Updates on the worldwide efforts for transmutation of spent nuclear fuel with accelerator driven systems

Bruce Yee-Rendon

Japan Atomic Energy Agency (JAEA)
Japan Proton Accelerator Research Complex (J-PARC)

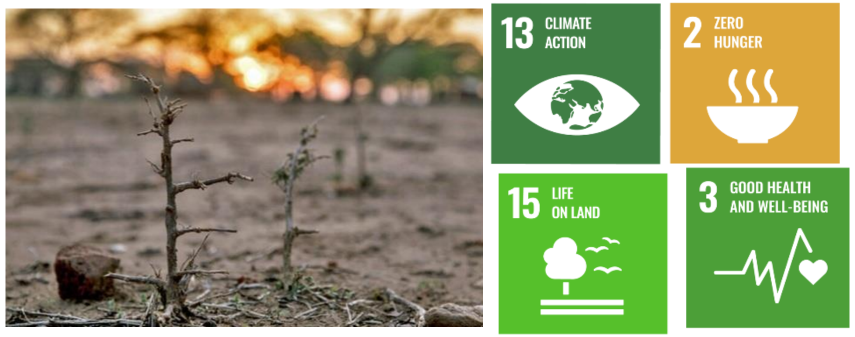
LINAC2026
Aug 16-21, 2026.

This work was supported by JSPS KAKENHI Grant Number JP24H00235.

Contents

Motivation: Global warming

- **Global warming** is a **major threat** to **human society** and the **planet's ecosystem**.



UN, Sustainable Development. https://www.un.org/en/teach/SDGsV

- As **energy** and heater producers are responsible of **44% of global greenhouse gas emission**, **energy sector** play a **key role** in the climate change[1].

- The International Energy Agency (**IEA**) proposed the "**Net Zero by 2050**"[2] roadmap to limit the increase in global temperatures to 1.5°C and thus **avoid a climate catastrophe**, while **providing affordable and sustainable energy**.

IEA, Net zero by 2050 : a roadmap for the global energy sector, https://www.iea.org/reports/net-zero-by-2050.

[1] IAE, Total CO2 emissions, https://www.iea.org/world/emissions#what-are-the-main-sources-of-global-co2-emissions
[2] IAE, Net zero by 2050 : a roadmap for the global energy sector, https://www.iea.org/reports/net-zero-by-2050.

Role of the Nuclear energy

"**Nuclear energy** is **essential** of achieving as part of the **Net Zero by 2050** plan", IAEA.

Advantages:

- **Low** carbon **emission**
- **Energy security**
- **Highly efficient** (energy production vs footprint)

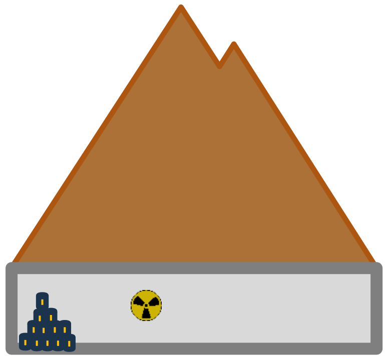
The IAEA predicts the **duplication** of global **nuclear power** by **2050**[1]

Challenges:

- Nuclear waste
- Security
- Public awareness
- Environment impact

Nuclear waste Storage:

- Long term ~**10^6 years**
- 260,000 tons (from 1950)[2]



High cost:

$37.1 Billion (USA's Nuclear waste budget)

[1] IAEA, *Nuclear Energy for a Net Zero World,* (Vienna: IAEA, 2021).

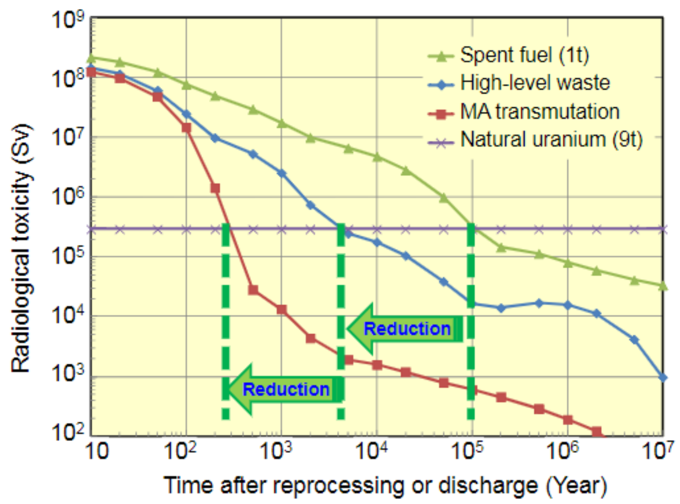
[2] IAEA, "New IAEA Report Presents Global Overview of Radioactive Waste and Spent Fuel Management", https://www.iaea.org/newscenter/news/new-iaea-report-presents-global-overview-of-radioactive-waste-and-spent-fuel-management

[3] U.S. Department of Energy, "*Audit of the Department of Energy's management of nuclear waste disposal"* (Report No. DOE-OIG-25-03), Nov. 2024.

Advantageous solution: Accelerator Driven Subcritical (ADS)

ADS is a **hybrid nuclear technology** that combines

High-power proton accelerator $\xrightarrow{p}$ Spallation target $\xrightarrow{n}$ Subcritical reactor

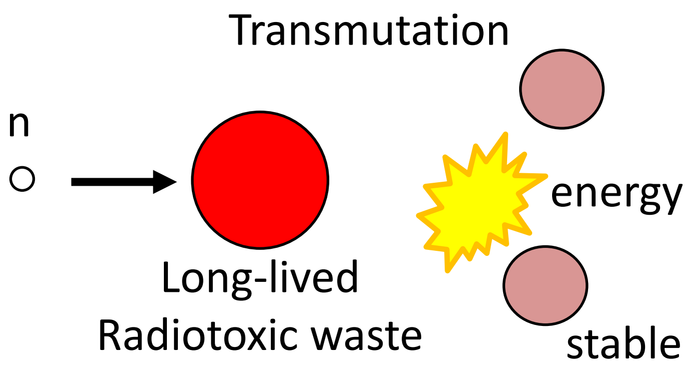


Reduction of radiotoxicity by P&T. H. Oigawa , "JAEA's R&D Activities on Transmutation Technology for Long-lived Nuclear Wastes", ImPACT Symposium, 2nd Dec. 2018.

Applications:

1) Nuclear waste:

Transmute long-lived radiotoxic elements (MA), **reducing volume, and toxicity**.



2) Energy production:

Th ADS (**Energy amplifier**).

3) Fuel production:

Fertility element → fission element (**Accelerator breeder**).

4) Nuclear medicine:

Production of **radioisotopes**.

Advantages:

- **Inherent safety:** the system is subcritical, thus the reaction stop when the beam is stop.
- **Fuel composition flexibility:** minor actinides, plutonium, non-fissile fuels (as Thorium).

Simplified ADS timeline

Early stage (1910-1950)	Revival (1980-2000)	Modern Era (2000-Now)

Early stage (1910-1950)

- **1919:** The first artificial transmutation (E. Rutherford)
- **1932**: Splitting the atom using an accelerator (J. Cockcroft)
- **1940s:** Accelerators as neutron sources (E. O. Lawrence(USA) and W.N. Semenov (USSR))
- **1949-52:** Materials Testing Accelerator Project (MTA), (accelerator breeder)

Revival (1980-2000)

- **1980s:** Renew interested in ADS projects transmutation (PHOENIX (BNL, USA), OMEGA (JAERI, Japan))
- **1992:** ATW (Los Alamos)
- **1993**: Energy amplifier (C. Rubia)
- **1994:** Venus 1 (China-CIAE)
- **1998:** European ADS Roadmap

Modern Era (2000-Now)

- **2009:** World's First Functional ADS Experiment (KUCA, Japan)
- **2011:** CiADS Phase I (China)
- **2018**: MYRRHA Approval
- **2019:** Transmutex company
- **2021:** CiADS Phase II (China)
- **2024:** MYRRHA Phase I Groundbreaking
- **2024**: Newton project (ARPA-E, DOE, USA)
- **2025:** Subcritical System Inc company

High intensity accelerators

The ADS accelerator must:

Beam's requirement	Value range	Challenge	Comment
Power	**few to tens of MW**	• Stable & efficient CW MW operation • Beam losses < 1 W/m	Defined by thermal power and subcriticality of the reactor (few MW for Demo & tenths for Industrial scale)
Energy	**several hundreds MeV to 2 GeV**		Efficient spallation source
Time structure	**CW**/ pulsed (for demo?)		Reactor operation compatibility
Availability	**Tens** of beam trips **longer than few min** and **thousands shorter than few min** per **year**	• Reduces # of trips and/or its duration	Avoid thermal stress in the reactor structure

Accelerator comparisons [1-3]:

Type of accelerator	**Linac**	Cyclotron	Synchrotron	FFAG
Power	**MW operation possible to operate a higher**	Restricted to few MW	MW operation	Hundreds of kW
Energy	**GeV operation**	< 1 GeV	GeV operation	< hundreds of MeV
Time structure	**CW operation**	CW operation	Pulse operation	Pulse operation (CW is possible)
Availability	**Reliability-oriented**	• No redundancy • No Fault compensation	• No redundancy • No Fault compensation	• No redundancy • No Fault compensation

Currently, **linacs** are the **best choice**

[1] H.A. Abderrahim et al, FERMILAB-FN-0907-DI (2010).
[2] W. Pan, FRXCB01, IPAC2014 (2014).
[3] B. Yee-Rendon et al, TU2AA01, LINAC2022(2022).

