# Overview of ADS projects in the world

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- The JAEA-ADS team, Japan, specially to Dr. Yasuhiro Kondo, Dr. Jun Tamura, Dr. Shin-ichiro Meigo, and Dr. Fujio Maekawa.
- The worldwide ADS community.

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- Motivation
- Brief introduction to ADS
- Worldwide ADS projects
- Summary

# Motivation

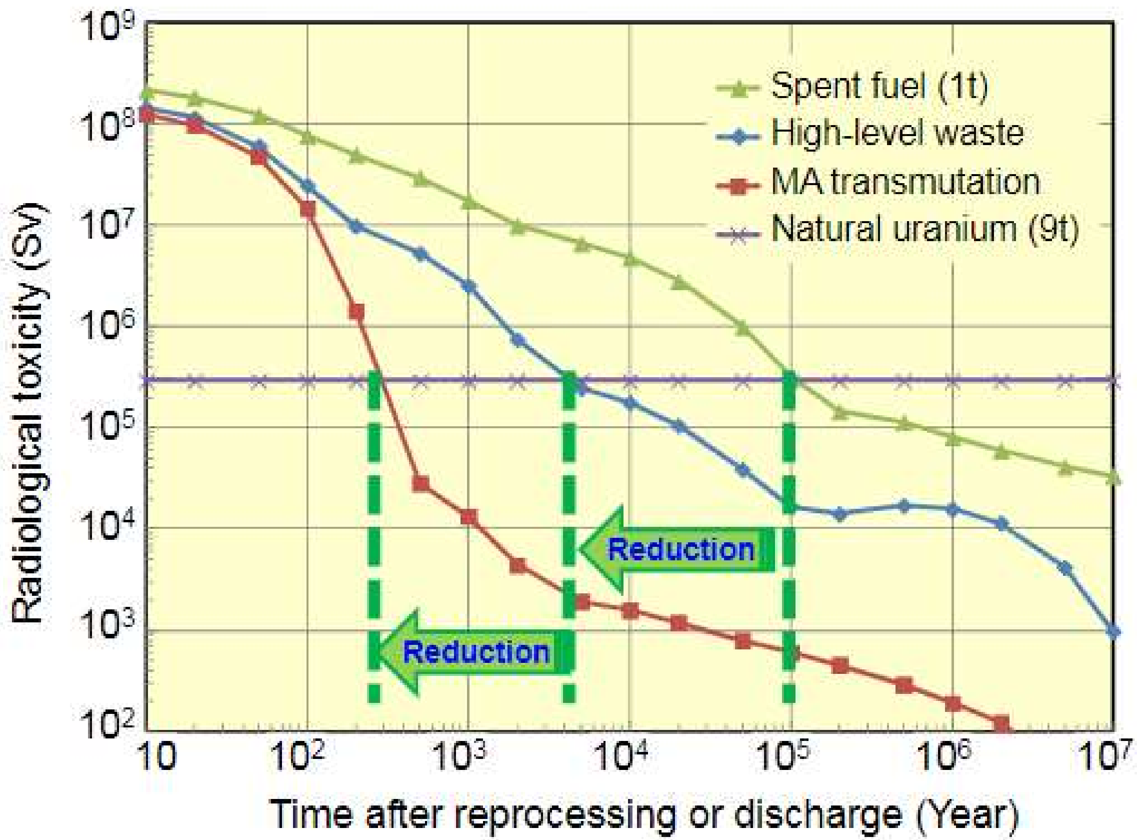
- Net Zero by 2050 roadmap proposed by the International Energy Agency (IEA) pointed out that nuclear energy plays an important role in achieving that goal.


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

- The international atomic energy agency (IAEA) indicates that radioactive waste management is one of the major challenges for nuclear energy.

# Motivation

- Accelerator-driven subcritical system (ADS) can transmute minor actinides and some long-lived fission products, reducing the geologic storage burden.




Radiological Toxicity:
Amount of radioactivity weighted by dose coefficient of each nuclide.

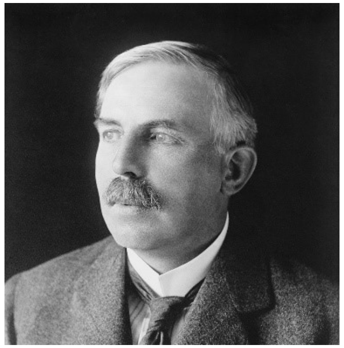
- Normalized by 1 ton of spent fuel.
- 9 tons of natural uranium (NU) is raw material of 1 ton of low-enriched uranium including daughter nuclides.

