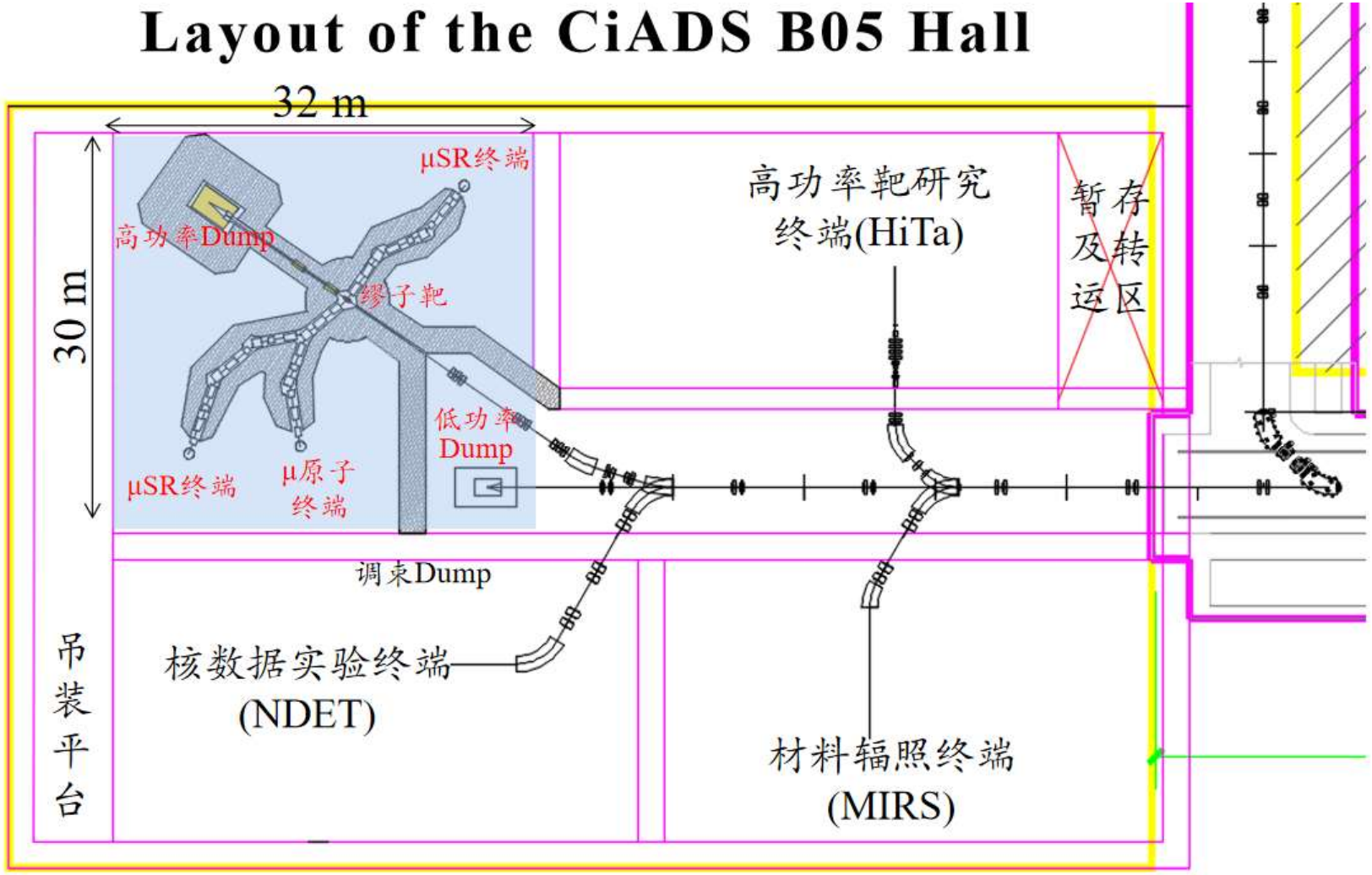
Beam Modes

- Exclusive beam time (100%).
- Beam on diff. terminals simultaneously (1/4 or 1/3 or 1/2) : QWR cavity's transverse field for low kicker, septum for high kicker, quadrupoles for focusing.



