IPAC23

14th International Particle Accelerator Conference
7 - 12 May 2023 | Venice Italy

Accelerator Driven Systems —— A Solution to Multiple Problems of Society

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Institute of Modern Physics, Chinese Academy of Sciences

Contents

- **Climate change: humanity’s greatest challenge**
- **Problems of existing nuclear energy**
- **Why ADS is a solution to nuclear energy**
- **Challenges facing accelerator for ADS**
- **Project plan of CiADS**
- **Conclusion**

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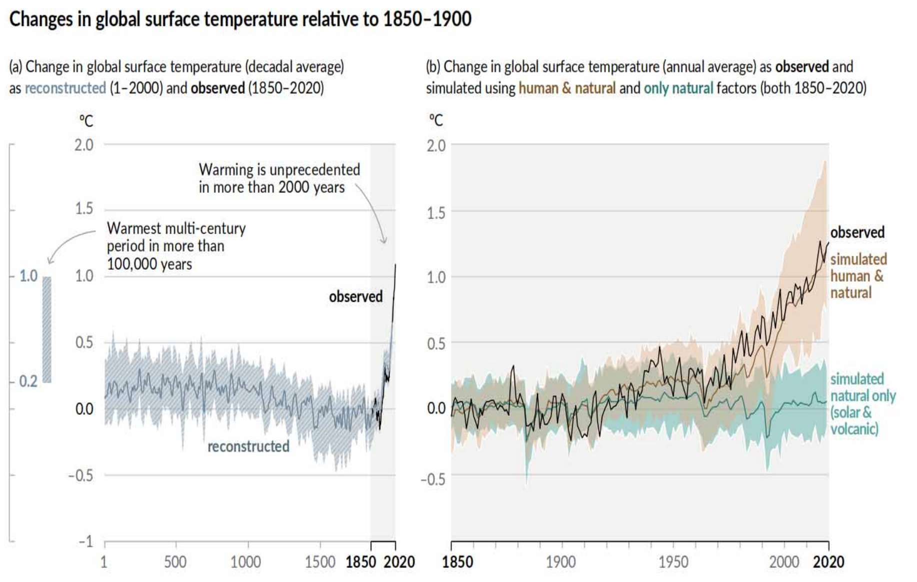
Threat of Climate Change

☐ Since the 1850s, human activities have caused climate change unprecedented in recorded history

- Last decade is the warmest in the last 100,000 years.
- Global temperature rise is speeding up.



https://report.ipcc.ch/ar6/wg1/IPCC_AR6_WGI_FullReport.pdf

☐ Main impacts of global warming

- Global retreat of glaciers, permafrost thaw, sea level rise (global mean sea level increased by 0.2 m between 1901 and 2018)
- More extreme weather events (heatwaves, heavy precipitation, droughts, and tropical cyclones)
- Ocean acidification and deoxygenation
- Desertification and land degradation, reduced food security and water security...

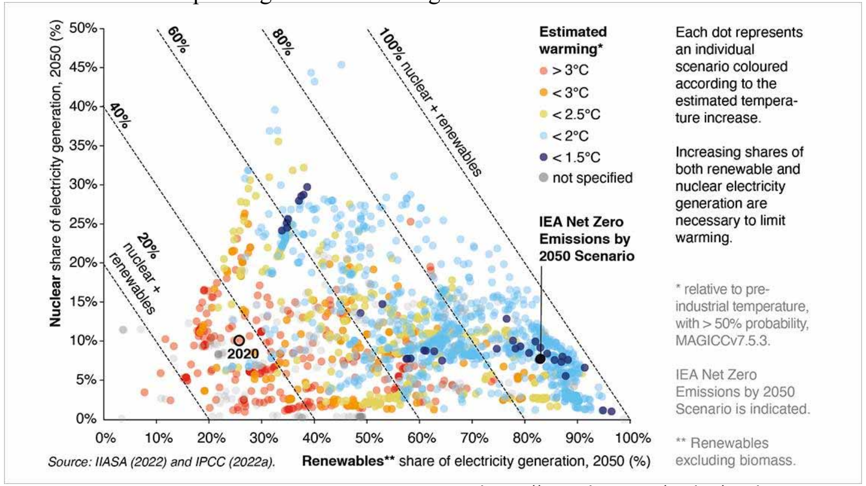
https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_LongerReport.pdf

Carbon Neutrality and Nuclear Energy

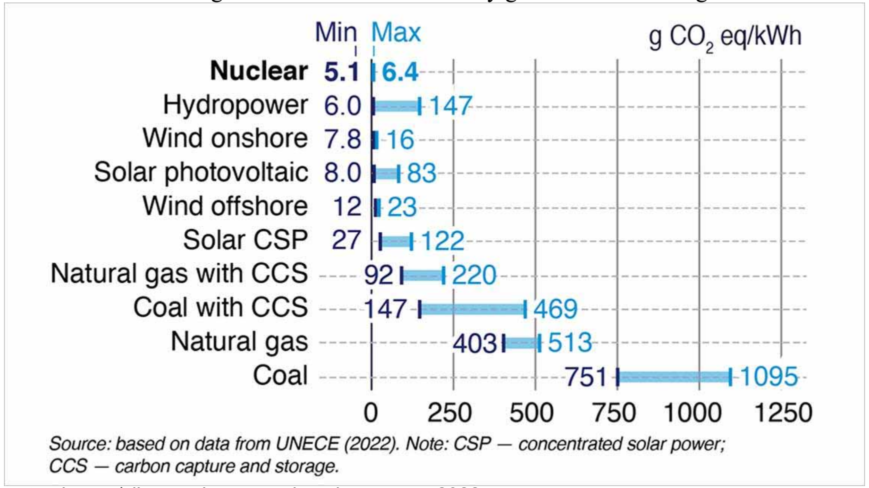
“Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels.”

—— ***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.

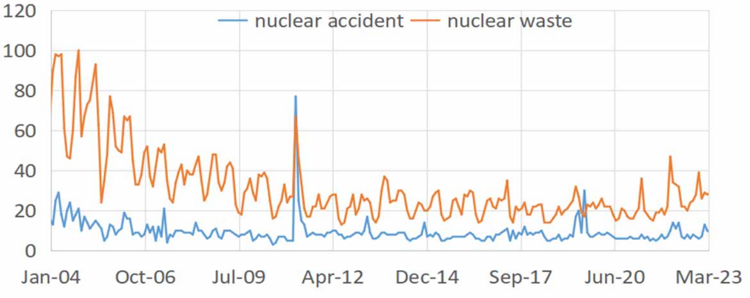


https://www.iaea.org/topics/nuclear-power-and-climate-change/climate-change-and-nuclear-power-2022

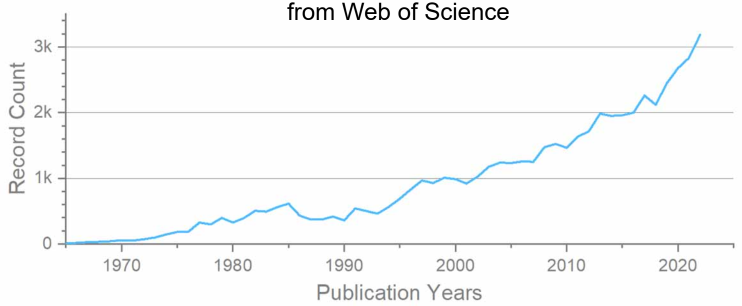
- To achieve carbon neutrality in the coming decades, a key to avoiding global warming of more than 1.5℃, investment in the energy sector must be scaled up and directed towards cleaner and more sustainable technologies that support climate change mitigation and adaptation.
- With one of the lowest carbon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

Public Opinion Wary of Nuclear Energy

Public attention on nuclear safety and nuclear waste from Google Trends



Academic articles on the topic of "Nuclear Waste" from Web of Science



- Public worries about nuclear safety and nuclear waste caused a wave of anti-nuclear attitudes

Nuclear energy policies of some countries:

- Germany: have abandoned completely
- Italy: have abandoned completely
- Switzerland: to withdraw on a step by step basis by 2050
- Belgium: phasing out nuclear energy by 2035

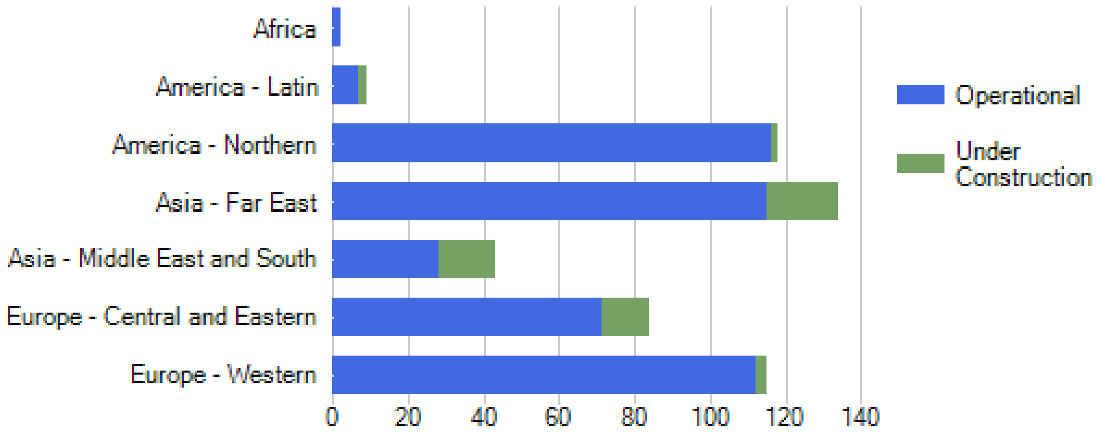
Anti-nuclear movement supporters gather to celebrate the shuttering of Germany's last three nuclear power plants on April 15, 2023 in Munich, Germany.

——*Johannes Simon* | *Getty Images News*

Nuclear Power Making a Comeback

◻ Nuclear power is gaining support 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.



◻ Nuclear power is coming back in many countries:

1. Japan: Under the new policy, Japan will restart as many existing reactors as possible and prolong the operating life beyond a 60-year limit.
2. Belgium: On 18 March 2022, the federal government decided to extend the operational life of the two youngest nuclear power reactors by ten years until 2035.
3. ...

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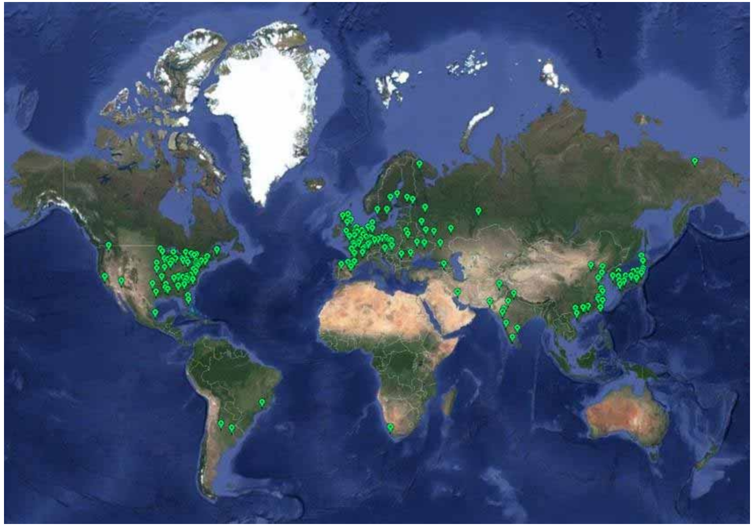
Problems Facing Nuclear Energy Today

- 450 nuclear reactors operating in 30 countries
- >10% of global electricity, 1/3 of low-carbon electricity
- ~700 reactors (commercial, experimental, prototype or research reactors) have been retired from operation, only 25 of them have been fully dismantled.



Regional Distribution of Nuclear Power Plants

- The accidents at Three Mile Island, Chernobyl, and Fukushima have profound impacts on the development of nuclear power.

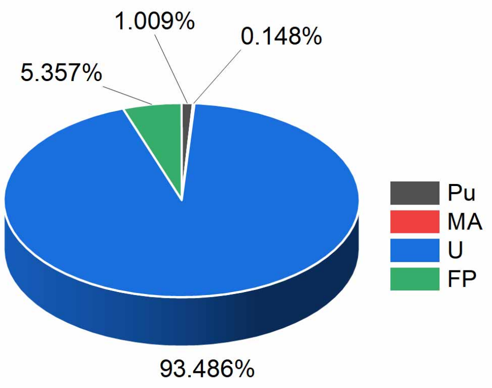
Fukushima Daiichi nuclear power plant is seen on March 17,2022.