ADS accelerator challenges

- **Stable & efficient CW**

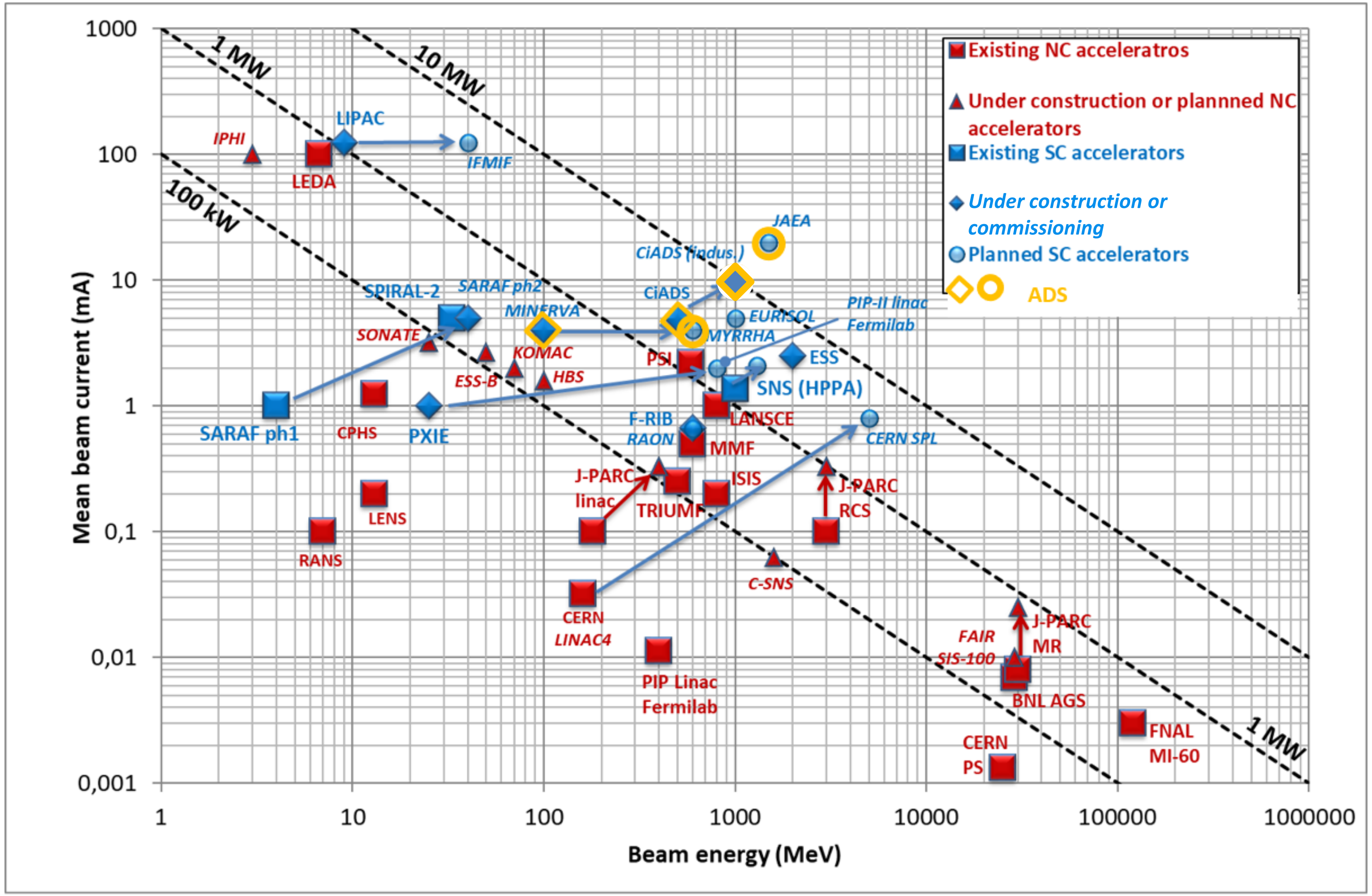
  (Ready-almost)

- **Beam loss < 1 W/m** at MW regime

  (Ready-almost)

Several accelerators have been designed and are operating in the MW region[1]: their R&D has paved the way for ADS machines.

ADS are **expanding** the barrier of **high-power** accelerators.



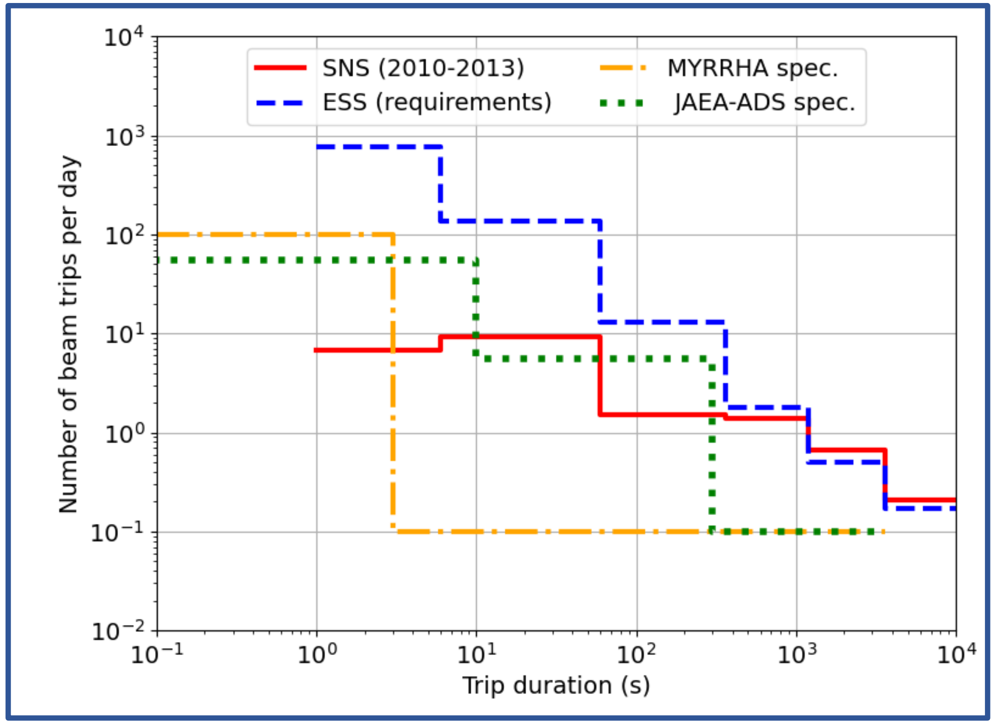
High-power map. Courtesy of J.L. Biarrotte and F. Bouly.

[1]J. Galambos, FRXPLM1, IPAC’19(2019).

High reliability

High reliability is required to avoid thermal stress in the reactor structures.

(almost-not yet)



Beam trips for different accelerators. Courtesy of SNS,ESS, and MYRRHA [1]. MYRRHA accepts less than 10 beam trips longer than 3 s per 90 days, and JAEA-ADS admits less than 42 beam trip longer than 5 minutes over one year.

Reliability-oriented design[2]:

Robust lattice design:

- Control of the beam loss.
- Simple design.
- Derating components operation.

Fault-tolerance:

- Serial and parallel redundancies.
- Large interested in cavity compensation [3,4].

Repairability:

- Online and manual.
- Maintenance.

[1] [1] D. Vandeplassche et al , MOYAP01, IPAC 2012 (2012); E. Bargallo et al, MOPTY045 , IPAC 2015 (2015), H. Takei et al, JNST.49. 384-397 (2012).

[2] J. L. Biarrotte, Reliability and fault tolerance in the European ADS project, in Proceedings of CAS 2011.

[3] A. Plaçais et al., THXA001, LINAC’24, (2004).

[4] V. S. Morozov et al., PRAB25, 020101,(2022).