Time period to decay below the NU level:

- Spent fuel 100,000 y ↓
- High-level waste 5,000 y ↓
- MA transmutation 300 y

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.

# A brief history of the ADS


Sir Ernest Rutherford.

ADS is based on the nuclear transmutation.

- **1919** E. Rutherford made the first artificial transmutation ($^{14}N$ to $^{17}O$).
- Late **1940's** E. O. Lawrence(USA) and W.N. Semenov (USSR) proposed accelerators as neutron sources.
- **1949-52** Materials Testing Accelerator Project (MTA), leader by Lawrence (USA), used accelerators for fissile material (accelerator breeder).
- **1952** W.B. Lewis (Canada) published a studied for fissile fuel production for the CANDU reactor.
- Next years were a slowdown in the development of accelerator breeder because the operation with hundred of mA beam, discovery of high Uranium ores, non-proliferation goals.
- In the **1980**s, a renew interested in ADS projects for the transmutation of actinides occurred: PHOENIX (BNL, USA), ATW (LANL,USA), OMEGA (JAERI, Japan).
- **1993** C. Rubia (CERN) proposed an ADS system based on thorium cycle (energy amplifier).
- **At present,** several ADS projects are in construction and/or commission (CiADS, MYRRHA) and in design (JAEA-ADS, CYCLAD, among others).

# ADS

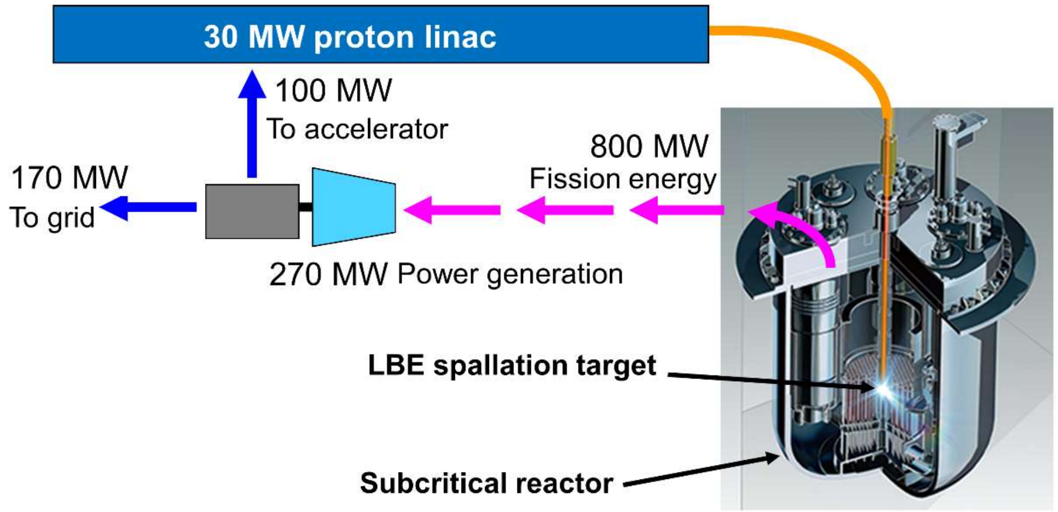
- ADS has three main components: accelerator, spallation target, and subcritical reactor.

High intensity-reliable accelerator:

- Energy : several hundred to few GeV.
- Power: few to tens of MW.

Spallation target:

- Neutron source by spallation process.




JAEA-ADS.

Subcritical reactor:

- Reactor requires an external neutron source to sustain the chain reaction.

## ADS can be employed to:

- Transmutation of nuclear waste.
- Generated energy.
- Breeding.

# ADS advantages & challenges

Some 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).

Some challenges on the accelerator part:

- Stable & efficient CW operation at MW regime.
- Beam loss < 1 W/m to facility the maintenance.
- High reliability: reduction of the beam trip frequency lower some order lower than the current accelerators (reliability-oriented design).

# High intensity accelerators

The ADS accelerator must:

- Beam power: ~ few to tens of MW (thermal power and subcriticality of the reactor).
- Beam energy : ~ 1 to 2 GeV ( for the efficient spallation source).
- Beam current : few to tens of mA.