—— *Shohei Miyano/Kyodo News*

The aftermath of two Level 7 nuclear disasters: the public is deeply concerned about nuclear plant safety and radioactive contamination

Problem of Thermal Nuclear Reactor

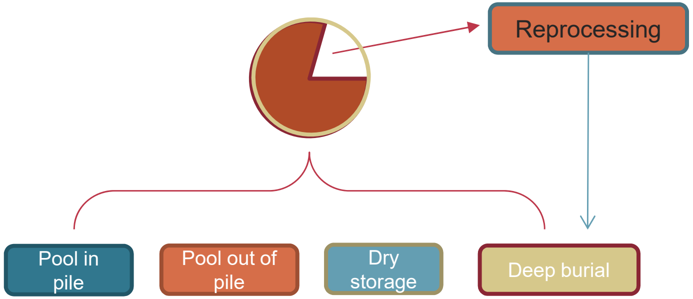
- Current technology: 8 tons of natural uranium -> 1 ton of nuclear fuel -> only 50 kg is burnt up into fission products
  - Reusable fuel (950kg) + depleted uranium (7 tons) has huge untapped potential for energy production that cannot be extracted by a thermal nuclear reactor
- Reusable fuel contains a large amount of unused uranium and transuranium elements generated in the reactor via neutron capture, such as plutonium, neptunium, americium, and curium
- Long-life, high-toxicity transuranium elements pose long-term harm to human environment



Isotopes	Half-life (Years)	DOSE (Sv)	Isotopes	Half-life (Years)	DOSE (Sv)
^{235}U	7.03×10^8	5.2×10^1	^{242m}Am	152	5.4×10^5
^{238}U	4.46×10^9	1.2×10^3	^{243}Am	7380	1.3×10^6
^{238}Pu	87.7	1.5×10^8	^{242}Cm	0.446	2.8×10^4
^{239}Pu	24110	7.1×10^6	^{243}Cm	28.5	5.8×10^5
^{240}Pu	550	1.1×10^7	^{244}Cm	18.1	6.3×10^7
^{241}Pu	14.4	3.0×10^7	^{245}Cm	8500	2.7×10^4
^{242}Pu	3.7×10^5	8.9×10^4	^{99}Tc	2.1×10^5	1.1×10^3
^{237}Np	2.14×10^6	7.3×10^3	^{129}I	1.57×10^7	5.9×10^2
^{241}Am	432.6	7.9×10^7	^{135}Cs	2.3×10^6	3.9×10^2

Where is the Spent Fuel?

- Spent fuel: reusable fuel + fission products (waste), extremely difficult to partition
- By the end of 2019, there were ~433,000 tons of spent fuel unloaded globally, with an average of ~11,300 tons of spent fuel unloaded annually from nuclear power plants worldwide.
- About 80 % of the world's storage is located in the United States and Western Europe.
- By 2035, UxC estimates that spent fuel emissions will be close to 618,000 tons and stockpiles will be close to 450,000 tons.



Pool storage

Dry storage

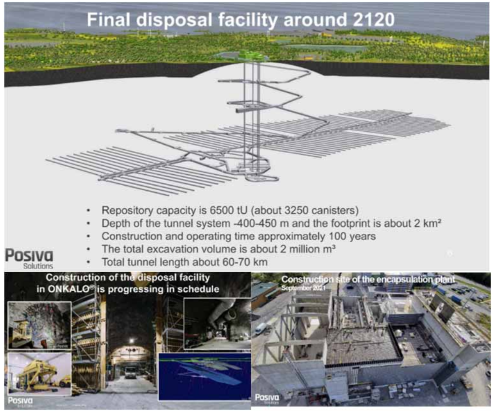
Carlyn Greene，《Global Spent Fuel Overview》

https://www.powermag.com/dry-cask-storage-booming-for-spent-nuclear-fuel/

Where will the Spent Fuel go?

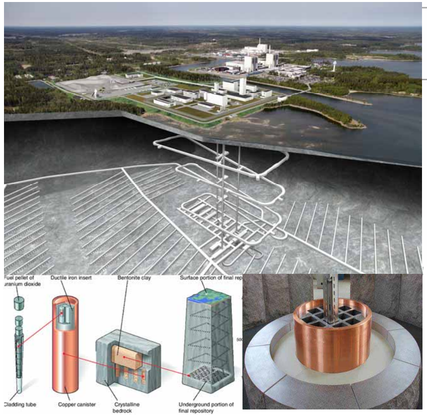
“Until now, all spent fuels are stored on-site or off-site in engineered storage facilities, pending final decisions on its disposition. No country has a geological repository for spent fuel storage or disposal. Neither have most countries decided on a final decision for spent fuel.”

https://www.iaea.org/newscenter/focus/radwaste-management/managing-spent-nuclear-fuel-global-overview



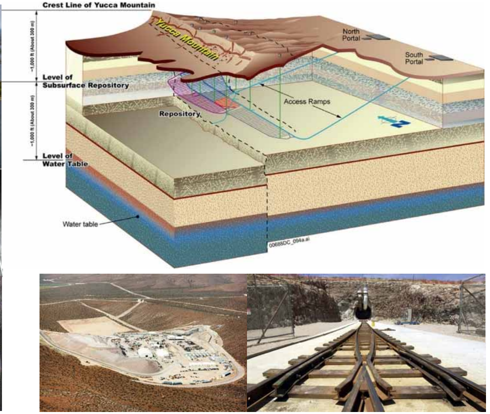
- POSIVIA disposal facility in Finland. 6,500 tons uranium, 450 m underground.
- Expected to begin operation in 2024 and close in 2120.

Pauliina Aalto, IAEA Radioactive Waste Management Conference, 2021



- Forsmark disposal facility in Sweden. 500 m underground.
- Construction started in 2022.

SKB company website



- Yucca Mountain in Nevada state of USA, 500~800 m underground, planned to dump 70 000 t HLW.
- 2500 scientists and 10.5 Billion dollars in 1983~2009.

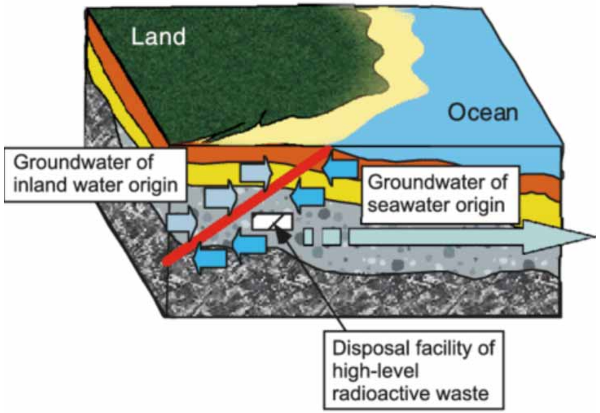
DOE website

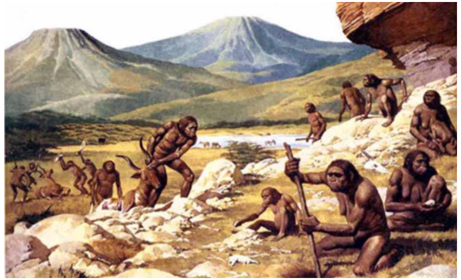
- North Mountain in Gansu province of China, 560 m underground, planned to dump HLW.
- Lab construction started in 2021.

Ju Wang, Liang Chen, IAEA RWM Conf, 2021

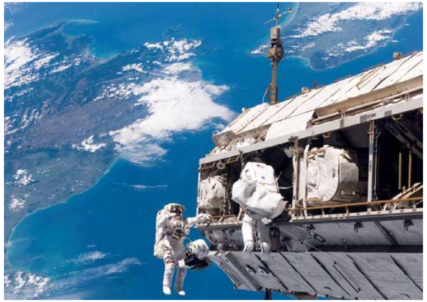
Geological Disposal Not Fail-Safe Solution

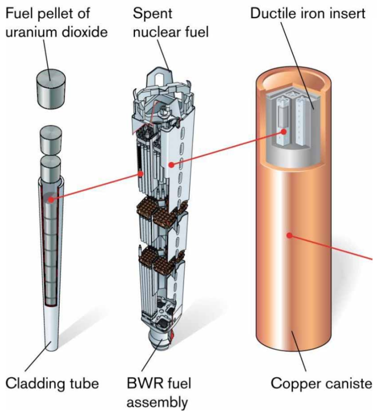
- Site requires： geological stability for millions of years, low underground water content, small flow, …….
- Disposal warehouses of disposal systems must stay safe over hundreds of thousands of years or even longer time scales.
- The high radiation waste container must remain intact for a hundred thousand years and maintain stability at high temperatures (decay heat).





Hundreds of thousands of years





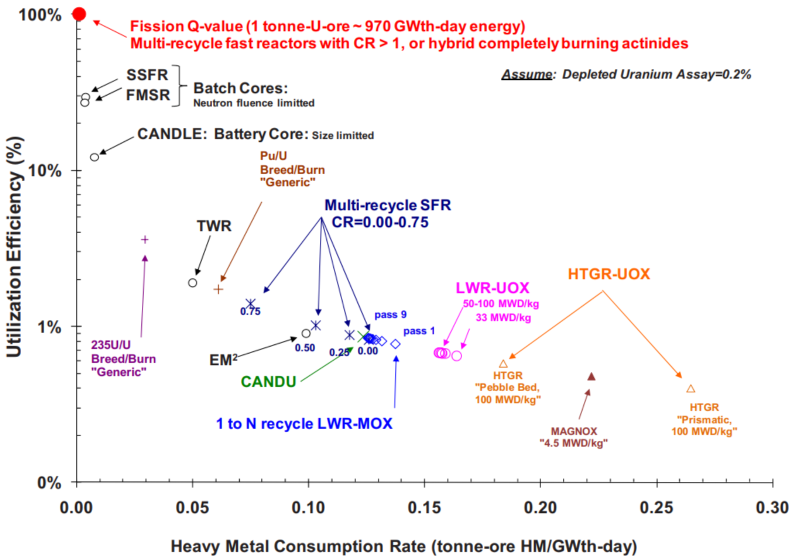
Source: Presentation "National strategy and roadmap for geological disposal in Finland" for Stimson site visit, STUK, 2018.

Summary of Current Nuclear Energy

Current nuclear energy technology is still primitive:

- only a small proportion of fuel is utilized **~ 1%**
- large amounts of potentially useful nuclear resources left behind
- spent fuel (unused resources and FP wastes) pose environmental hazards
- direct geological disposal of spent fuel carry unknown risks for hundreds of thousands of years

Uranium resource utilization efficiency as a function of consumed natural uranium "mass-in"



Samuel Bays Steven Piet , The Effect of Burnup and Separation Efficiency on Uranium Utilization and Radiotoxicity

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Nuclear Reactions in the Reactor

Under irradiation by high-flux neutrons in the reactor, fuel nuclides are converted into various transuranic nuclides through neutron reaction and decay. After long-term irradiation, the final spent fuel will contain hundreds of radioactive nuclides.