(partially)Worldwide ADS activities

Activity	Accelerator	Purpose	Status
MYRRHA (Europe/Belgium)	2.4-MW SRF proton linac	ADS demo	Phase I (100-MeV linac) under construction
CiADS (China)	3-MW SRF proton linac	ADS demo	Phase II commissioning
JAEA-ADS (Japan)	30-MW SRF proton linac	Transmutation of nuclear waste	Design
ADS program (India)	10(30)-MW RF proton linac	ADS Th based nuclear reactor	20-MeV injector commissioning
TAC (Turkish)	2.5-MW SRF proton linac	ADS Th based nuclear reactor	Standby
Subcritical Systems Inc (USA)	20-MW SRF proton linac	Nuclear energy production	Design
SHINE Technologies (USA)	15 (30)-kW D+ linac	Neutron based transmutation	R&D
Newton project (USA, ARP-E)	NA	Enable the technology for nuclear transmutation	Supporting 10 projects
KUCA (Japan)	100-W proton FFAG	Experimental studies for ADS	Operation
TRANSMUTEX (Swiss)	2(4) -MW proton Cyclotron	Medical Isotopes (HI-BEAM), nuclear energy production and nuclear waste	R&D

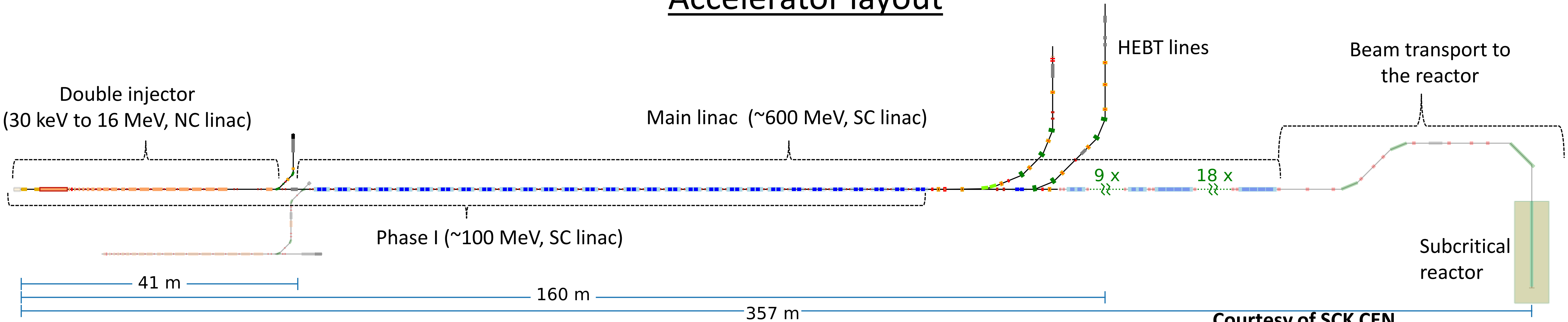
General information of MYRRHA

- The Multi-purpose hYbrid Research Reactor for High-tech Application (**MYRRHA**) will be located in Mol, Belgium.

MYRRHA	
Proton linac	
Energy (MeV)	600
Beam current (mA)	4
Operation modes	CW
Target	
Max Power (MW)	2.4
Material	LBE
Fast Reactor	
Keff	0.95
Thermal Power (MW)	50-100

1. **Phase 1** currently being implemented at SCK CEN (Belgium)[1]:
   - 100 MeV, 4mA CW SC-linac
   - User stations for fusion material research and radio-isotope production
   - Prelicensing for the reactor
2. Phase 2 & 3 will include:
   - The extension of the linac to 600 MeV
   - The subcritical reactor (70MWth)

Accelerator layout

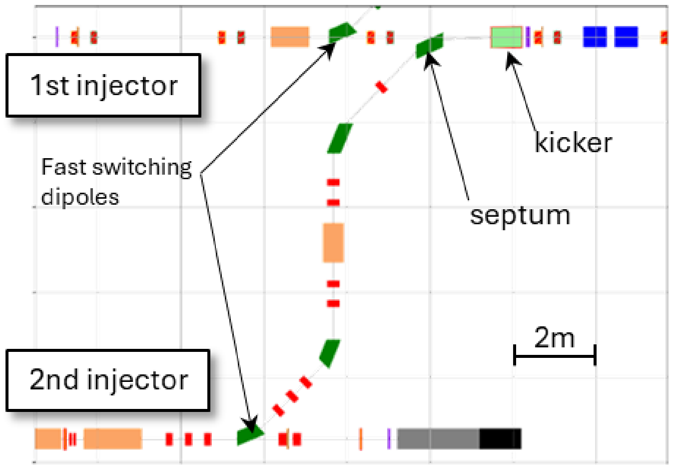


Courtesy of SCK CEN

[1] U. Dorda et al, THP4014 , IPAC 2026, (2026).

MYRRHA Phase I activities

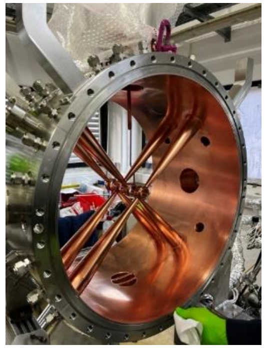
Beam optics [1-3]:



Updated injector layout

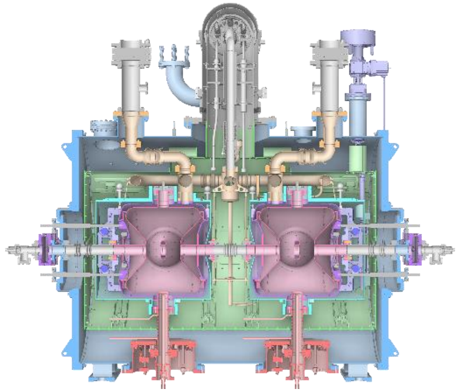
Cavities and Cryomodules [1]:

Courtesy of SCK CEN



NC: series production starting at RI

SC cavities: series production >50% done at RI



Cryomodule: Design completed, tenders assigned

Other components[1]:

- Solid state amplifiers: Cryoelectra
- Beam dumps: ESS Bilbao
- Collaboration with DESY on LLRF
- Magnets: framework agreement being set up
- Control system: EPICS
- Timing system: White rabbit

Building construction [1]

- Utility building (RF gallery & infrastructure) construction completed
- Main building & accelerator tunnel: **Construction start in fall'26**

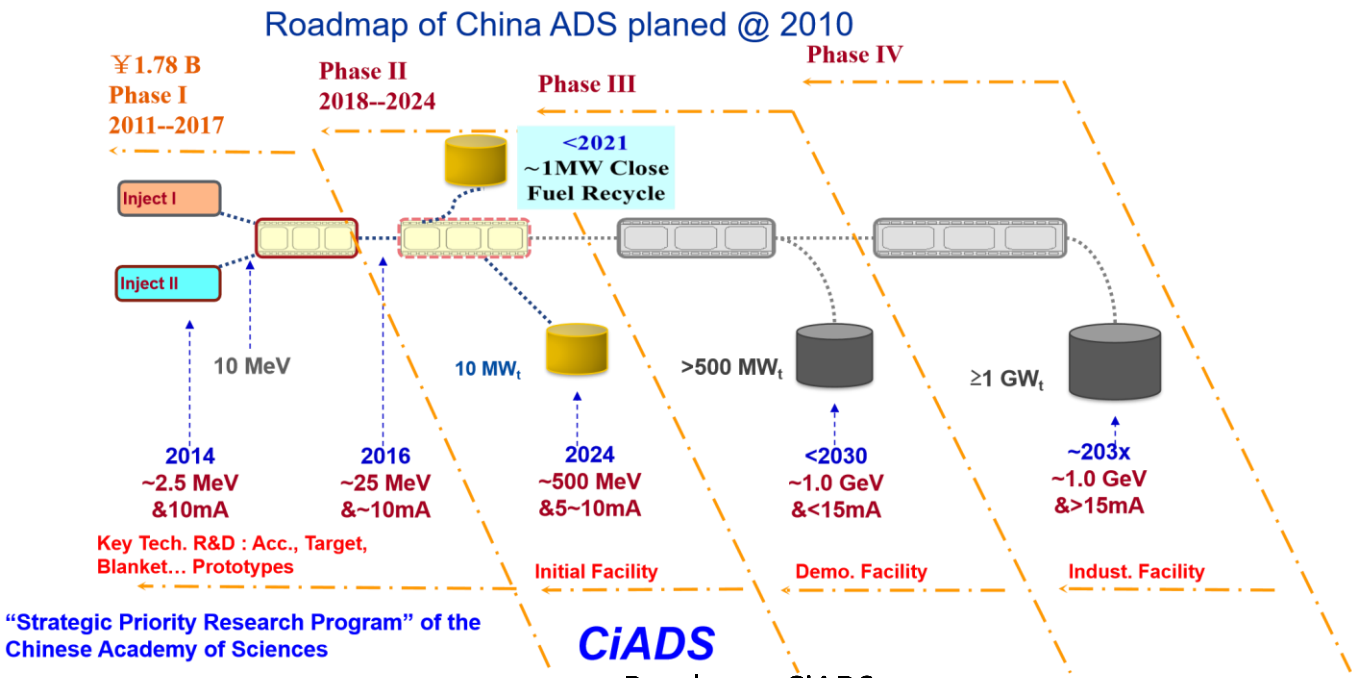
Entered full implementation phase

[1] U. Dorda et al, THP4014 , IPAC 2026, (2026).
[2] L. De Keueleere et al, THP4056, IPAC 2026, (2026).
[3] L. De Keueleere et al, THP4057, IPAC 2026, (2026).