The following table shows a comparison of type of accelerators, but currently only ADS studies have been done based on linacs and cyclotrons [1]:

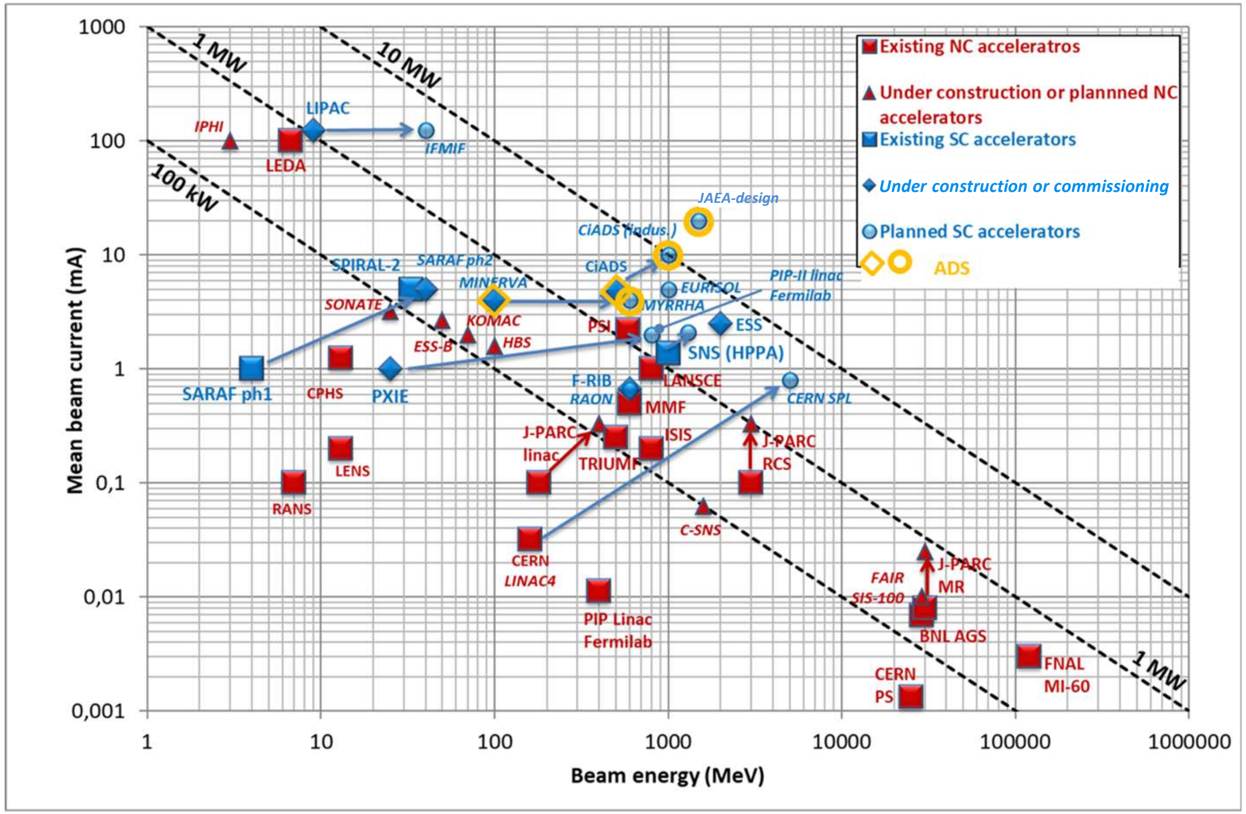
| Type of accelerator | Linac | Cyclotron | FFAG | Synchrotron |
|---|---|---|---|---|
| Advantages | • High energy<br>• Redundancy<br>• Lowest losses<br>• Beam quality | • Cyclic<br>• Cost effective<br>• Compact<br>• Stable | • Cyclic<br>• Strong focusing | • Cyclic |
| Disadvantages | • Expensive | • Max energy ~ 1 GeV<br>• Extraction<br>• Tuning | • CW difficult<br>• Required more develop | • Pulsed (space-charge, target) |
| Example | SNS | PSI | KURRI | J-PARC RCS |