- Fission of nuclear fuel is the main reaction process that maintains reactor operation
- Neutron capture and decay are important ways of transition between nuclides
- In fact, there are hundreds of reaction channels between neutrons and fuel nuclide

Main neutron reactions and decay mode

- Neutron capture (n,γ)

$$^{A}_{Z}X + ^{1}_{0}n \rightarrow \left(^{A+1}_{Z}X\right)^{*} \rightarrow ^{A+1}_{Z}X + \gamma$$

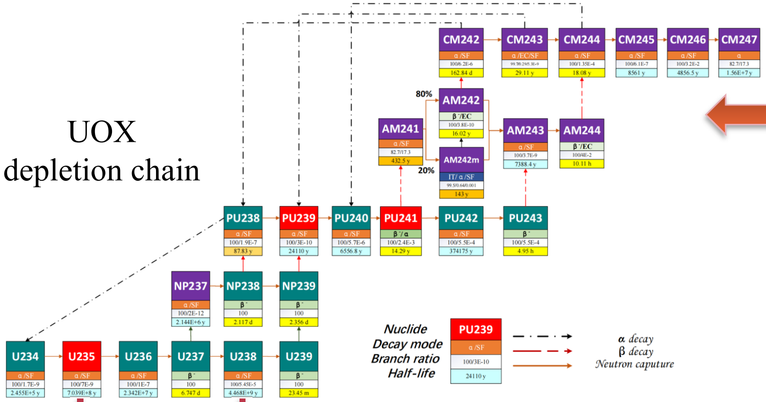
- Fission (n, f)

$$^{235}_{92}U + ^{1}_{0}n \rightarrow \left(^{236}_{92}U\right)^{*} \rightarrow ^{A_1}_{Z_1}X + ^{A_2}_{Z_2}X + \nu\, ^{1}_{0}n$$

- Decay (α、β)

$$^{A}_{Z}X \rightarrow ^{A-4}_{Z-2}Y + ^{4}_{2}He \qquad ^{A}_{Z}X \rightarrow ^{A}_{Z+1}Y + ^{0}_{-1}e$$

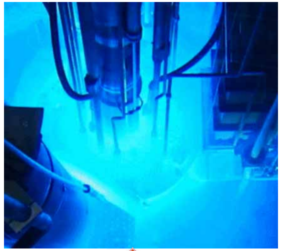
UOX depletion chain



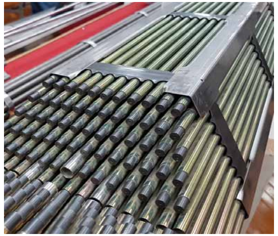
Uranium-235 (half-life: 700 million years)

Uranium-238 (half-life: 4.4 billion years)

Fuel burning



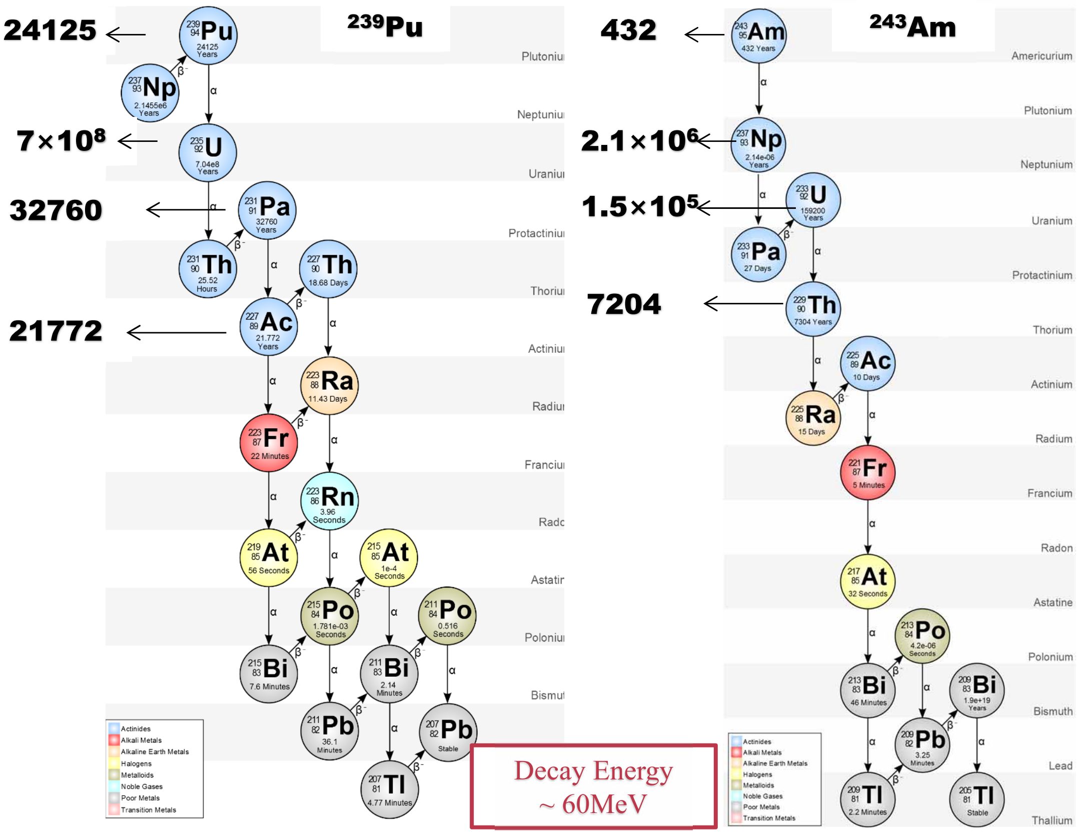
Fresh fuel



Disposal: Spent Fuel Undergoes Decay

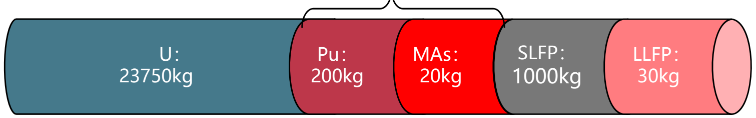
- Transuranium elements in geologically buried spent fuel can only be converted into stable nuclides such as lead or bismuth through a long decay chain
- Actinide elements have a half-life of several hundred to ten thousand years and a natural degradation cycle of over a million years
- The decay of actinide elements continues to release alpha particles and gamma rays, causing long-term harm to the ecological environment

Transuranium elements decay Half-life (Year)



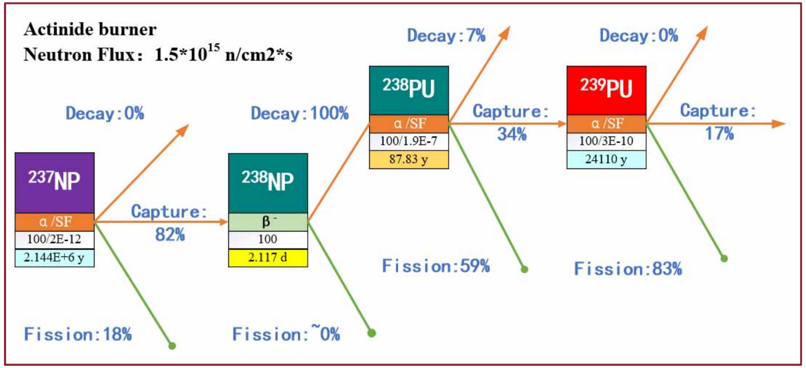
Decay Energy ~ 60MeV

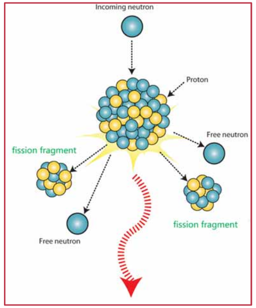
Transuranium elements

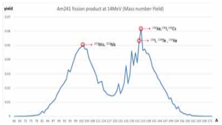


Incinerator: Spent Fuel Undergoes Fission

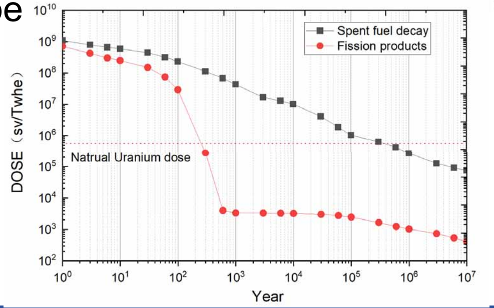
- Actinides in spent fuel can be efficiently and effectively utilized through fission, ultimately being converted into fission fragments.
- Fission fragments, whose half-life and toxicity are much smaller than those of transuranium elements, can be rapidly degraded.
- The concentrated combustion of transuranium elements in the reactor can fully utilize the fission production capacity, and the reusable fuel will be completely incinerated on the scale of ten years







Fission products

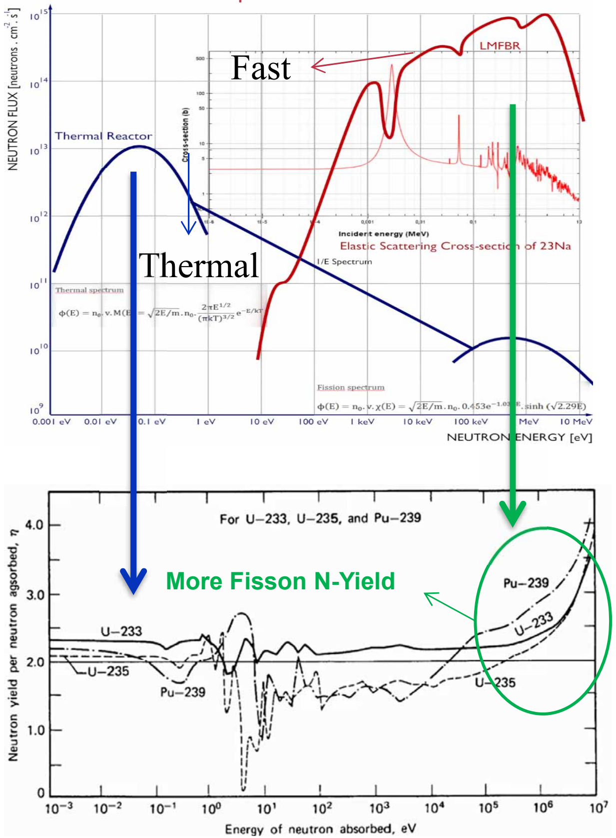


Energy~ 200MeV

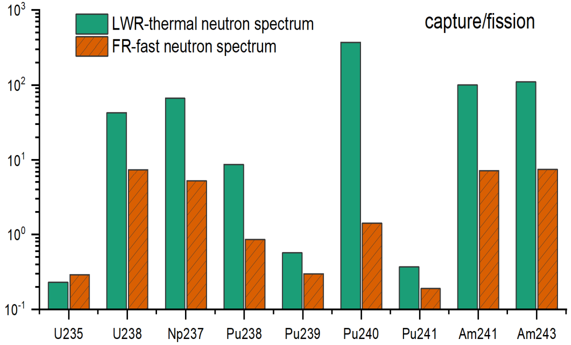
Merits of Fast Neutron Reactors

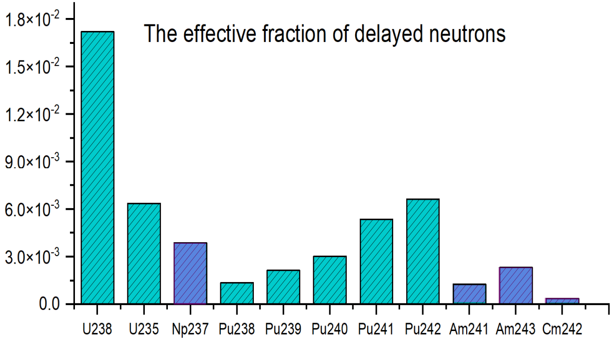
- Fast neutrons ideal for burning transuranium elements
  - Larger fission cross section
  - Produces more neutrons per reaction
- Capture to fission ratio of MAs
  - High in thermal neutron reactors, impossible to realize net reduction of MAs
  - Much lower for fast neutrons, net reduction of MAs easily achievable

Neutron spectrum Thermal VS Fast



Fisson N-Yield with absorbed neutron energy





Drawbacks of Fast Neutron Reactors

How to maintain a reactor under critical neutron balance:

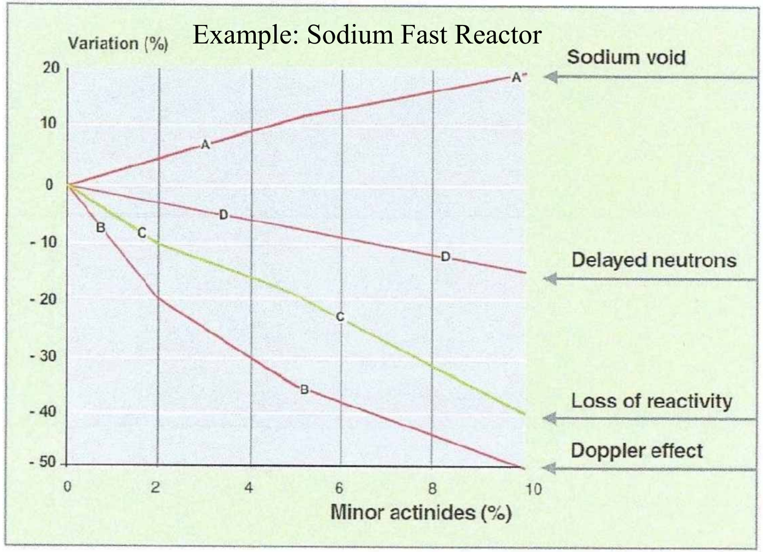
$$W_R = W_0 \, exp\left(\frac{K_{eff} - 1}{l} t\right) \qquad l = l_p + \sum_{i=1}^{6} \beta_i t_i$$

l: mean neutron lifetime
l_p: prompt neutron lifetime
β_i: i-group delayed neutron proportion
t_i: i-group delayed neutron lifetime