Muon Source plan at CiADS

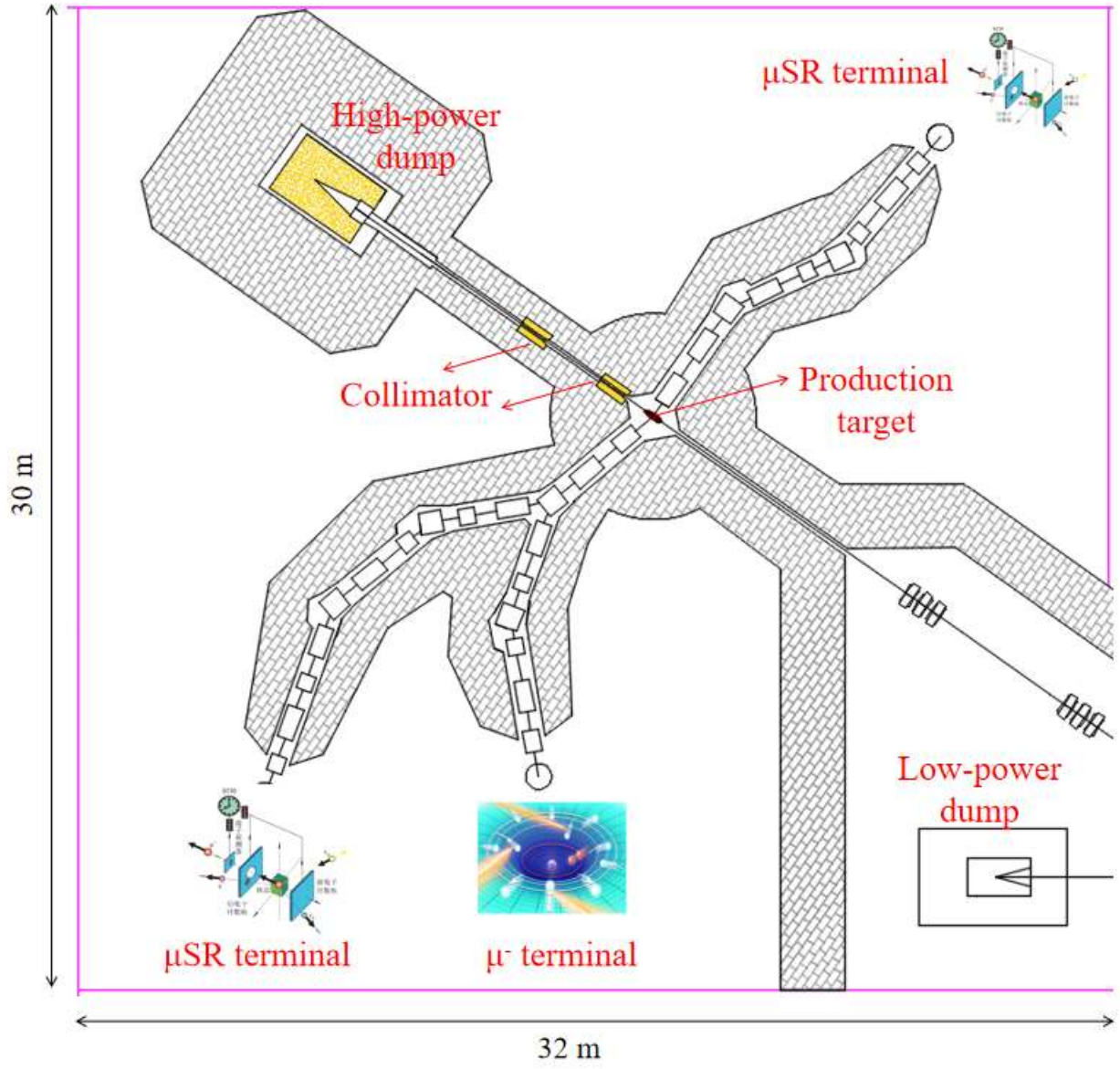
- An area of 32 m×30 m for the low power dump, muon source and the high power beam dump.
- The muon production target and two collimators be set upstream of the dump.