[1] M. Seidel ,"ADS accelerator", ThEC13, Oct. 2014; W. Pan, "Overview of worldwide accelerator for ADS", IPAC2014, June 2015; and R. Barlow, "Alternative designs for ADSR drivers FFAGs and electron linacs", on workshop on the "Status of Accelerator Driven Systems Research and Technology Development" , 7-9 Feb. 2017

# Stable & efficient CW and Beam loss < 1 W/m at MW regime

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

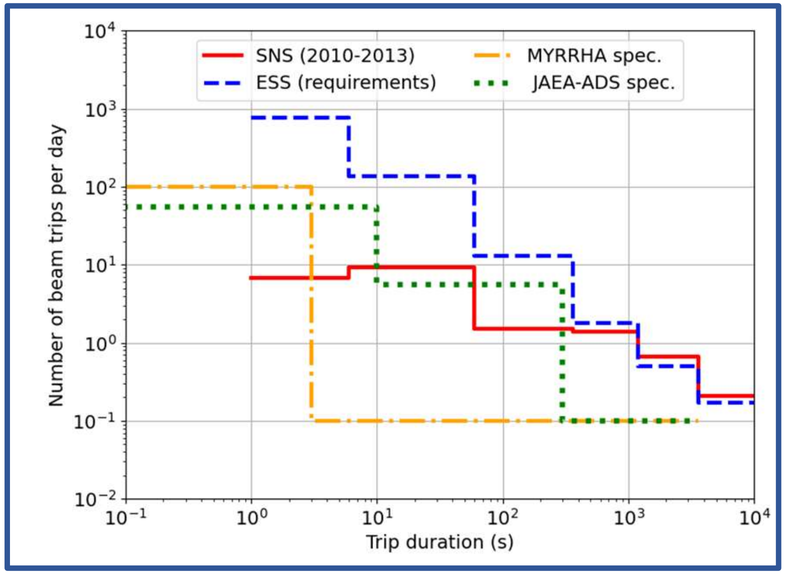
ADS are expanding the barrier of high-power accelerators.




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

# High reliability

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




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.

**Repairability:**

- Online and manual.
- Maintenance.


[1] D. Vandeplassche, et al " Accelerator Driven systems, IPAC 2012, E. Bargallo, et al "ESS reliability and availability approach", IPAC 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.