Two types of neutrons: prompt and delayed
Too many prompt neutrons: reactor can go supercritical very quickly
Delayed neutrons keep reactors safe by maintaining stability

As proportion of MAs increases

- Sodium void effect intensifies, leading to large increase in reactivity
- Reduction in delayed neutrons, making the reactor less stable
- Decrease in magnitude of negative temperature coefficient, smaller negative feedback to keep the reactor stable



Relative variations of core parameters as a function of the MAs′ fraction in the fuel

MAs incineration rate should be at least less than 2.5% in fast reactors (even 2.5% is considered very risky)
Fast reactor is still not a solution to complete utilization of nuclear fuel or the minimization of radioactive waste

Van den Eynde, G. ARCAS, ADS and Fast Reactor comparison Study in Support of Strategic Research Agenda of SNETP

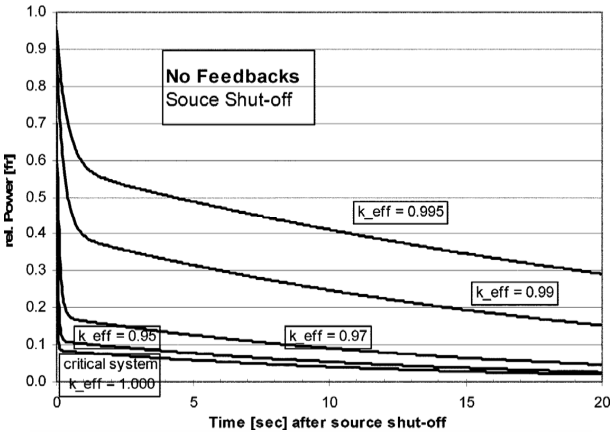
Promising Solution: Accelerator-Driven System

ADS consists of accelerators, spallation targets, subcritical reactors, and energy production systems.

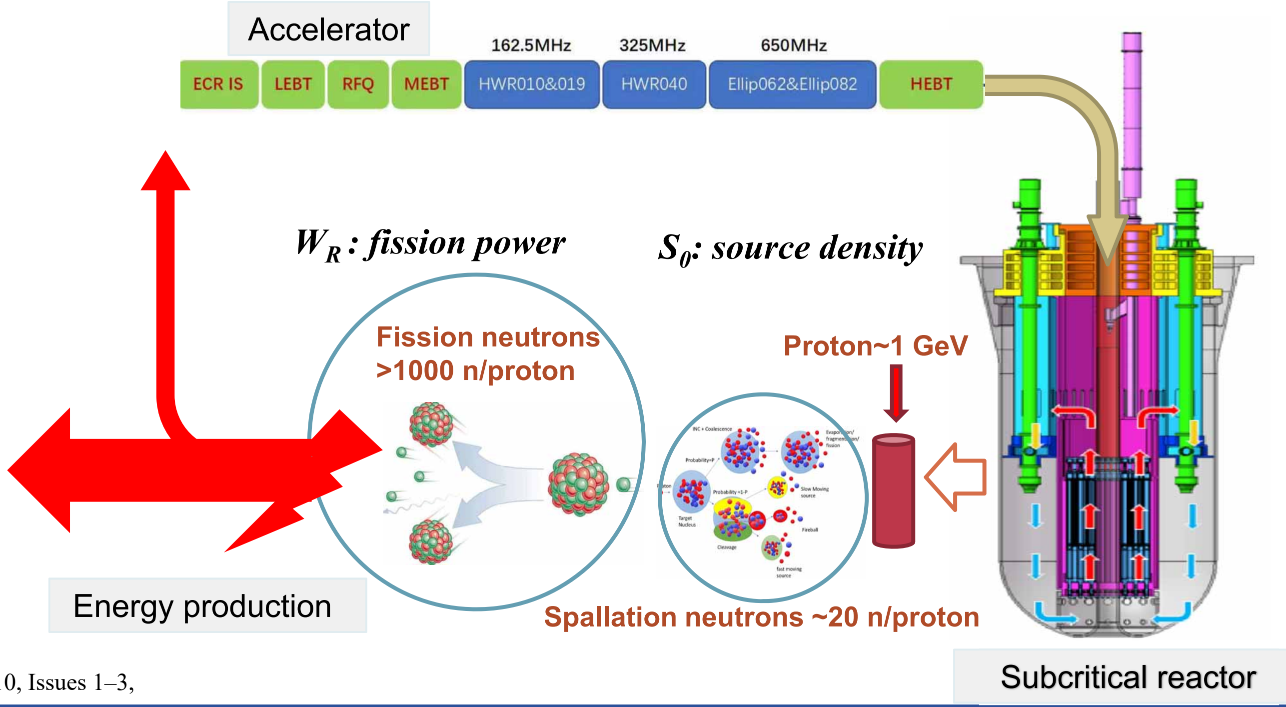
The subcritical reactor is driven by a high energy proton accelerator, works like an energy amplifier.

How does ADS work safely

$$W_R = \frac{Q\varphi^* S_0}{\bar{\upsilon}}\left(\frac{K_{eff}}{1-K_{eff}}\right)$$



Rapid core shutdown at deep subcritical (K_{eff}<0.98) after beam shutoff



W.M. Schikorr, Nuclear Engineering and Design, Volume 210, Issues 1–3,

Merits of ADS

- **Great flexibility with respect to fuel composition**

  For a subcritical reactor $K_{eff} < 0.98$, prompt neutrons have no influence on the safety control of the reactor. This means that the reactor can accommodate arbitrary fuel with large minor actinide concentrations, natural uranium, thorium and even fission fragments.

- **Potentially enhanced safety**

  The enhanced safety of ADS is due to the fact that once the accelerator is turned off, the system will shut down. The high tolerance level of ADS with respect to the fuel's neutronic properties should make them excellent tools to study new reactor concepts by relaxing many safety conditions.

For example, an accelerator can feed different subcritical systems like molten salt, gas or lead cooled reactors. Such prototypes could allow studies of corrosion, radiation defects and fuel evolution in realistic conditions with less stringent criticality control-related constraints.

Evolution of ADS

E. O. Lawrence
MTA
1950s

US-ANL
Closing the fuel cycle
with Pu-recycling for P&T
1972

1970s
US-ORNL
Theoretical P&T

1970s~1983
German-GRCK
France-CEA
European Commission-
Theoretical and experimental R&D program in the fuel cycle and included the P&T option.

1973
JP-JAERI
A closed system for radioactivity

US-BNL-
Hiroshi Takahashi
Cyclotron
Transmutation
1986

JP-AEC-JAERI
+JNC+CRIEPI
Takakazu Takizuka
"OMEGA" R&D program
1988

1990
US-BNL-
Hiroshi Takahashi
The Role of accelerators in the nuclear fuel cycle

US-LANL-Charles D. Bowman
ADTT
1992
ATW
1994

Russia-ITEP
ENNG-XADS=HWR+Linac(ISTRA-36)

JAERI-
Y. Kato
H. Katsuta
ADS:MSR
1992

EC-CERN
Carlo Rubbia
EA (Energy Amplifier)
US-BNL-
Hiroshi Takahashi
ADEP
Phoenix
ADPF
1993

1994
China-CIAE
Venus 1 (propose)

CERN
TARC
1995

France-CEA
MASURCA →MUSE1 →MUSE2 →MUSE3 →MUSE4
1996
CERN + Italy-
ENEA+INFN+CIRTEN
LBE-XADS
EAP80

Korea
HYPER
1997

1997
Belarus+US-ANL
YALINA

ADONIS→ MYRRHA
Belgium-
SCK•CEN
1998

JAERI-T. Takizuka+K. Tsujimoto
ADS:Linac+SFR/LFR→JAEA-ADS

US-DOE-ANL-
Y. Gohar
Accelerator Driven Test Facility (ADTF)
1999

2000
China-CIAE
Venus 1
(Project start)

India-DAE
SC-ADSP
2001

2001
European Commission
PDS-XADS(Preliminary Design Study of an eXperimental Accelerator Driven System)
France-FRAMATOME+CEA
Gas cooled XADS

Carlo Rubbia,
Noulis Pavlopoulos,
Anatoly Zrodnikov
NWB(Nuclear Waste Burner)
2003

2004
Ukraine+US-ANL
KIPT
Russia-JINR
+KTH+CIEMAT
+CEA+JIENR
Subcritical Assembly at Dubna (SAD)

EURATOM
EUROTRANS (European Research Program for the TRANSmutation of High-level Nuclear Waste in an Accelerator-driven System),
EFIT (European Facility for Industrial Transmutation)
Belgium-SCK •CEN
MYRRHA-Draft 2→XT-ADS→FASTEF→ Rev.1.6
Aka rev.1.4
FAst Spectrum Transmutation Experimental Facility
2005

2005
Russia
Cascade Subcritical Molten Salt Reactor (CSMSR)

2009
JP-Kyoto U
KUCA

China-Wenlong Zhan
ADANES (propose)
2010

France+Belgium+Spian
VENUS-F
2011

US 2011
GEM*STAR

China-CIAE+IMP+USTC
Venus 2 2012

2013
Russia-INR
5-10MW LBE ADS

2014-15
China-IMP+CNNC(CIAE)+IHEP+GNC+HIPS
The China initiative Accelerator Driven System (CiADS)

2018-19
Belgium-SCK•CEN
MYRRHA (approval)

China
10 MW CiADS
start building
2021

Evolution of ADS

E. O. Lawrence
MTA
1950s

US-BNL-
Hiroshi Takahashi
The Role of accelerators in the nuclear fuel cycle
1990

US-LANL-Charles D. Bowman
Accelerator-Driven Transmutation Technology Project(**ADTT**)
1992

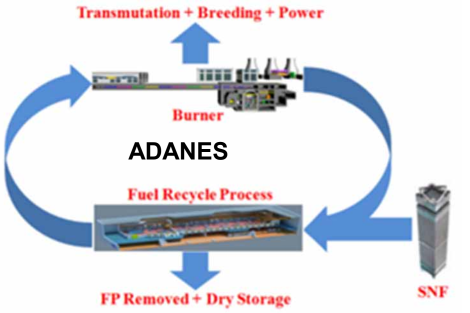
Accelerator driven Transmutation of nuclear Waste (**ATW**)
1994

European Commission-CERN
Carlo Rubbia
EA (Energy Amplifier)

US-BNL-Hiroshi Takahashi
Accelerator driven energy producer (**ADEP**)
Phoenix concept
Accelerator driven particle fuel transmuter (**ADPF**)
1993

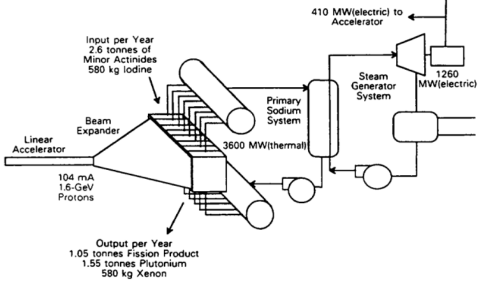
US-DOE-ANL-Y. Gohar
Accelerator Driven Test Facility (**ADTF**)
1999

China-Wenlong Zhan
Accelerator Driven Advanced Nuclear Energy System (**ADANES**)
2010



2021
China
10 MW CiADS begins construction

Phoenix concept



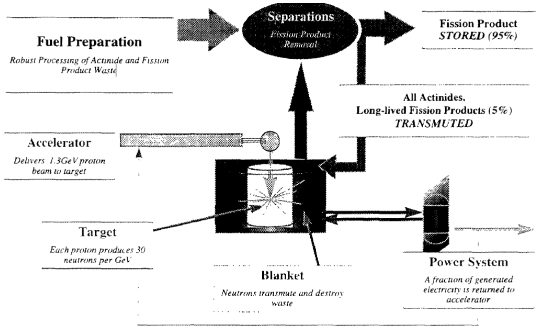
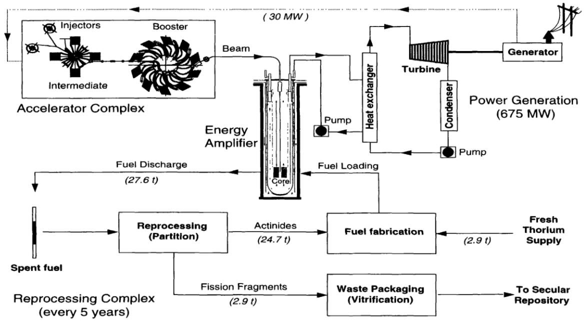