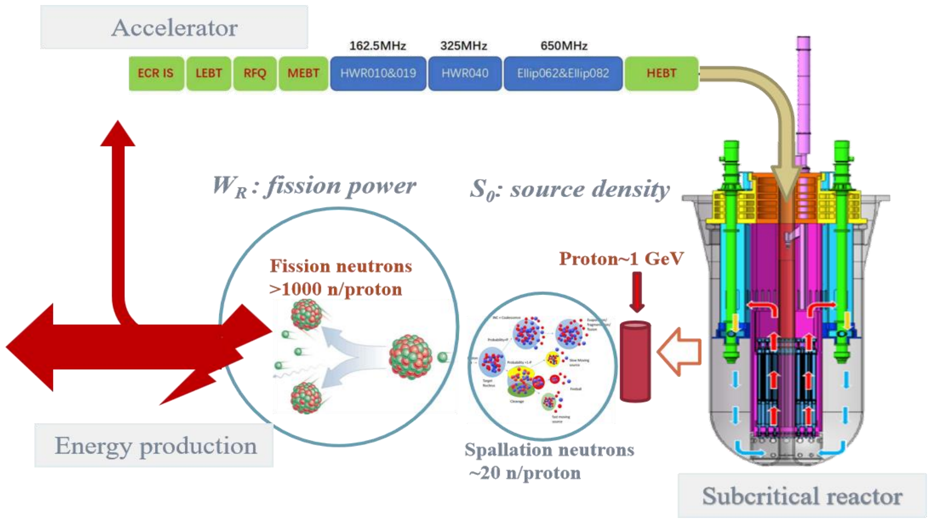
General information of CiADS

- China initiative Accelerator Driven System (**CiADS**) is the **first step** of our **ADS plan**, it located in **Huizhou, China**.
- CiADS will be the world's **first MW-level ADS prototype**.

CiADS	
Proton Linac	
Energy (MeV)	600
Beam current (mA)	5
Operation modes	CW / Pulse
Target	
Max Power (MW)	3
Material	LBE
Fast Reactor	
Keff	~ 0.75 / ~ 0.96
Thermal Power (MW)	~ 7.5 / ~9.76



Road map CiADS.



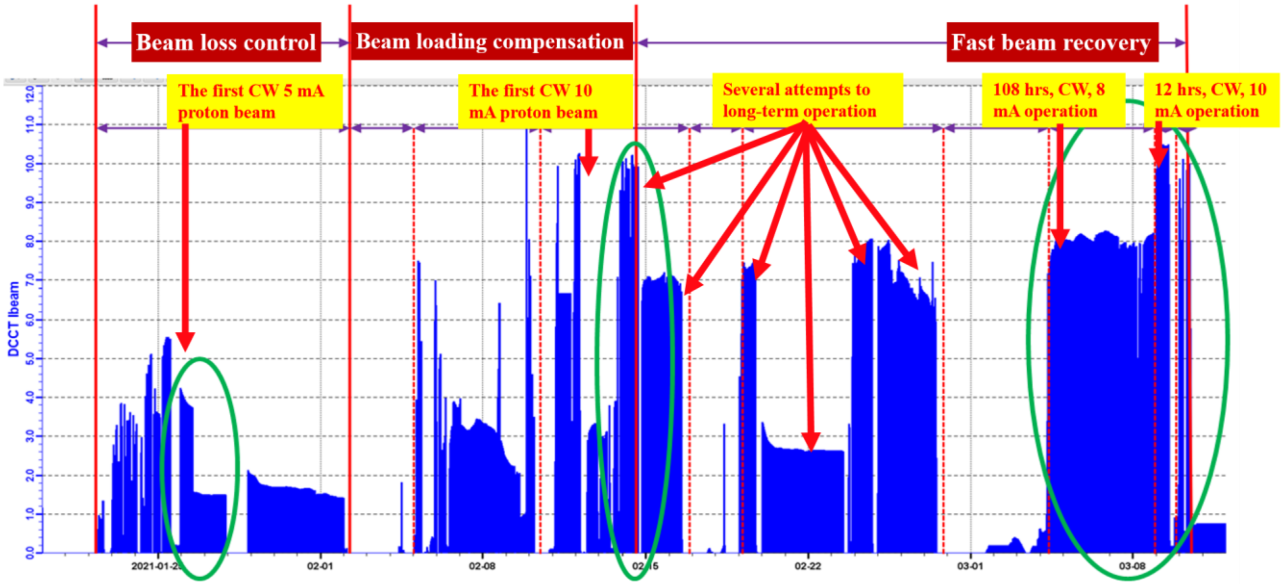
Courtesy of IMP

CAFe and CiADS Present Status

Phase I CAFe

Courtesy of IMP

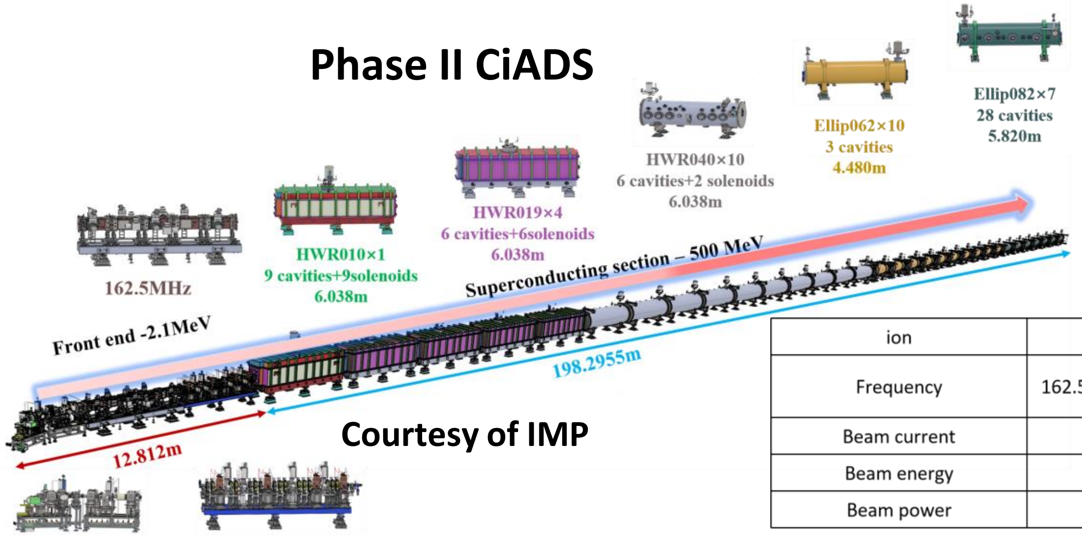
ion	Frequency	Beam current	Beam energy	Beam power
P	162.5/325MHz	0~10mA	20MeV	Up to 200KW



The CW beam current of 10 mA has been **demonstrated for a long-term operation** with the **availability up to 96.2%** [1].

[1] Z. Wang et al, TUZA003, LINAC2024, (2024).