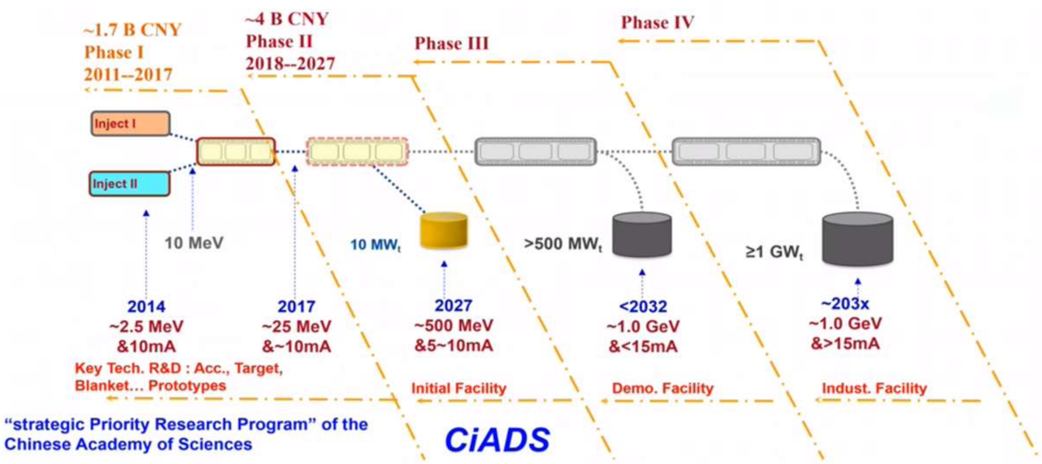
# (partially) Worldwide ADS activities

| Activity | Accelerator | Purpose | Status |
|---|---|---|---|
| CiADS (China) | 2.5 (10)-MW SRF proton linac | ADS demo | Commissioning |
| MYRRHA (Europe/Belgium) | 2.4-MW SRF proton linac | ADS demo | Construction |
| JAEA-ADS (Japan) | 30-MW SRF proton linac | Transmutation of nuclear waste | Design |
| SKKU –ADS (Korea) | 5-MW SRF proton cyclotron | ADS Th based nuclear reactor | Design |
| KIPT (Ukraine) | 0.1-MW electron linac | ADS demo | Scientific program under develop (2020) |
| IFSR (India) | 1-MW SRF proton linac | Energy production | Design |
| ADS-Troitsk (Russia) | 0.75-MW proton linac | ADS demo | Design (Using the existing Troitsk facility) |
| Mu*STAR (USA/Muons, Inc.) | 2.5-MW SRF proton linac | Transmutation of nuclear waste | Design |
| CYCLAD (Europe/consortium) | 5-10-MW proton cyclotron | Transmutation of nuclear waste | Design |

# General information of CiADS

- China initiative Accelerator Driven System (CiADS) will be located in in Huizhou, China.

| CiADS | |
|---|---|
| Proton Linac | |
| Energy (MeV) | 500 |
| Beam current (mA) | 5 |
| Operation modes | CW / Pulse |
| Target | |
| Max Power (MW) | 2.5 |
| Material | LBE |
| Fast Reactor | |
| Keff | ~ 0.75 / ~ 0.96 |
| Thermal Power (MW) | ~ 7.5 / ~9.76 |



Road map CiADS.

Civil construction.

CiADS linac schematic.

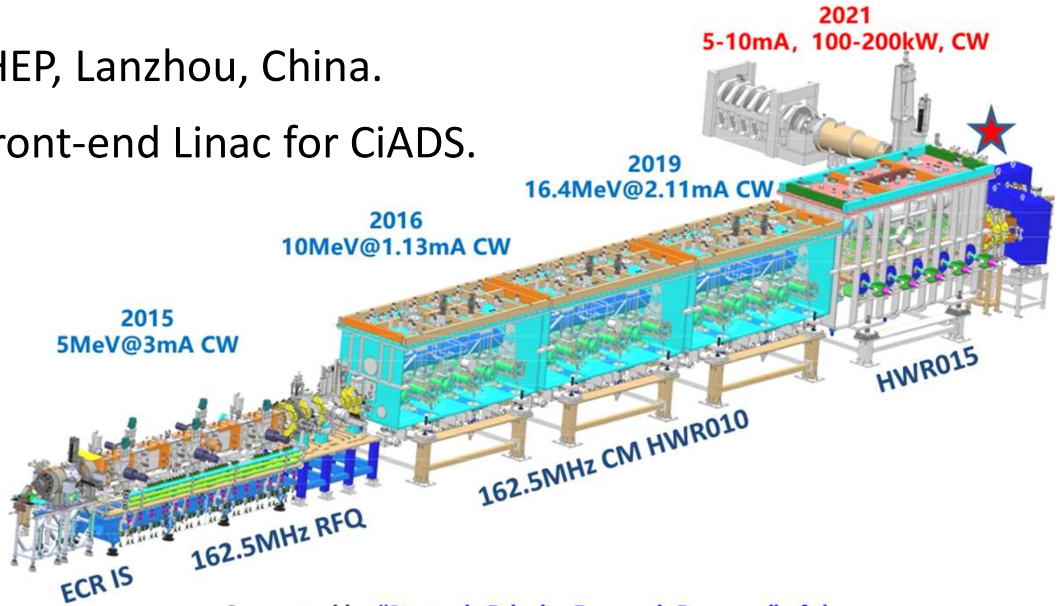


Courtesy of Prof. Yuan He.