Muon Source plan at CiADS

Phase I:

- Proton beam of 500 MeV & 300 kW on the target, ~10 kW energy deposit. Or 2.5 MW in the future.
- Solenoid-based capture and transport, total efficiency of ~10%, surface muon rate of $5 \times 10^9/s$.
- 1 production target, 2 capture solenoids, supporting at least 3 muon beam lines ($2\ \mu^+ \& 1\ \mu^-$) to work simultaneously.
- Providing surface and slow muon beam for μSR covering important sample environments.
- **Phase II: upgrade to 2 GeV/ 10 mA**



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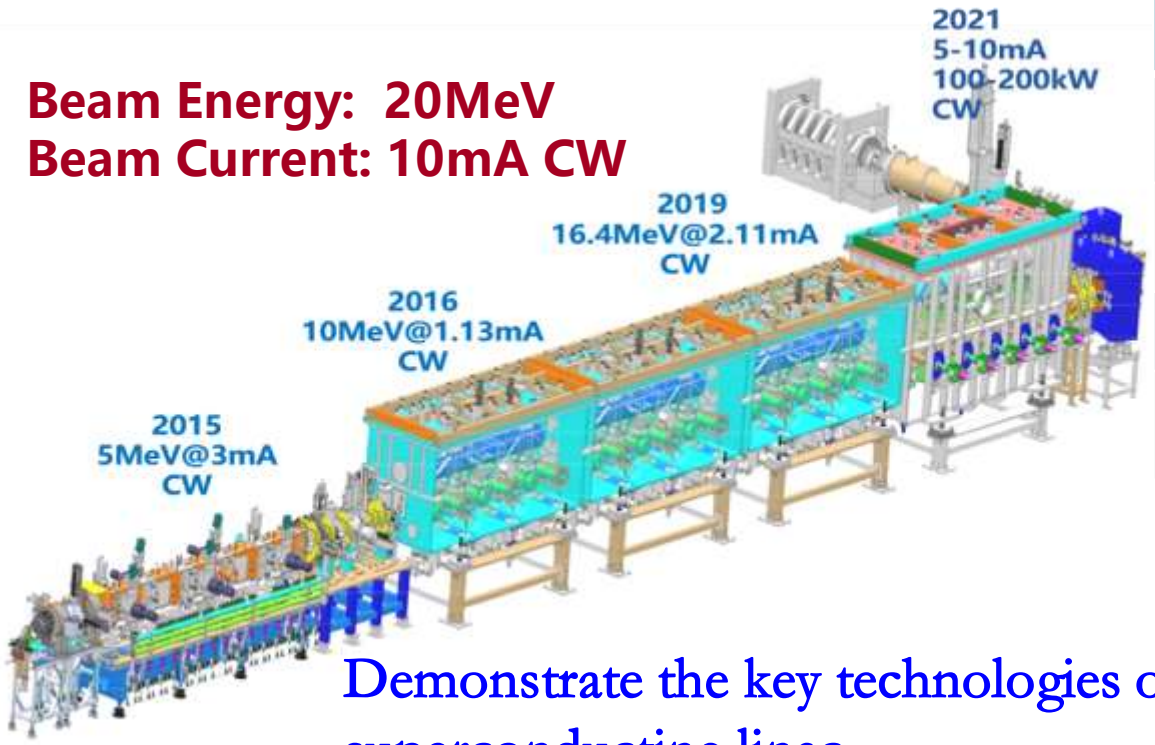
Development of Demo Linac for ADS — CAFe