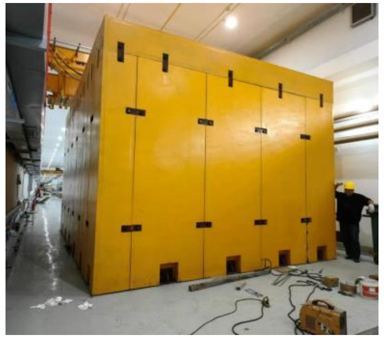
Phase II CiADS



Courtesy of IMP

ion	P
Frequency	162.5/325/650MHz
Beam current	5mA
Beam energy	600MeV
Beam power	3MW

Installation completed to CM062



25 KW beam dump

Ellip-082 SC cavity

650 MHz SSAMP

Power Supply System

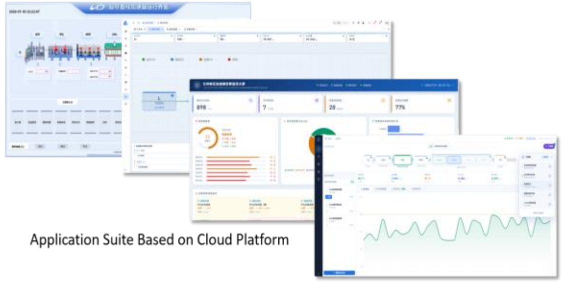
LLRF System

The CiADS linac will **commissioning** with a beam power of **25KW in 2026.**

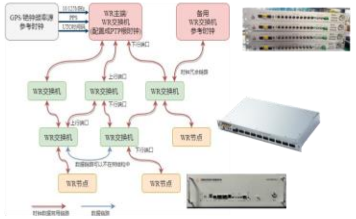
See Y. He et al, **TH1A005**

Other activities

Private Cloud Computing Platform



Application Suite Based on Cloud Platform



A Timing and Protection System Based on White Rabbit Real-Time Network

General Intelligent Accelerator information Terminal

Control System of CiADS

- Generalized & Modular Deployment Architecture
- Highly Reliable Real-Time Timing & Protection
- Layered Integrated Operation & Control System

System View (Partial)

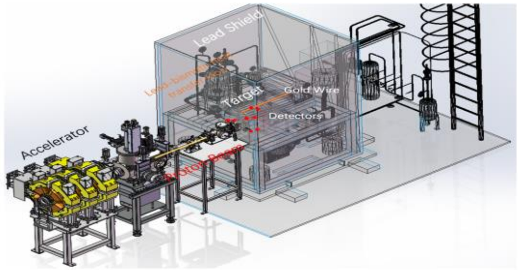
LBE Quality Control System

Flow Curve-Operation Test

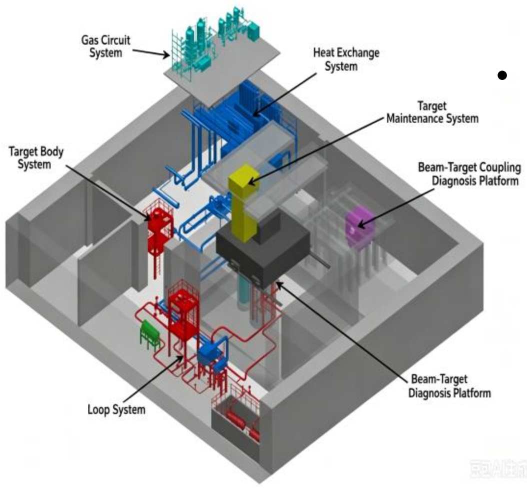
CiADS Reactor Mock-up

- Main equipment prototypes (vessel, internals, pumps, HX, cooler) developed & validated.
- LBE Coolant Quality Control—— Enabling Stable System Operation
- Coupled operation of LBE melting system, component loop, secondary & tertiary loops demonstrated; passed 120 h continuous test.

Thermal Prototype of Spallation Target



Target window prototype



Spallation target thermal testing terminal

- The key systems of target have completed the construction design review and started processing and manufacturing 。

CiADS Spallation target

CiADS cryogenic system

- Complete the construction of a cryogenic system with 18kW/4.5K (4kW/2K)
- Supporting facilities including the recovery and purification system, ambient-temperature pipelines and helium gas storage system have been put into service.

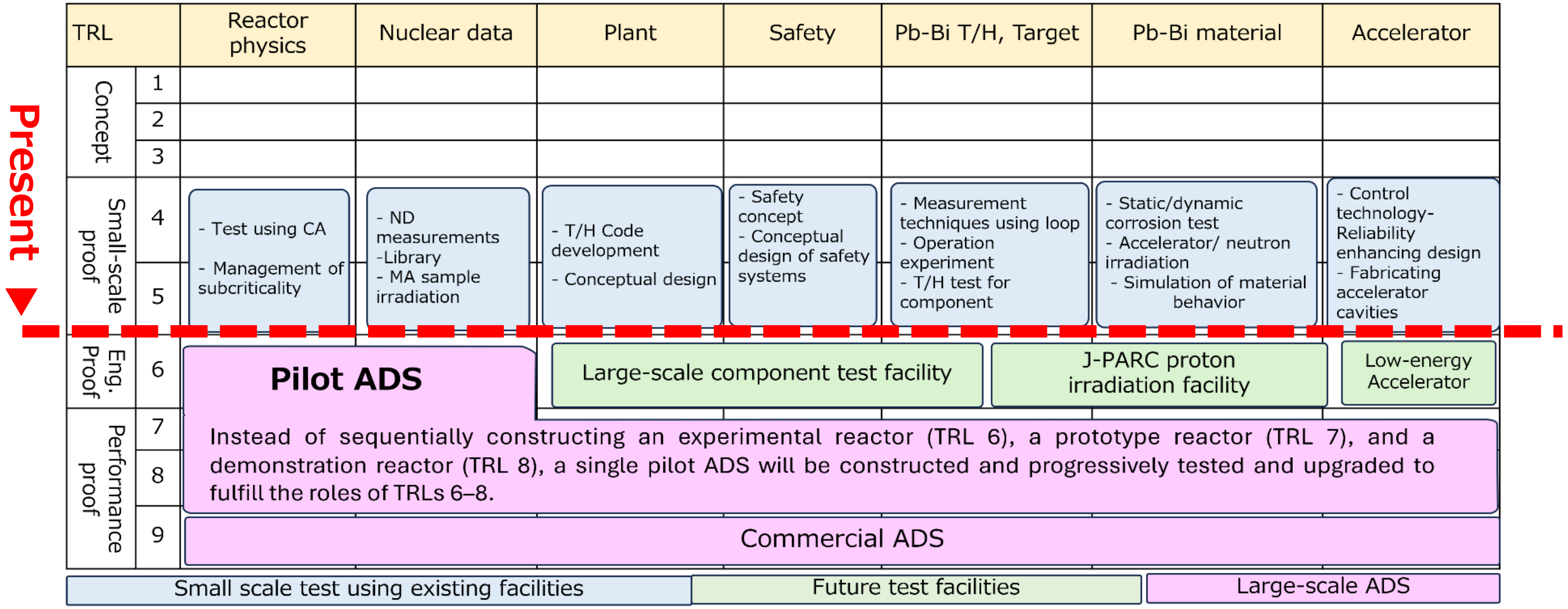
See Y. He et al, **TH1A005**

Courtesy of IMP

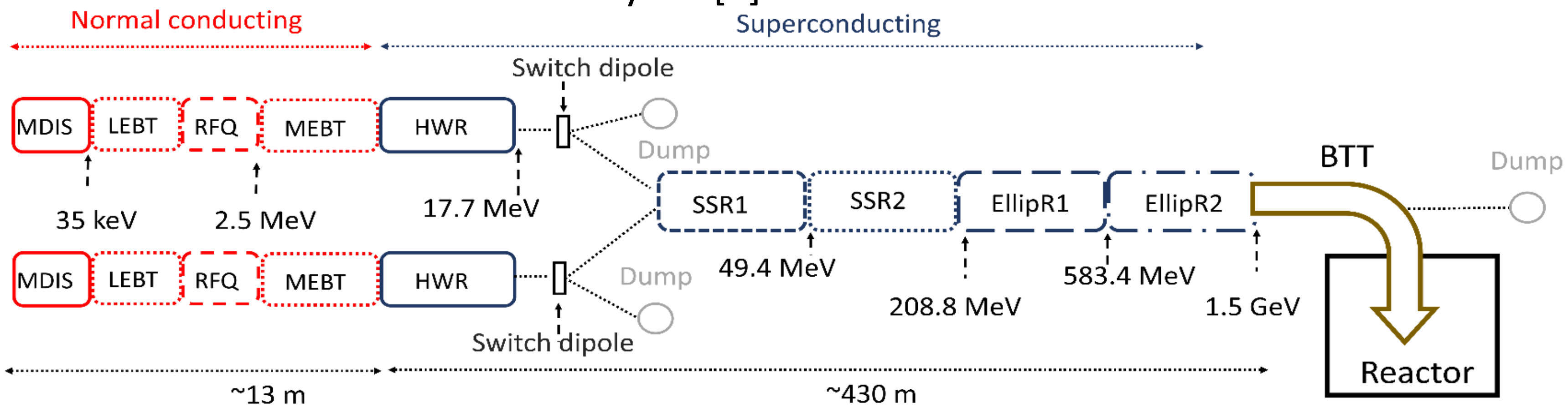
General information of JAEA-ADS

JAEA-ADS	
Proton linac	
Energy (GeV)	1.5
Beam current (mA)	20
Operation modes	CW
Target	
Max Power (MW)	30
Material	LBE
Fast Reactor	
Keff	0.97
Thermal Power (MW)	800

Technology readiness level (TRL) road map of ADS development in Japan [1]