# CAFe: ADS Front-end Demo Facility

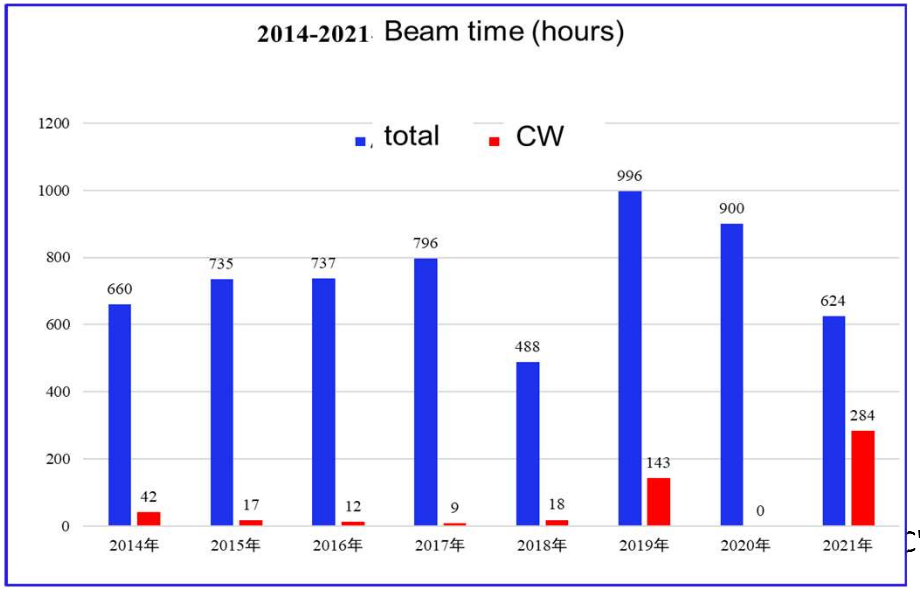
- Construction 2011-2017, IMP cooperate with IHEP, Lanzhou, China.
- Goal: to demonstrate 10 mA CW beam of SRF front-end Linac for CiADS.
- 2018 to date, upgrading.

| | |
|---|---|
| ions | P， $H_2^+$， α |
| Frequency (MHz) | 162.5 |
| Current (mA) | 10 |
| Input RFQ energy (keV) | 40 |
| Output RFQ energy(MeV) | 3.1 |
| Final energy (MeV) | 20/30/40 |
| Temperature (K) | 4.5 |




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

CAFe scheme.



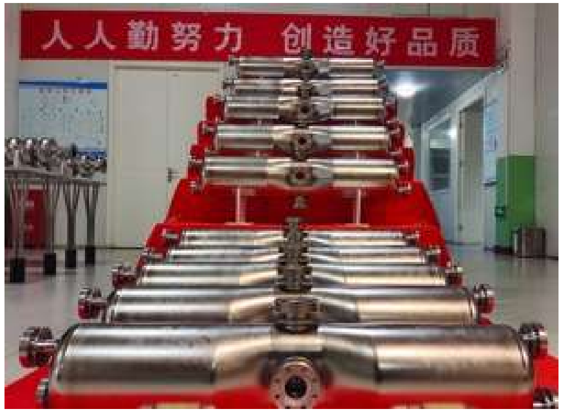

- High beam power test Jan- Mar. 2021

| | | | |
|---|---|---|---|
| Beam power (kW) | 126.1 | 174.4 | 205.5 |
| Current (mA) | 8 | 10.1 | 10.2 |
| Operation time (h) | 108 | 12 | 0.2 |
| Availability (%) | 93.5 | 96.2 | -- |

Courtesy of Prof. Yuan He.

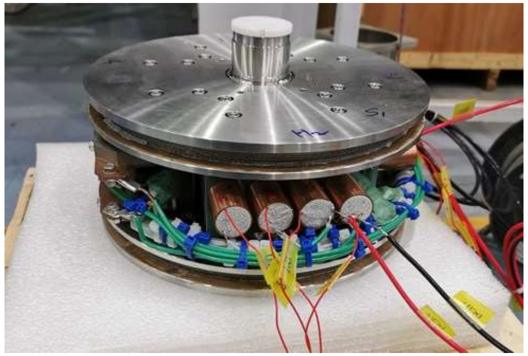
# Other activities

RFQ fabrication.