Beam Energy: 20MeV
Beam Current: 10mA CW



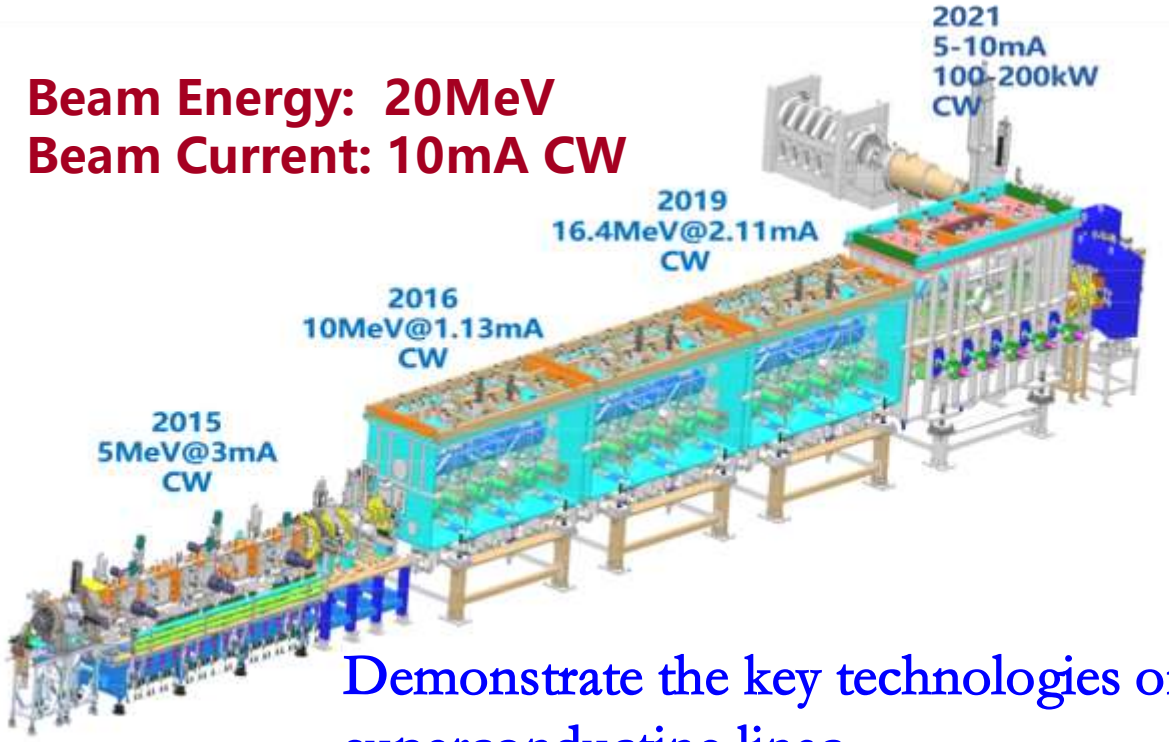
Demonstrate the key technologies of superconducting linac

	Ion source	RFQ	CM1	CM2	CM3	CM4
FREQ	DC	162.5 MHz	162.5 MHz	162.5 MHz	162.5 MHz	162.5 MHz
Energy	35 keV	2.1 MeV	5 MeV	10 MeV	18.5 MeV	20 MeV
Type	ECR	4-vane	HWR010	HWR010	HWR010	HWR015
Num.CAV	1	1	6	6	5	6

- **2011~2021, CAFe was constructed and commissioned to verify the CW current of 10 mA, the value for industrial ADS version.**
- **CAFe Goal: to demonstrate 10 mA CW beam of superconducting front-end Linac for ADS.**