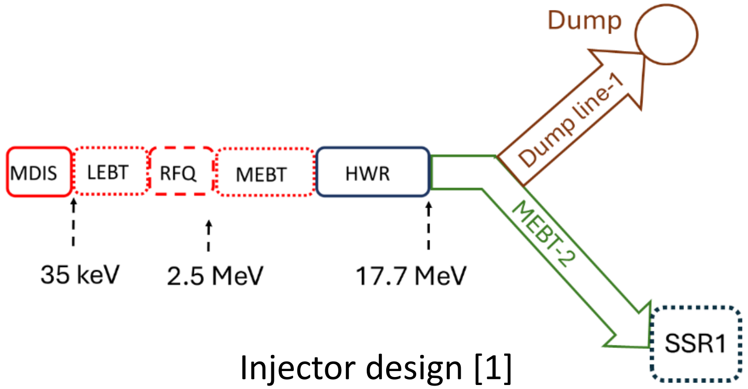
JAEA-ADS layout [2]



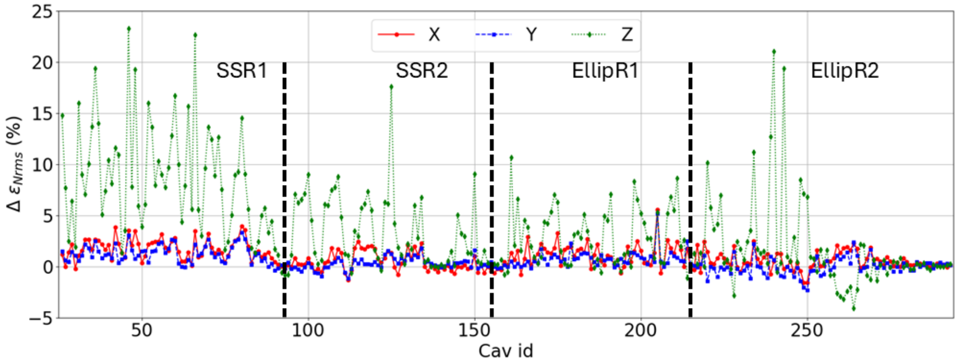
[1] K. Nishihara et al., "Conceptual Design of Pilot Plant for Accelerator-Driven System ", Global 2026.
[2] B. Yee-Rendon et al, PRAB25,080101 (2022).

JAEA-ADS activities

Beam optics: **Desing completed**

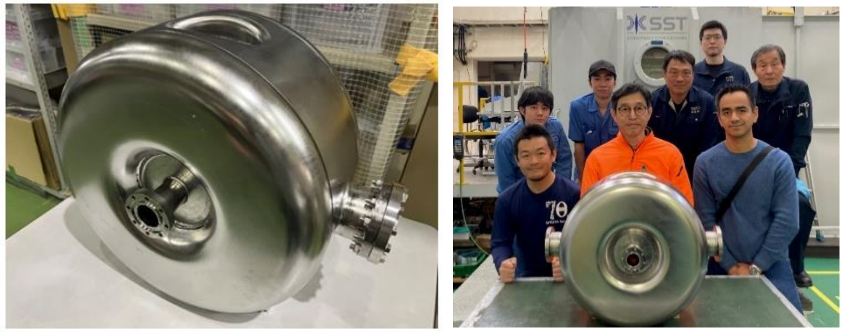


Injector design [1]

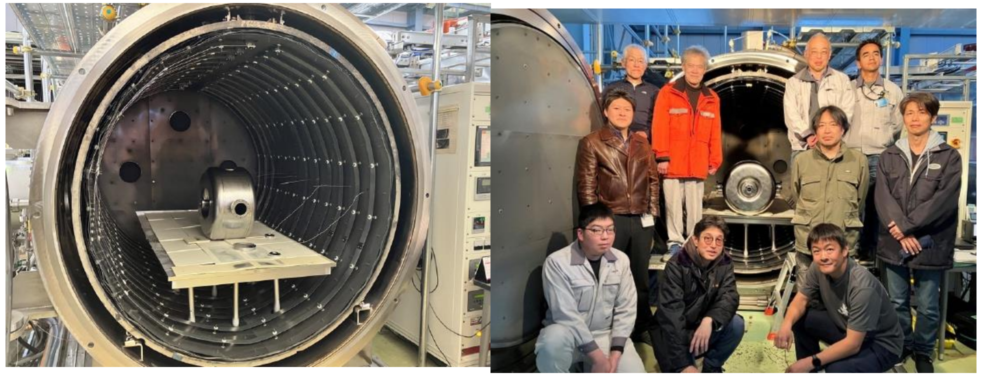


Cavities compensations [2]

Cavities:



Cavity assembly completed [3]

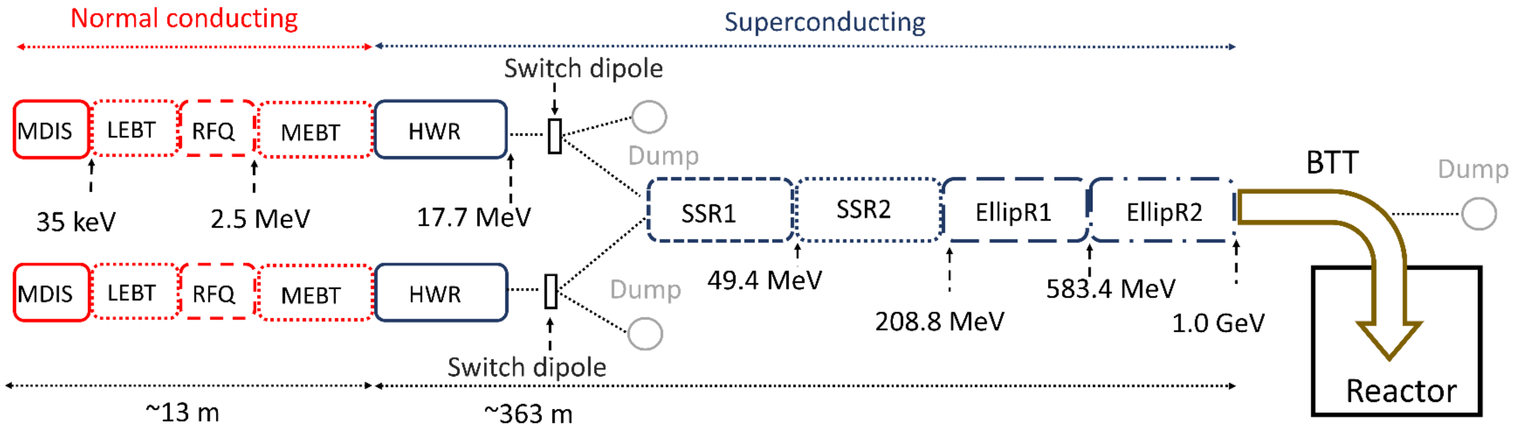


Surface treatment [4]

[1] B. Yee-Rendon et al, FRO602 , PASJ2025, (2025).
[2] B. Yee-Rendon et al, WEP4621, IPAC 2026, (2026).
[3] J. Tamura et al, THP39, SRF 2025, (2025).
[4] J. Tamura et al, WEP4619, IPAC 2026, (2026) .

Pilot-ADS

Motivation: A **Pilot**, reduced scale (10 MW), **ADS design** is a proposed by JAEA as a **wise-step approach to full scale ADS (30-MW)**.



Main parameters.

	Pilot ADS
Thermal output (MW)	200
Fuel	MOX (initial)
Proton energy (GeV)	**1**
Proton current (mA)	**10**
Max criticality	0.95

Status: The **design report** for the **Pilot ADS** has been **published** [1].

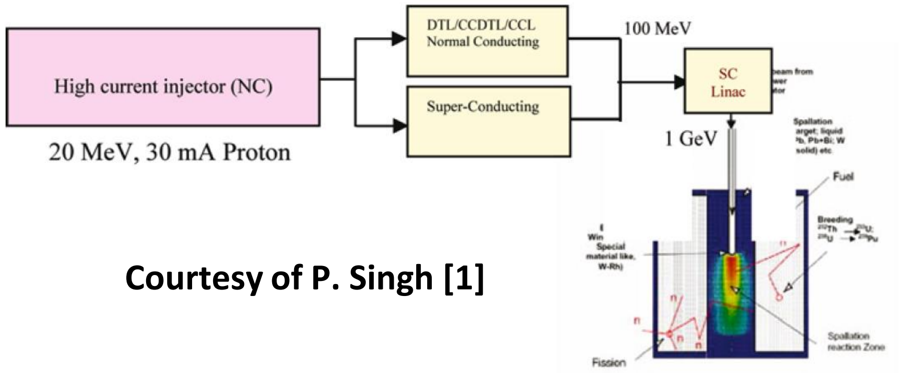
[1] K. Nishihara et al., "Conceptual Design of Pilot ADS", JAEA-Research 2025-013, (2026). DOI: 10.11484/jaea-research-2025-013.