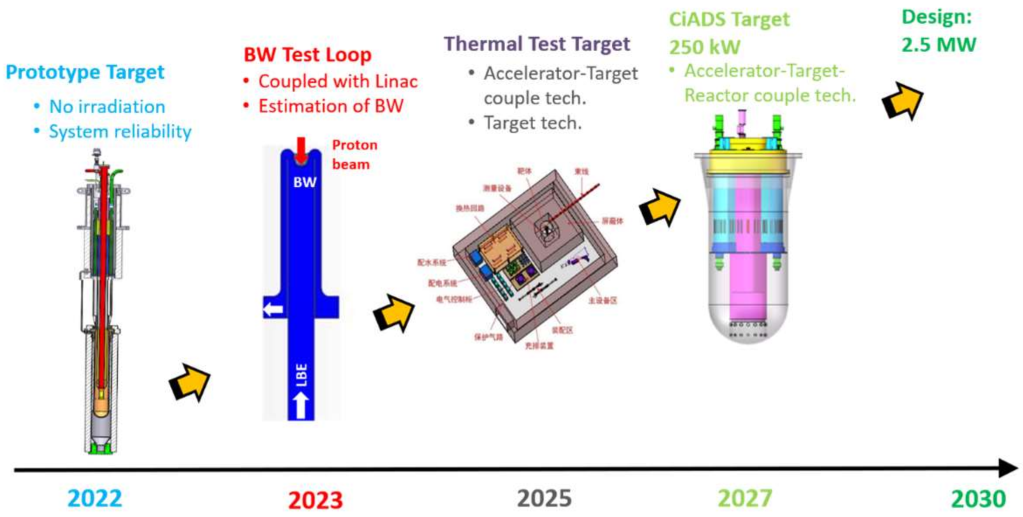



Cavity prototyping. More details in TU1AA01.

650 MHz SSAMP @ 150 kW.



Superconducting solenoids Prototyping.



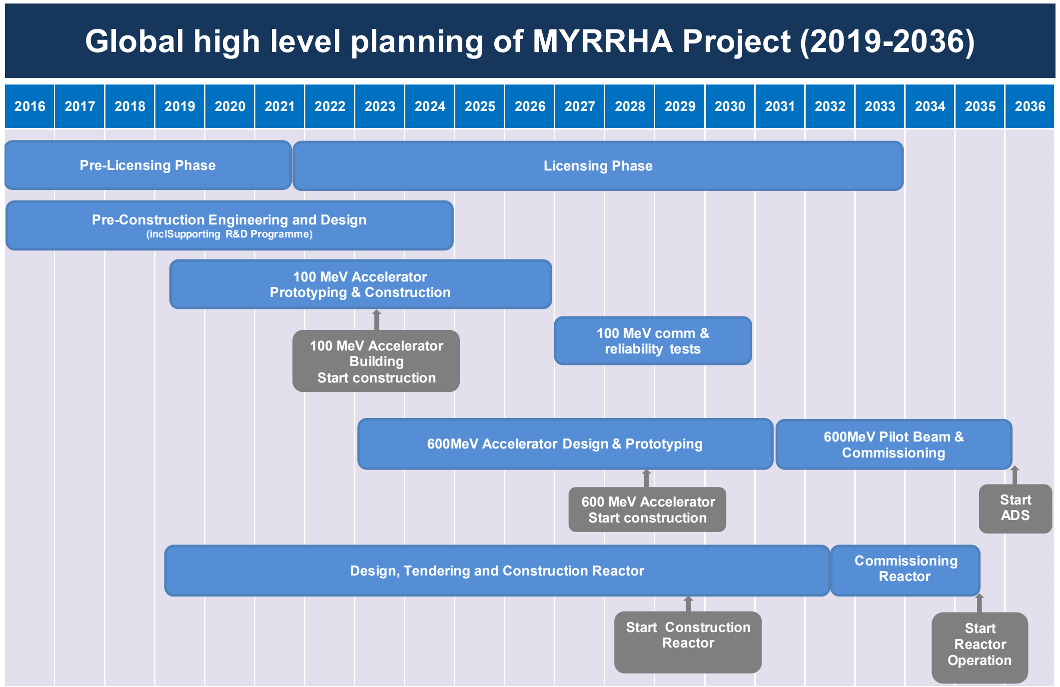

Plan of Development of LBE Target.

Courtesy of Prof. Yuan He.

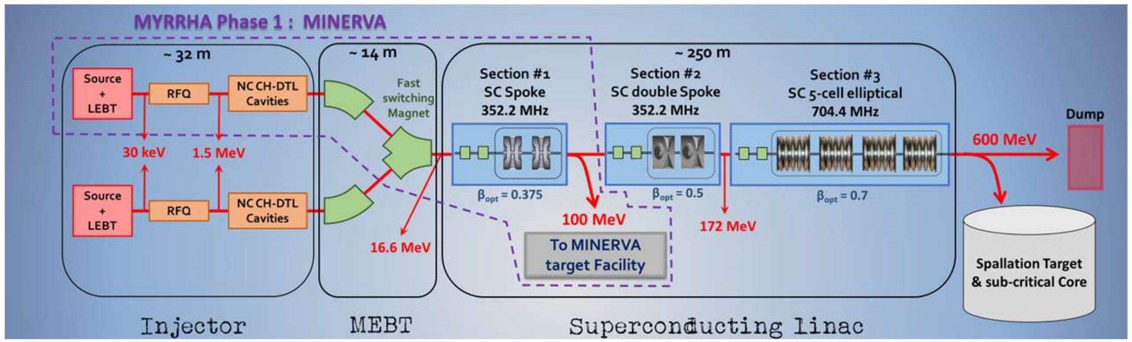
# General information of MYRRHA

- 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 |




Road map MYRRHA.