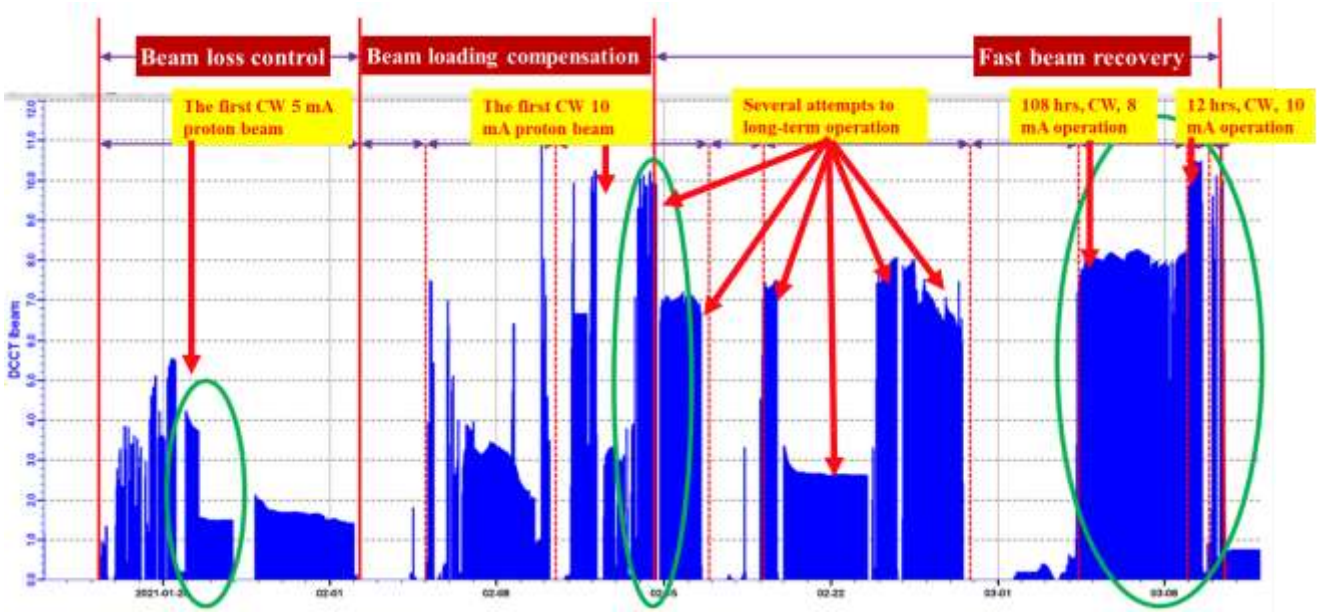
Development of Demo Linac for ADS — CAFe

Beam Energy: 20MeV
Beam Current: 10mA CW

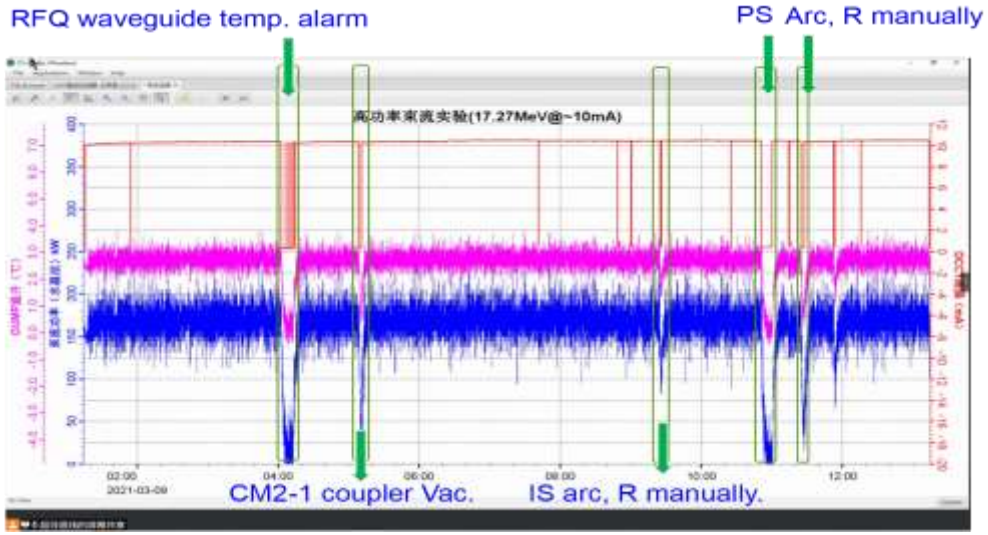


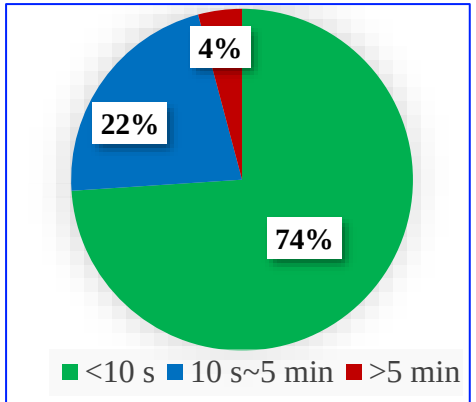
Demonstrate the key technologies of superconducting linac