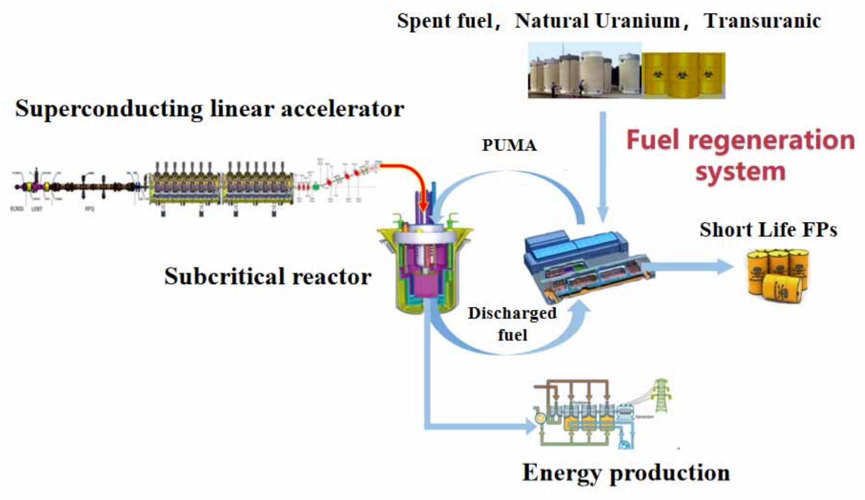
FIG. 1. A general layout of the ATW components

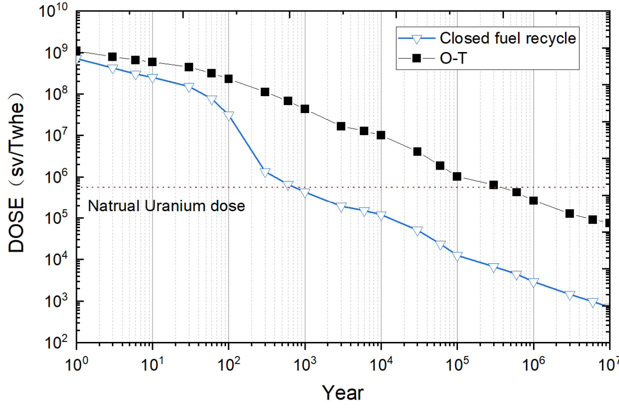


Nuclear System with an Ideal Fuel-Cycle

Accelerator Driven Advanced Nuclear Energy System

- Renewable fuel ——Partially removes fission fragments from spent fuel
- Robust fuel (PUMA=Pu+U+MA): fine separation of uranium, plutonium, and minor actinides not required
- Advanced burner——External neutron driven subcritical reactor
- Breeding, transmutation and energy production integrated using PUMA

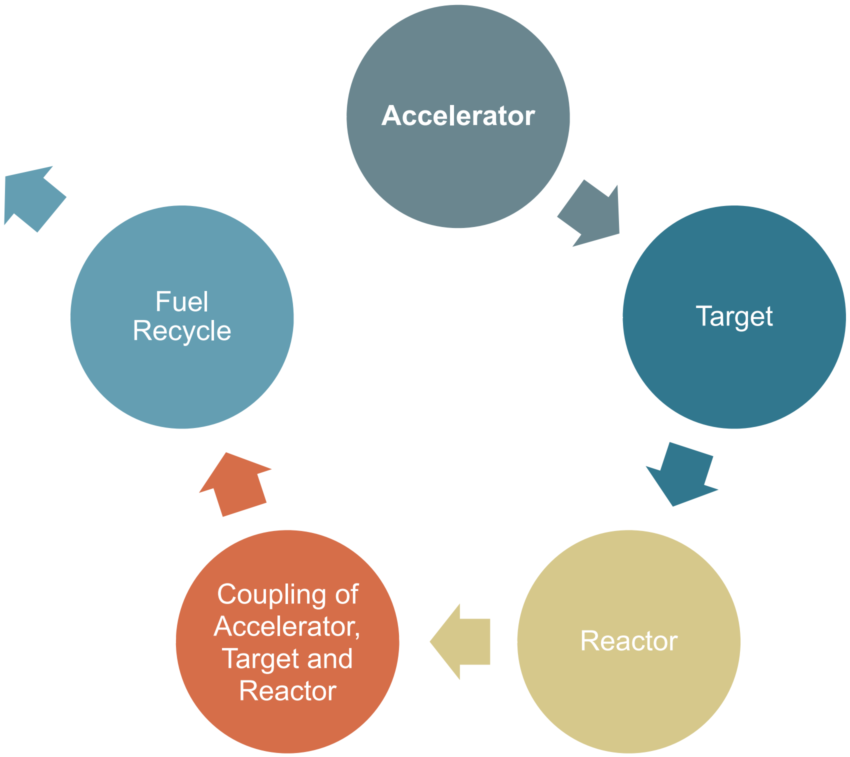




- **Environment-friendly innovative closed fuel cycle**
  - Natural resources preservation
  - Burn the spent fuel storage from current reactors
  - Fully utilize nuclear energy resources > 95%
  - Waste minimization < 400 years

Contents

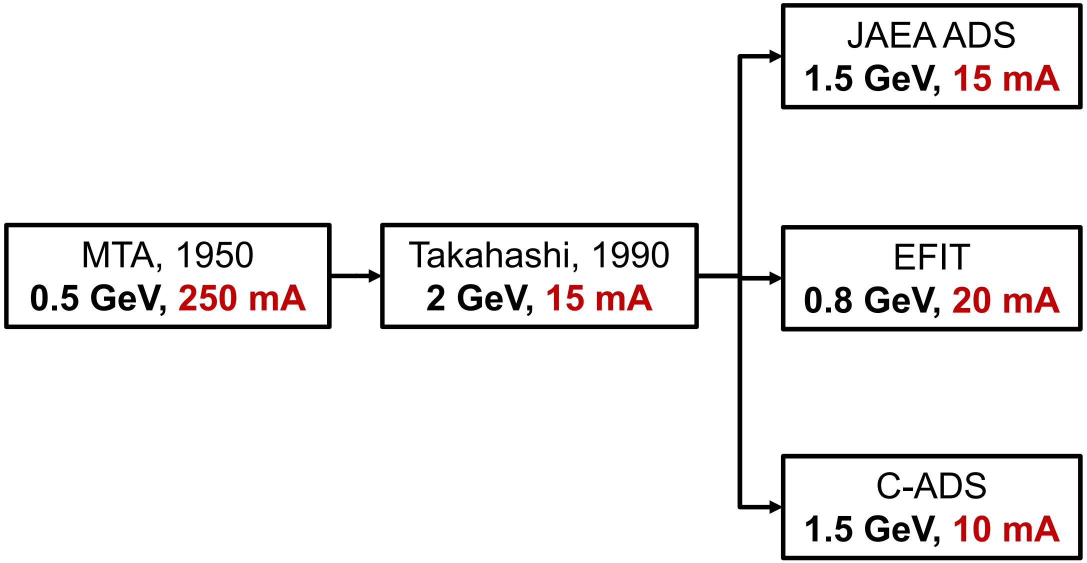
Challenges of ADS



- **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 reactor**
  - Fast neutron reactor
  - Lifetime ≥ 40 y
- **Accelerator-reactor coupling**
  - Spent fuel partitioning
  - Radiation-hard and corrosion-resistant materials

Major Challenges of ADS Accelerators

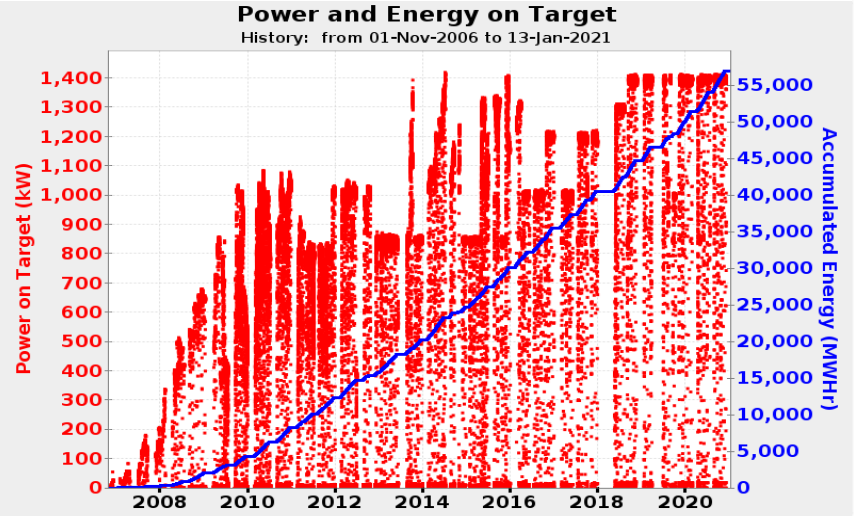
For an industrial scale ADS, CW beam current should be ≥ 10 mA.

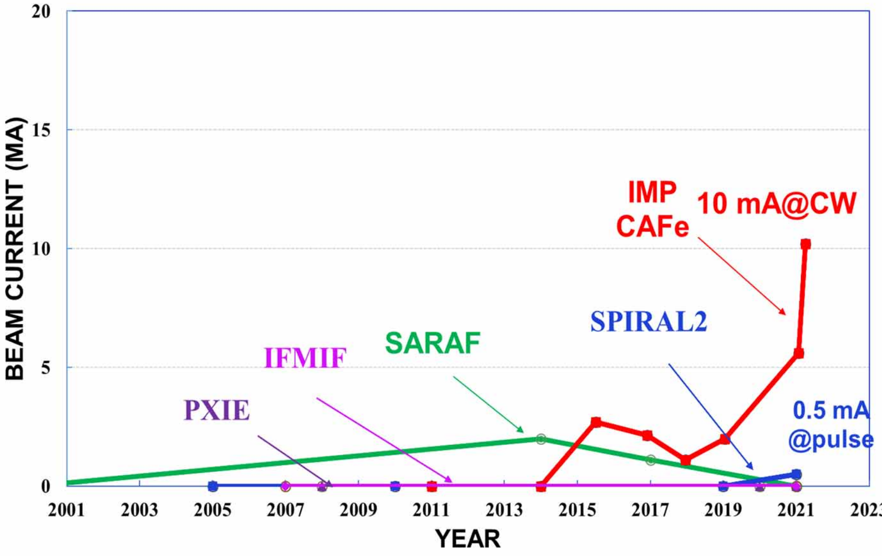


Main accelerator parameter requirements of industrial scale ADS

Parameters	Value
Beam Power	10~60 MW
Proton Energy	0.8~2 GeV
Beam Current	**10~30 mA**
Beam Time Structure	**CW**

Power and Current Ramping of SC Linacs





I_{ave}=1.4 mA

Spallation Neutron Source Ramping power to 1.4 MW from 2008 to 2021

A. Aleksandrov, Warm and cold SNS LINAC commissioning, ARIES workshop, Jan 25 - 29, 2021

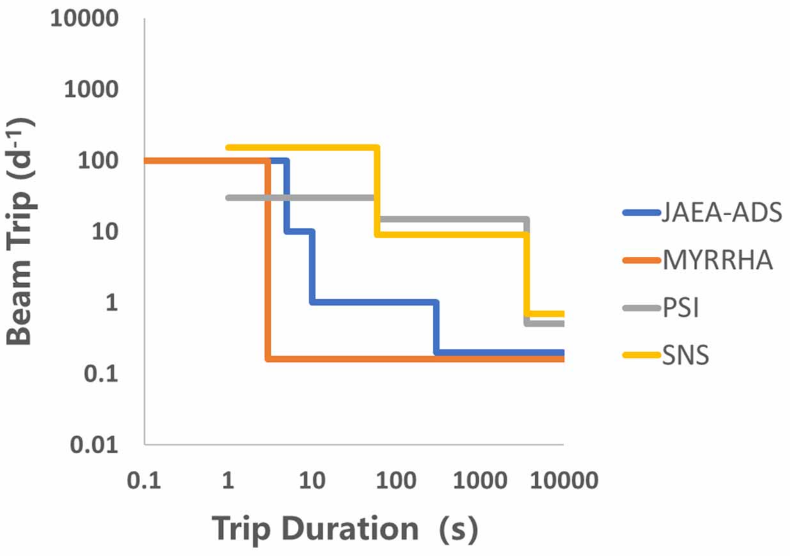
10 mA CW proton beam was realized at CAFe in 2021

Zhijun Wang' talk, This Conf, 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 requirements compared to existing high power proton accelerators
high depend on the type of reactor

Beam trip requirements of industrial scale ADS

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

ADS-Oriented SC Linac: General Features

What features should an ADS-oriented SC linac have?