ADS research in India

- ADS research activities developed by the Bhabha Atomic Research Center (**BARC**), India.

ADS research in India [1]	
Proton linac	
Energy (GeV)	1
Beam current (mA)	10-30
Operation modes	CW

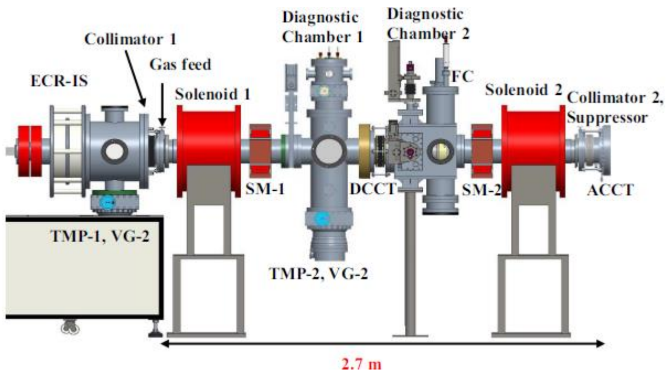
Accelerator layout



Courtesy of P. Singh [1]

Injector's research:

1) Commissioning Low energy high-intensity proton accelerator (**LEHIPA**) [2,3]



Courtesy of P. Priyadarshini [2]

LEHIPA [2]	
Energy (MeV)	20
Beam current (mA)	2

2) Design of the medium energy high-intensity proton accelerator (**MEHIPA**)

MEHIPA [4]	
Energy (MeV)	200
Beam current (mA)	10

Courtesy of A. Pathak [4]

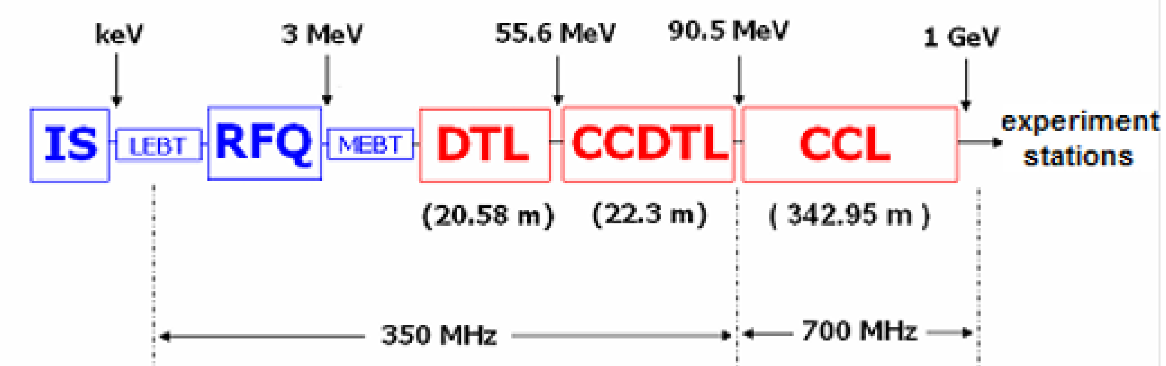
[1] P.Singh et al, PRAMANA ,68,331-342 (2007).
[2] P. Priyadarshini et al, Phys. Src. 99, 085312 (2024).
[3] P. Priyadarshini et al, PRAB 29, 0604201 (2026).
[4] A. Pathak et al, PRAB 23, 090101 (2020).

TAC

- Turkic Accelerator Complex (**TAC**) developed by 10 Turkish Universities: **1-GeV proton linac**

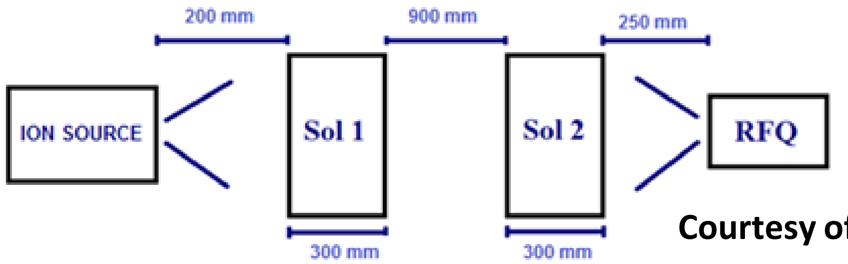
TAC [1]	
Proton linac	
Energy (GeV)	1
Beam current (mA)	2.5
Operation modes	CW

Accelerator layout



Courtesy of M. Arik [1]

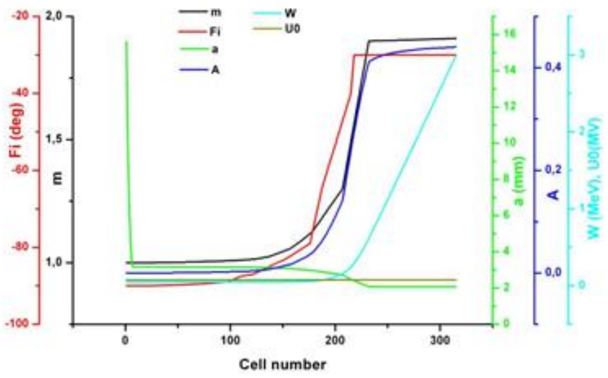
LEBT's optimization [2,3]



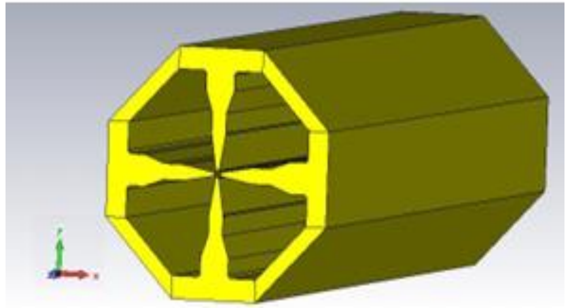
Courtesy of H.F. Kisoglu [3]

Schematic LEBT design

3-MeV RFQ design



RFQ parameters



RFQ model

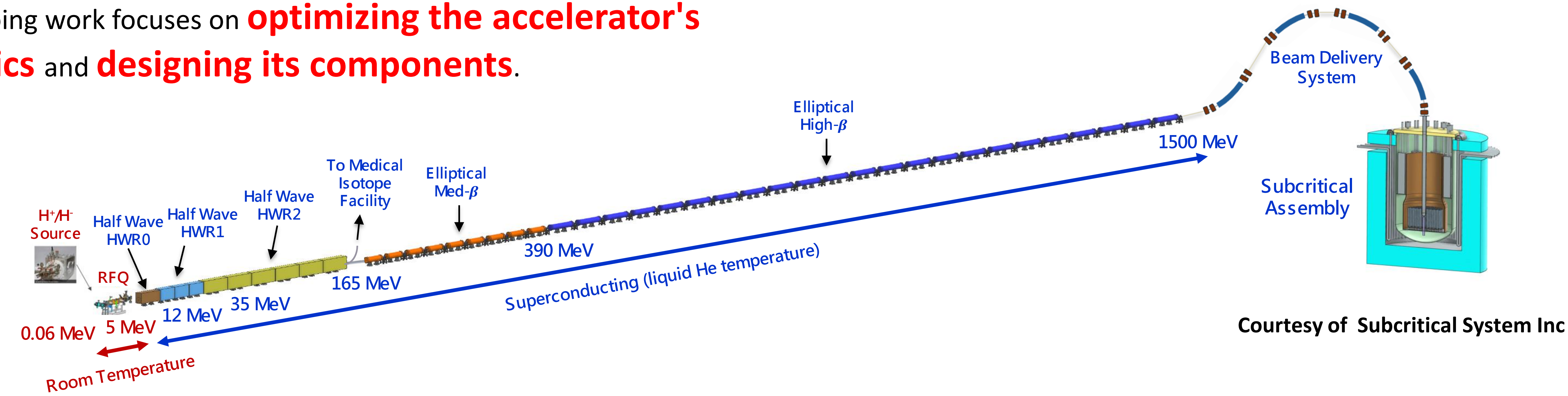
Courtesy of H.F. Kisoglu [4]

[1] M.Arik, et al, arXiv:1206.4957 (2012).
[2] A. Caliskan, et al, arXiv:1210.5845 (2012).
[3] H. F. Kisoglu, et al, arXiv:1401.1076 (2014).
[4] H. F. Kisoglu, et al, arXiv:1405.6085 (2014).

Subcritical System Inc

Subcritical Systems Inc., an Austin, Texas-based company, is developing an Energy Amplifier (EA) — an **H^+/H^- superconducting linac** driving a subcritical assembly for safe **nuclear energy** and **medical isotope** production.