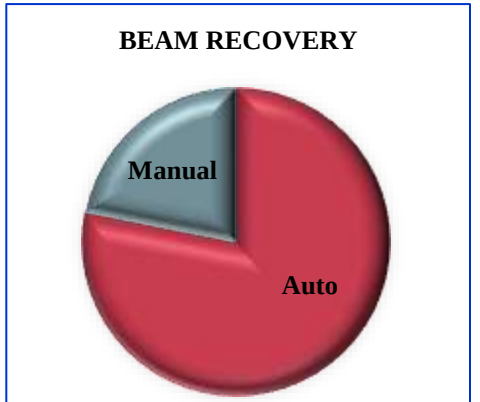
High Current Demonstration

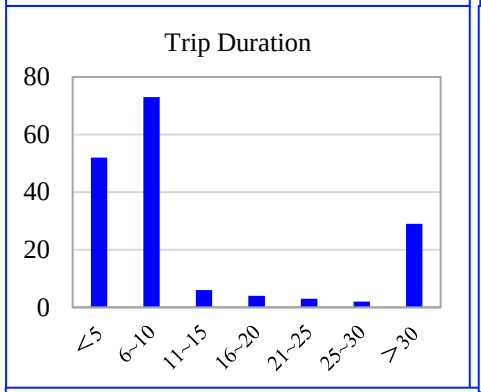


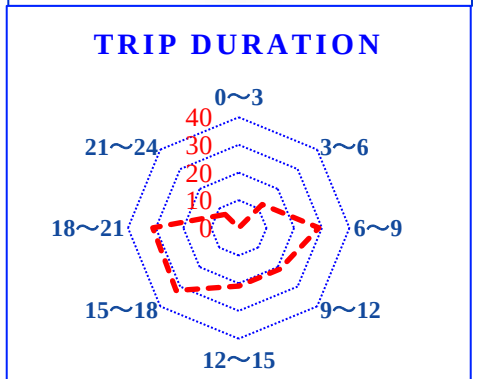
Operation mode:
CW
High current:
10 mA
Availability:
> 90%
Max Power:
200 kW

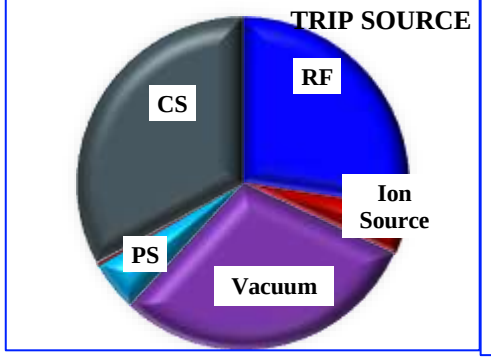


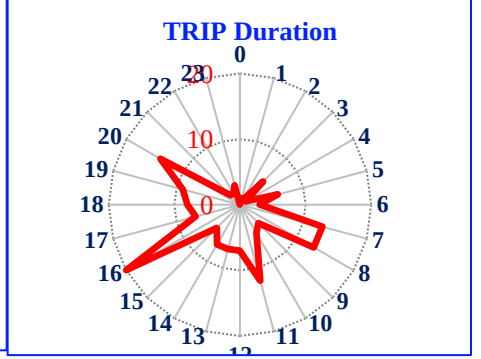












Summary

- China has breakthroughs in high-intensity proton facilities. The 100-kW-beam-power milestones have been achieved at CSNS and CAFe.
- Three proton facilities base on SC linac —— CSNS II, HIAF and CiADS —— are now constructing.
- A muon source will be built in the CSNS II and the muon consideration on CiADS and HIAF are planning.

Thanks for your attention!

Welcome Advice and Collaborations !