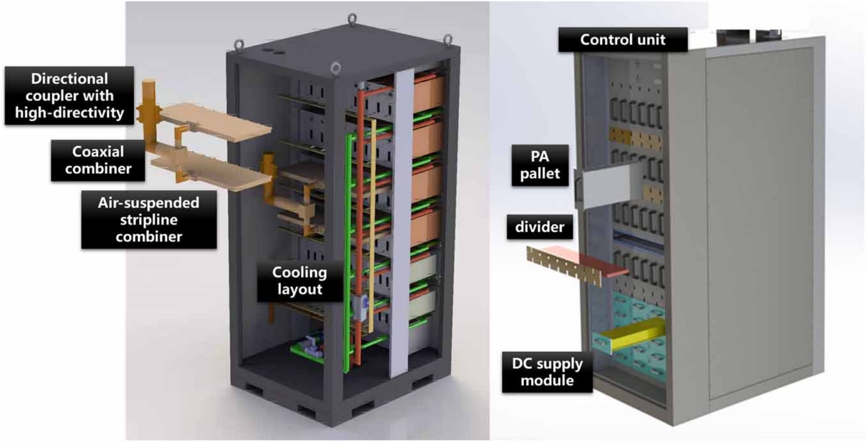
- **Overall system design ------ disturbance isolation： shut down the machine less than two times per year**
  - Each cavity or solenoid quench is isolated from any other, the cooling system or structure will not propagate the disturbance. This means individual independence – no body is VIP.
- **Beam line elements failure ------- fault compensation： beam recovery in seconds**
  - When any one cavity or solenoid fails, the lattice can be compensated by other elements, beam status will recover in 3 seconds
- **Subsystem hardware failure -------- fast recovery : beam recovery in milli-seconds**
  - Arc, phase jitter, field fluctuation, and so on, will be overcome by fast recovery scheme in less than tens of milli-seconds

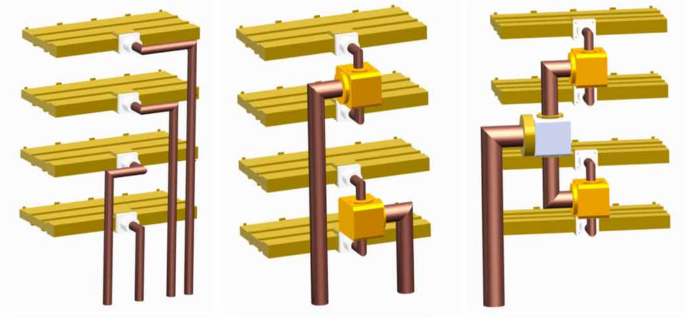
加速器驱动嬗变研究装置
China Initiative Accelerator Driven System

Philosophy of hardware design for an ADS-oriented linac

- **Modularization**
  - Topology of high power components: multi-module in parallel, easy to plug and pull
- **Redundancy**
  - A redundancy of at least one module or pellet supports hot-swap without loss of function
  - Spare capacity for compensation
- **High power efficiency**
  - Balance the power efficiency and redundancy
- **Edge intelligence**
  - Components' functionality are efficiently monitored, recorded and repaired
- **Cloud brain**
  - AI strategy based on the feedback from all diagnostics (positions, profiles, losses, …)
  - Automated commissioning and beam tuning

High Reliability Design of SSAMP





a. One rack to four cavities | b. One rack to two cavities | c. One rack to one cavities

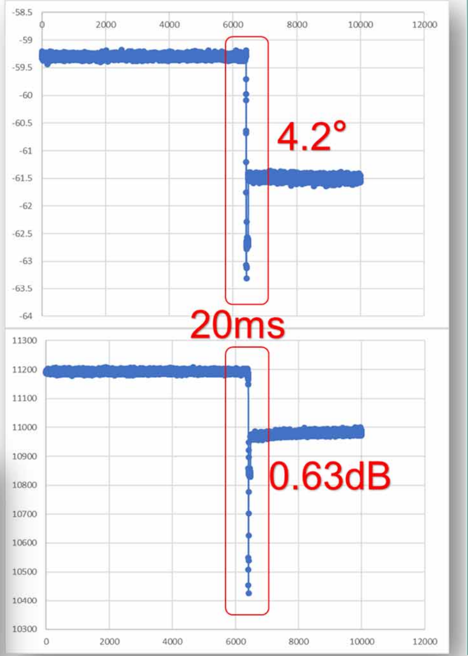
Design goal: 24*365 non-stop, maintenance-free operation

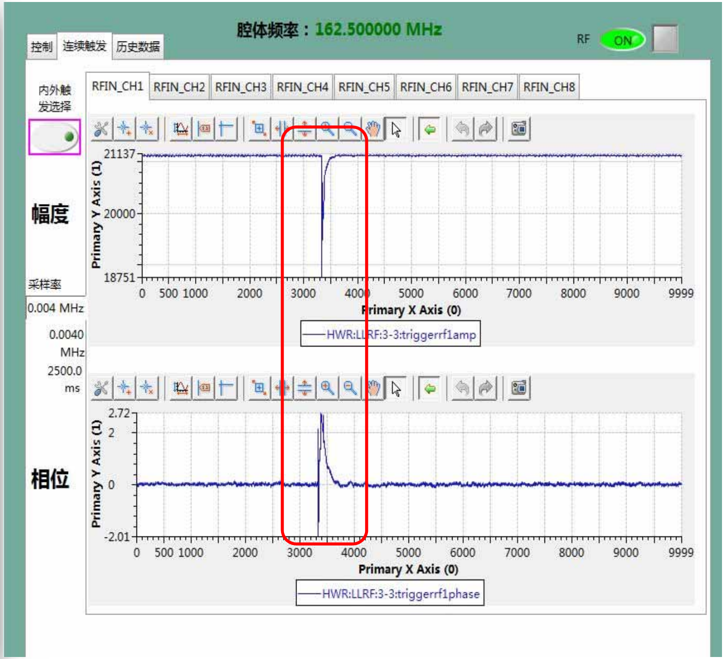
- Reliability: simplified structure, segregation between electrical and cooling elements, fixed connections
- Availability: modular hot swap, redundancy via spares
- Maintainability: parts can be replaced online
- Inspectability: smart front end, edge computing
- Expandability: flexible composite, readily upgradable

Standardized solid state power system

- Standardized structures : diagnostics, RF, composite, power supply, electrical equipment, cooling, monitoring
- RF module: 81.25MHz, 162.5MHz, 325MHz, 650MHz series unified
- Power supply module: fixed voltage versions
- Diagnostics module: standardized digital control units

Hot-swap Test



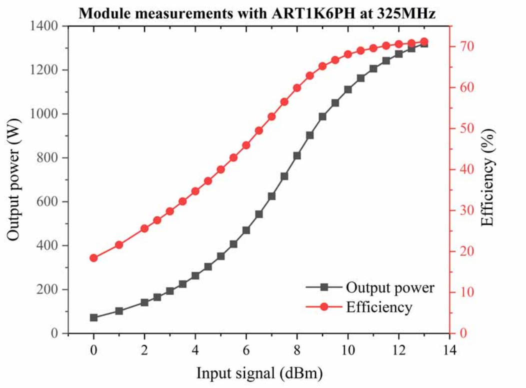


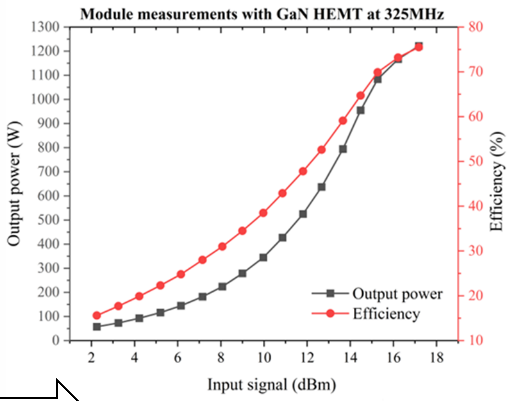
-for hot-swap, we measured a 6-ways combiner with a RT-cavity.

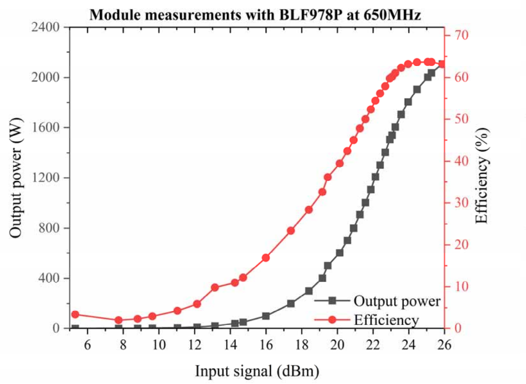
-for fluctuations of 0.63dB and 4.2°, LLRF can recovery in 100ms.

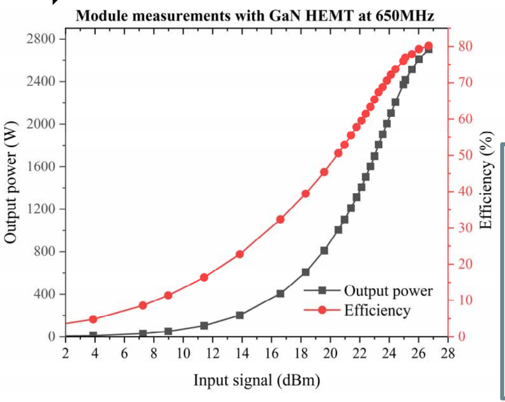
-more technologies for hot-swap are under development.

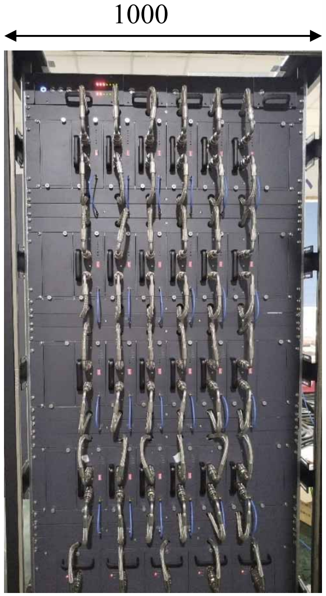
High Power GaN AMP in Series

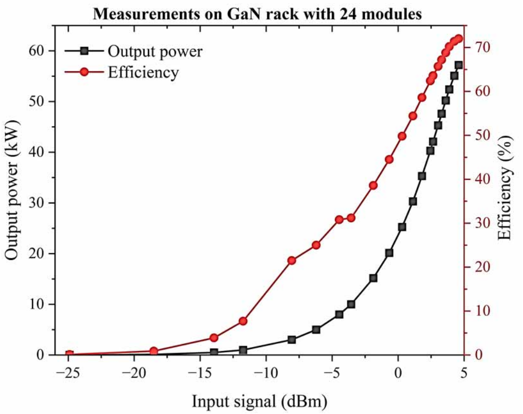




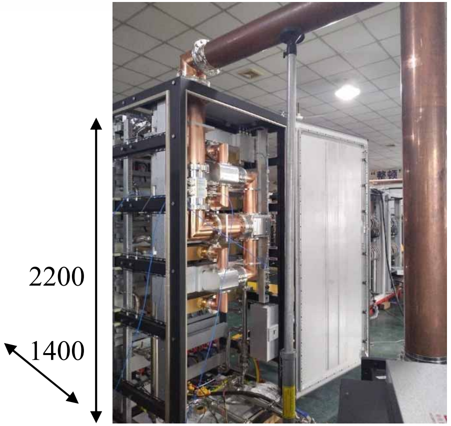








The GaN HEMT SSPA prototype was completed in Dec. 2022, every pellet is ~ 2.8 kW CW from two combined transistors. The full reflection with random phase was considered for SC cavity. The measurements of 57.3 kW CW at 650 MHz were carried on the dummy load (less than P-1 dB point due to limitation from DC power supply).