Ongoing work focuses on **optimizing the accelerator's optics** and **designing its components**.



Courtesy of Subcritical System Inc

1.5 GeV
H^+ beam energy

20 MW
Peak beam power

300 MWe
Net electric power generated

200 Ci/yr
Ac-225 production using 165 MeV 5 mA H^-
~ 100x current global production

[1] Subcritical Systems Inc, Website, https://subcritical.com/

SHINE Technologies

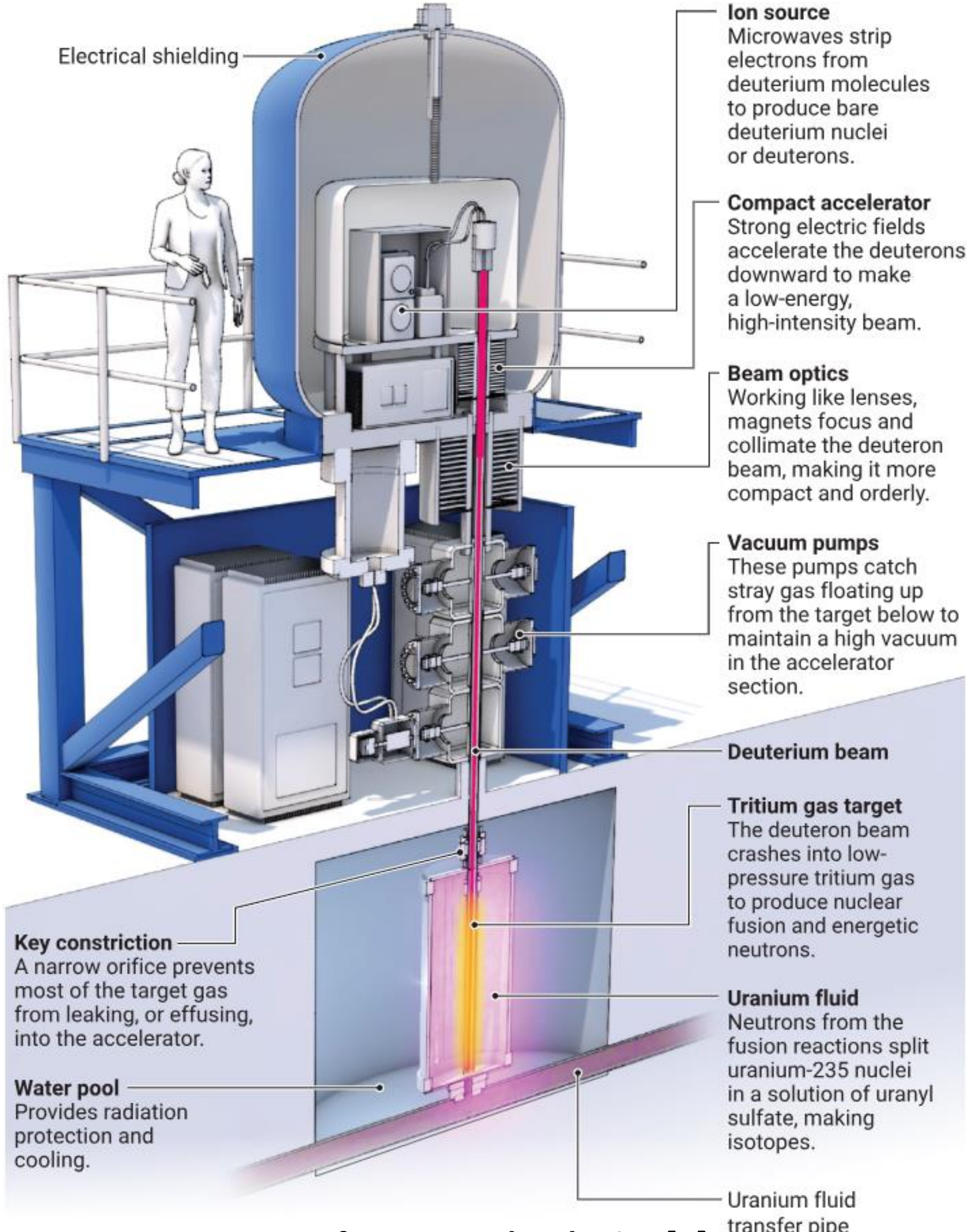
SHINE Technologies is a U.S. nuclear fusion company based in Janesville, Wisconsin [1], focused on fusion energy, neutron testing, nuclear medicine, and **nuclear waste recycling.**

Linac:

SHINE utilizes a **CW D+** accelerator with energies of up to **300 keV** and a beam current between **50 and 100 mA.**

Work

- **FLARE**: DT source operational for radiation testing.
- Future sources: **Chrysalis** (Isotopes production) and **UKAEA LIBRTI** (Tritium generation testing).
- **REDUCE** (Recover Elements - Destroy Undesirables - Create Energy): ARPA-E [3].



Courtesy of SHINE Technologies [2]

[1] SHINE Technologies, Website, https://www.shinefusion.com/
[2] SHINE Technologies, , "Technology Introduction." presented at NRC Kick of Meeting, March 2011. https://www.nrc.gov/docs/ML1107/ML110760025.pdf
[3] ARPA-E, "Programs and initiatives", REDUCE: Recover Elements - Destroy Undesirables - Create Energy, https://arpa-e.energy.gov/programs-and-initiatives/search-all-projects/reduce-recover-elements-destroy-undesirables-create-energy

Newton project

Nuclear **E**nergy **W**aste **T**ransmutation **O**ptimized **N**ow (**NEWTON**) by ARPA-E (USA, 2024) [1]

Goal: **enable the technology for nuclear transmutation.**

Categories:

A. **Beam technology**

B. Target technology

C. Integration tech for A & B into a techno-economic analysis and life-cycle assessment

Accelerator focus:

- **Reduce costs**
- **Increase efficiency & reliability**
- …

10 project supports (7 focus in accelerators)

Topic	Organization
Nb3Sn Proton Driver Linac for Accelerator Driven Systems	Argonne National Laboratory (ANL)
Superconducting Nb3Sn Cavities for Efficient and Reliable 10 MW Proton Linacs	Jefferson Science Associates, LLC
High-Efficiency Continuous-Wave RF Sources for High-Power Particle Accelerators	Jefferson Science Associates, LLC
SMART-OPS: Self-learning Machine intelligence for Accelerator Reliability, Trip Optimization, and Performance Stabilization	UT-Batelle LLC
Highly Reliable Ion Source and Injection Beamline to Maximize Proton Beam Availability	Transmutex U.S.A., Inc.
Compact Deuteron Accelerator to Produce Neutrons for Transmutation of Used Nuclear Fuel	Omega-P R&D, Inc.
Technical Approach to Achieving Attractive Ads Economics Based on Near-Term High Current Cyclotrons	SUNY University at Stony Brook
EINSTEIN: Enhanced Integrated Nuclear Systems for Transmutation and Efficient Isolation of Nuclides	University of Illinois, Urbana-Champaign
Liquid Lead Suspended Fuel Subcritical Fission Blanket for Nuclear Waste Transmutation	ANL
REDUCE: Recover Elements - Destroy Undesirables - Create Energy	SHINE Technologies, LLC

[1] ARPA-E, Newton, https://arpa-e.energy.gov/programs-and-initiatives/view-all-programs/newton

Summary

- **ADS** is an **advantageous solution** to the problem of **nuclear waste storage** and **low-carbon energy production** , thus contributing to a **sustainable society**.
- Its technology is **innovating** the fields of **high-power accelerators**, **fast reactors**, and the **nuclear fuel cycle**. It is particularly advancing **high-intensity accelerators**, allowing them to operate with **greater power, reliability, efficiency**, and **minimal beam loss.**
- ADS has generated **worldwide interest** among research centers, but it also caught the attention of the private sector. **Several ADS** projects are currently in the **design** and **construction** phases and will soon enter the **commissioning stage**.

Acknowledgements

Many thanks to my colleagues for their help:

- Dr. Ulrich Dorda, SKC CEN, Belgium.
- Dr. Yuan He and Zhijun Wang, IMP, China.
- Dr. Saleh Sultansoy, TOBB University of Economics and Technology, Turkey.
- Dr. Stuart Henderson and Dr. Joshua Yoskowitz, Subcritical Systems Inc, USA.
- Dr. Matthew Nyberg, SHINE Technologies, USA.
- Dr. Rongli Geng, Jlab, USA.
- Dr. Donovan Maire, Transmutex, Swiss.
- The JAEA-ADS team, Japan, specially to Dr. Kenji Nishihara, Dr. Yasuhiro Kondo, Dr. Jun Tamura, Dr. Shin-ichiro Meigo, and Dr. Fujio Maekawa.
- The worldwide ADS community.