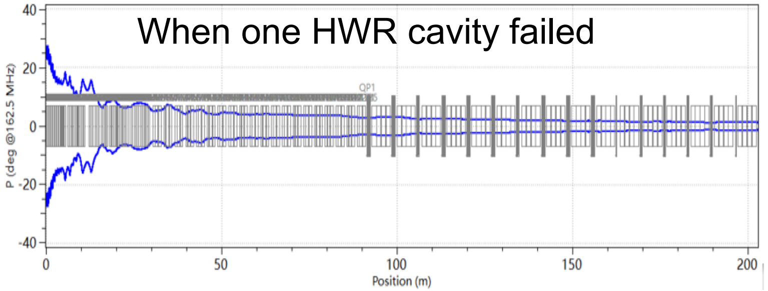
Reliability by Hybrid Fault-Compensation

Propose hybrid fault-compensation for low energy and high energy section

HWR010 | **HWR019** | **HWR040** | **Ellip062** | **Ellip082**

Energy compensation for velocity acceptance
Twiss parameter matching

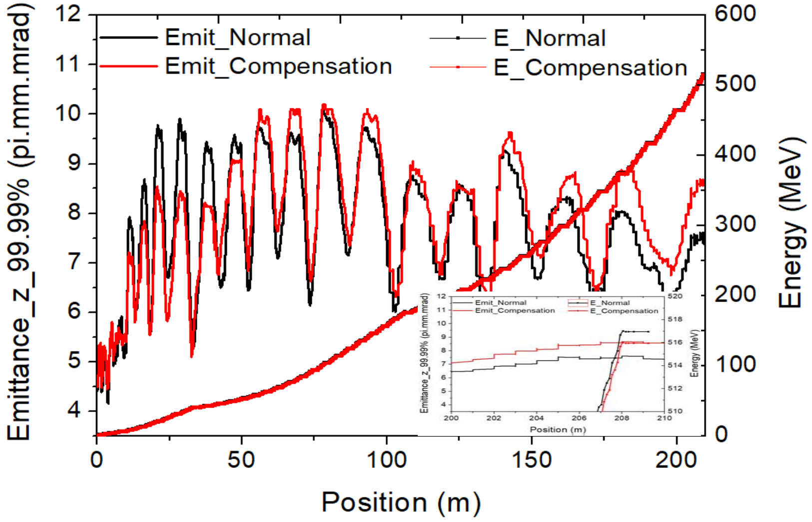
Energy compensation



Longitudinal envelope after compensation

Compared with the normal condition:

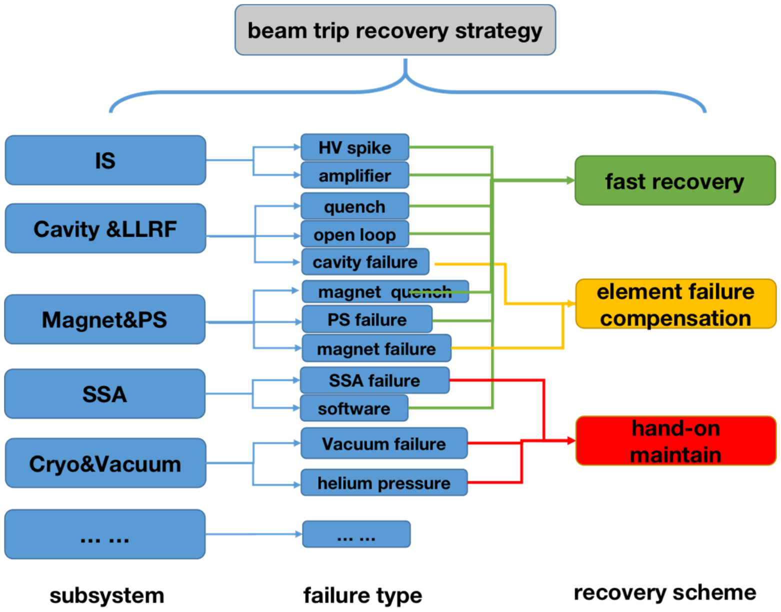
- RMS emittance growth < 15%
- Output energy stability < 0.2%

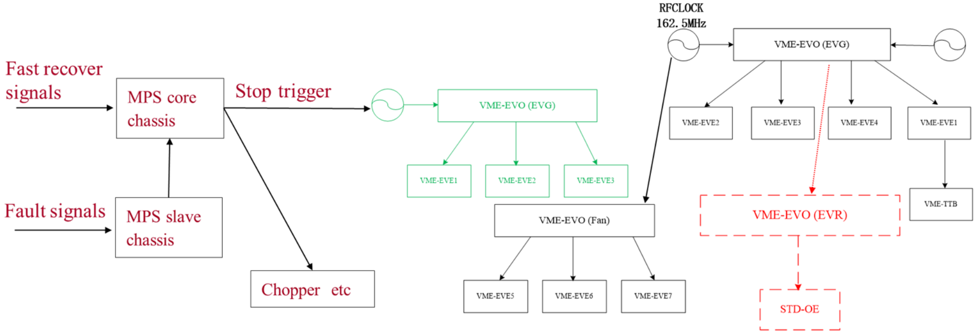


Beam emittance and energy evolution after compensation

Reliability by Auto Recovery

Auto recovery scenario and technique for CW beam are developed

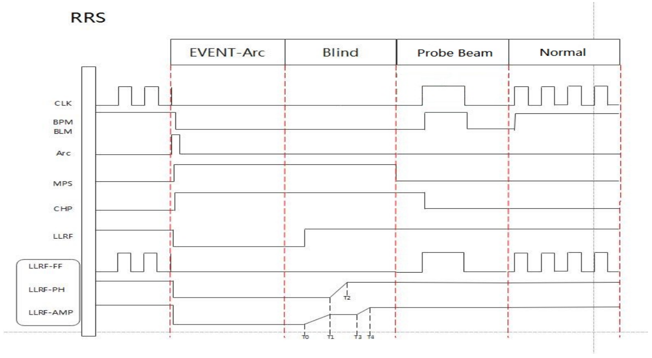




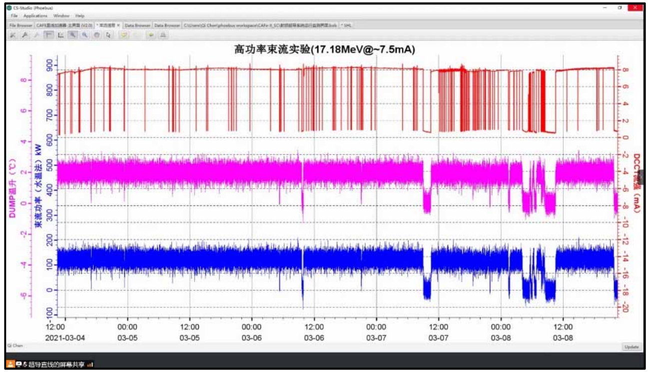
CW beam recovered by MPS and Timing system

- If Fault is a "Fast Recovered", only the trigger signals of chopper and FF are stopped. Accelerator is auto-recovered.
- If Fault is a "Failure", both the trigger signals and chopper are stopped. Accelerator waits for 5 second for next beam shot.
- If Fault is an "Emergency", the trigger signals, LEBT FC, chopper are stopped.

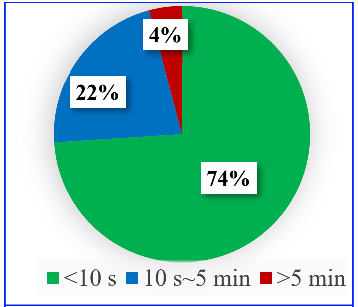
Auto Recovery Validated at CAFe

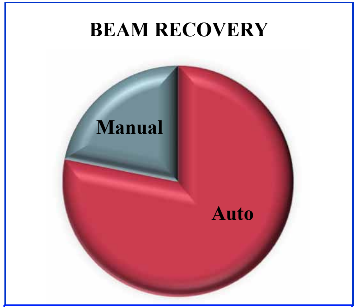


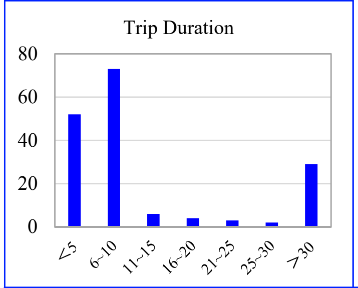
10 s beam automatic recovery logistics

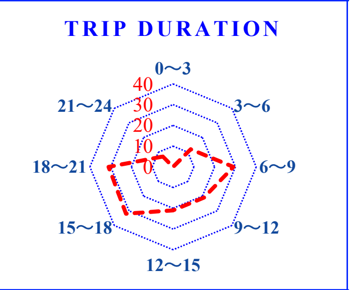


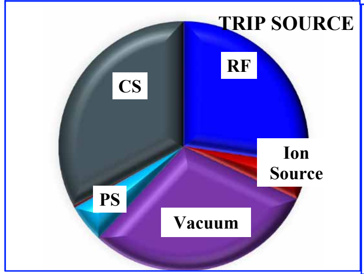
Beam current record for 108 hours operation

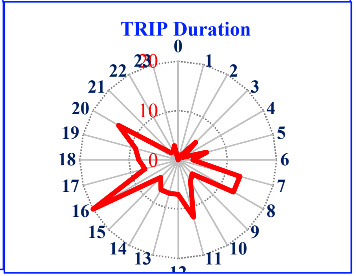












Beam Energy	17.27±0.03 MeV
Beam Current	7.30±0.02 mA
Beam Power	126.0 kW
Planed Operation Time	108 hours
Beam Availability	93.6%
SRF Availability	98.0%
MTBF	135 min
MTTF	9.3 min

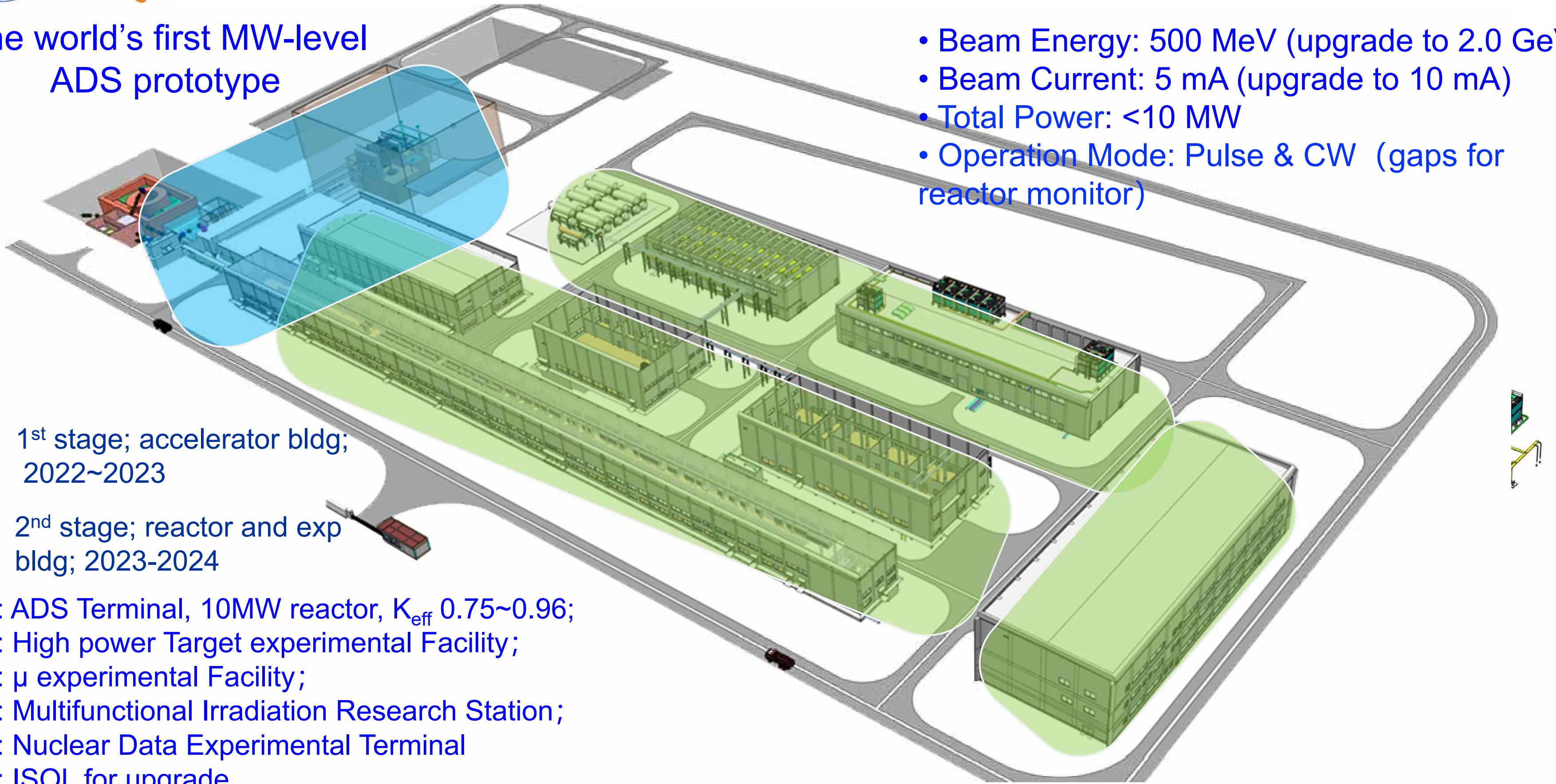
- 78% of trips are auto-recovered
- 3 long trips：
  - Mechanical pump before DUMP failed and replaced
  - Timing system failed
  - LLRF chassis failed

Contents

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
- Operation Mode: Pulse & CW （gaps for reactor monitor）



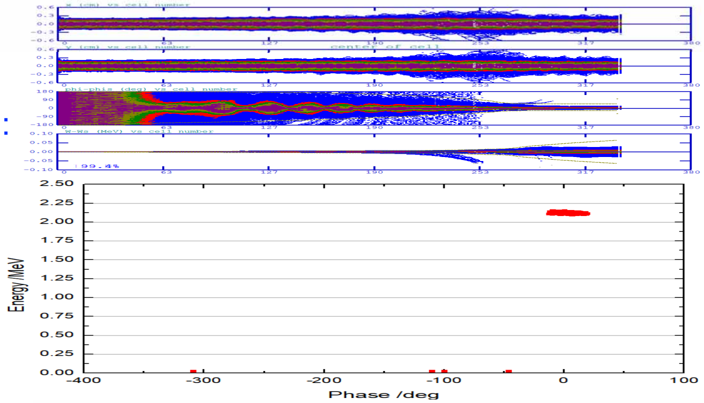
1st stage; accelerator bldg; 2022~2023

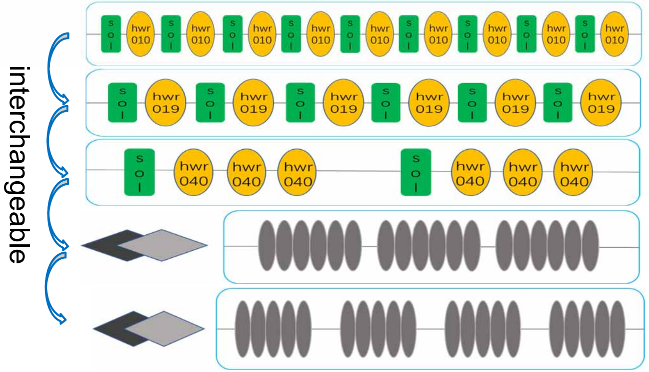
2nd stage; reactor and exp bldg; 2023-2024

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

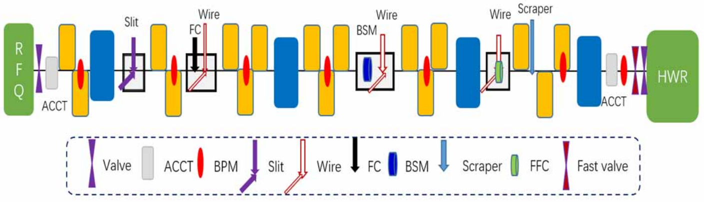
Beam Dynamics Optimization towards High Power Operation and Industrialization

Longitudinal: energy separation





Transverse: phase space collimation

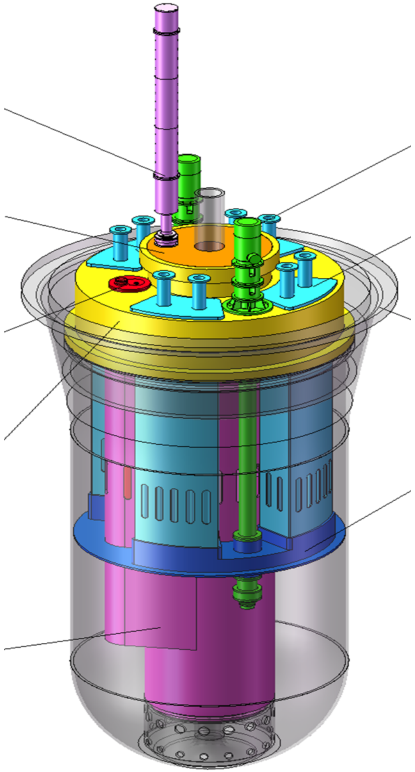


- "Clean" high power beam from room temperature front end

- All accelerating units (SC cavities + magnets) have the same length, readily interchangeable
- Low/medium energy SC segment: multiple focusing periods per cryomodule to reduce space charge effects
- High energy SC segment: one focusing period per cryomodule to reduce the impact of mismatch
- Collimation in warm section to reduce beam loss in SC segments

Subcritical Fast Reactor

	Top level spec.
type	LBE sub- FR
Power	10MWt (incl. beam)
fuel	UO_2 (19.75%)
K_{eff}	0.75~0.96
Main coolant Configuration	Pool-loop
Main coolant driven mode	Forced circulation
Coolant	LBE
Main coolant pressure	Normal
Main coolant temp	280-380℃
Main heat exchanger	Main exchanger×4
Main pump	Mechanical pump×2
Secondary Loop coolant	LBE
Secondary Loop pressure	Normal
Secondary Loop Temp	220-230℃

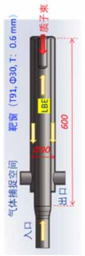


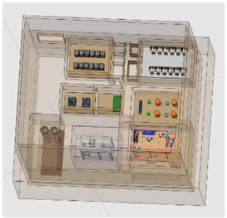
Roadmap for High Power Spallation Target

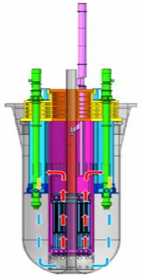
Realizing the world's first high-power spallation target coupled with the reactor, achieving acceptance indicators.

- System equipment reliability and target thermal hydraulic testing.
- Accelerator-target coupling technologies （beam scanning, collimating...）
- Validation of target window

2022	2023	2025	2027
Thermal prototype →	Target window testing prototype →	Hot test terminal →	CiADS spallation target



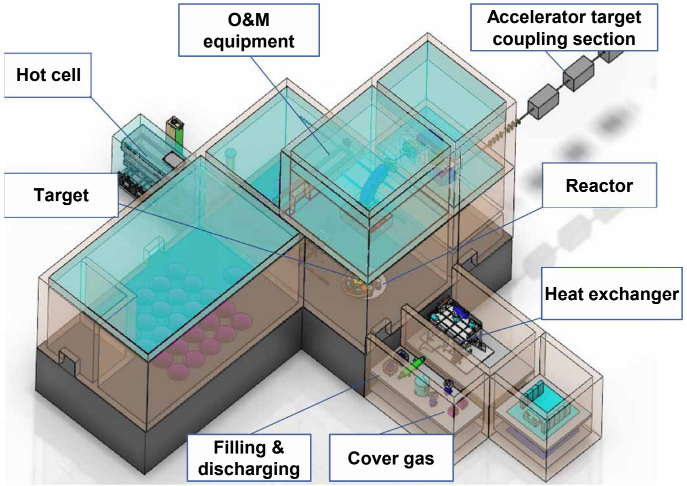




Built completed and conducting experiments

Preparing for the test experiment

Technological design completed



The challenges of CiADS spallation target：

- Reactor embedded installation, no beam window, liquid metal cooling, length > 6m, diameter < 0.5m, beam power ~2.5MW
- A 2.5 MW liquid lead-bismuth target operating in real reactor environment carries high technical risks

Reference prototype：MEGAPIE，beam power~0.8MW（575MeV，1.4mA），4 months’ operation，continuous operation for 4 hours

Civil Construction of CiADS

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

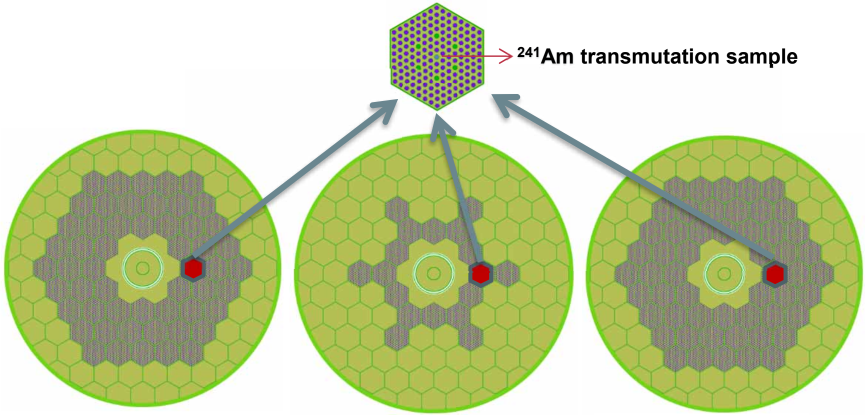
- Accelerator ~2.5MW
- Target ~2.5MW
- K_{eff}~0.75
- Reactor ~7.5MW

- **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

Transmutation and Upgrade Plan

- Upgrade of reactor to 100 MW with all fuel bars inserted
- The feasibility study of ^{241}Am and ^{237}Np transmutation experiment will be carried out.

k_{eff}	Neutron flux ($n/cm^2/s$)	Total power (MW)	^{237}Np	^{241}Am
			90 d	
0.96	1.15E+15	100	1.57%	2.73%

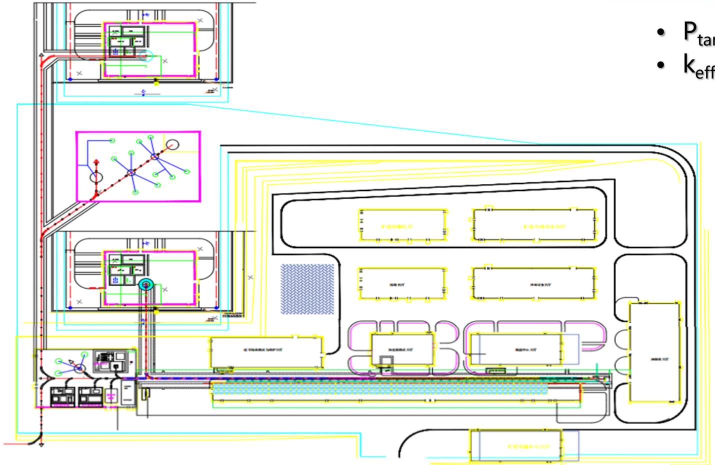


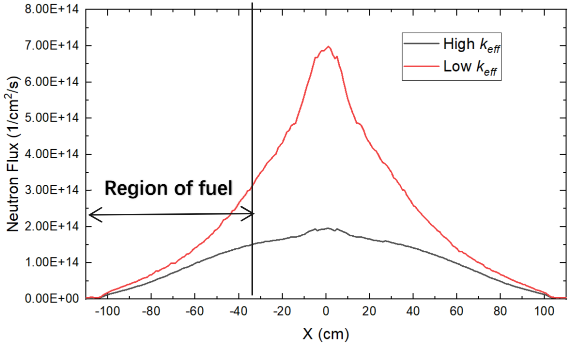
- P_{target} 250kW
- k_{eff}~0.96

- P_{target} 2.5MW
- k_{eff} ~0.75

- P_{target} 2.5MW
- k_{eff} ~0.96

- The proton linac will upgrade to 1.5 ~ 2 GeV and 10 mA
- A second reactor of 600 MW is planned to be constructed





1. Low k_{eff} with high accelerator current intensity in subcritical reactor
2. Significantly increasing the neutron flux rate in the reactor.

Contents

Conclusion

- ADS is a solution to multiple problems of the nuclear energy system. It will also help to resolve climate change by reducing carbon emission.
- ADS is full of challenges. Fortunately, China (CiADS), EU (MYRRHA), India and Japan are firmly taking the first steps.
- CiADS will be constructed within 10 years. It will make the first demonstration of MW ADS to pave the way towards commercial ADS.
- The accelerator community has a duty to advance sustainable energy and sustainable society. ADS gives us an ideal opportunity to engage in this worthwhile pursuit.

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Thank you for your attention !