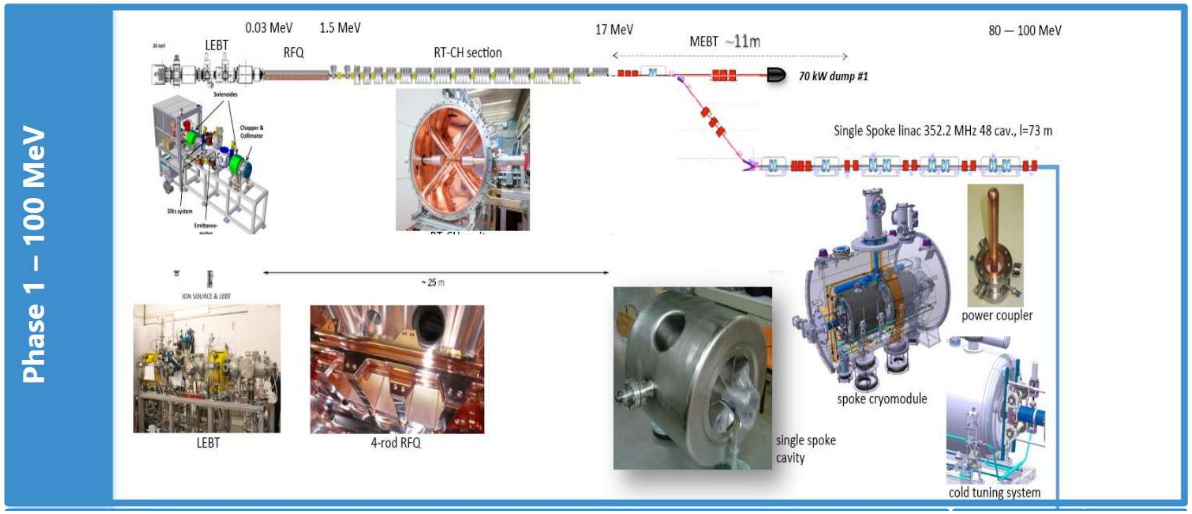



MYRRHA-ADS schematic. F. Bouly, et al, “Superconducting LINAC design Upgrade in view of the 100 MeV MYRRHA PHASE I” , IPAC’19.

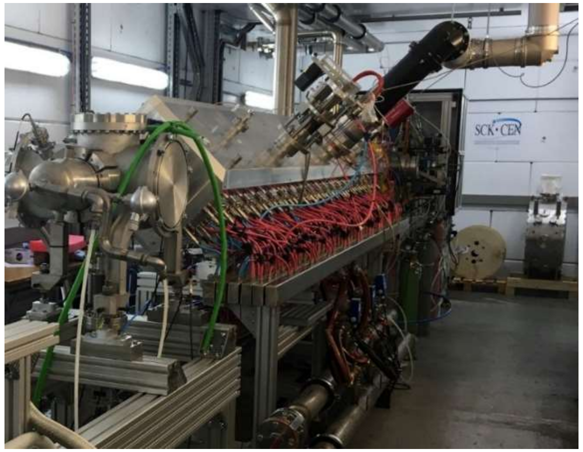
Courtesy of MYRRHA/MINERVA project.

# MINERVA: MYRRHA Phase I

- MINERVA is under construction at MOL in Belgium.
- Goal: to demonstrate 100 MeV, 4 mA CW beam as initial phase and technology demonstrator.
- First 100 MeV targeted for end 2027.
- Operational injector test stand incl. RFQ [1].
- For more details please visit the works MOPOGE020 , TUPOJO003 , TUPOJO023, TUPOPA016 , TUPOGE04, and THP0GE04.




MINERVA layout.




MINERVA RFQ in the test stand.

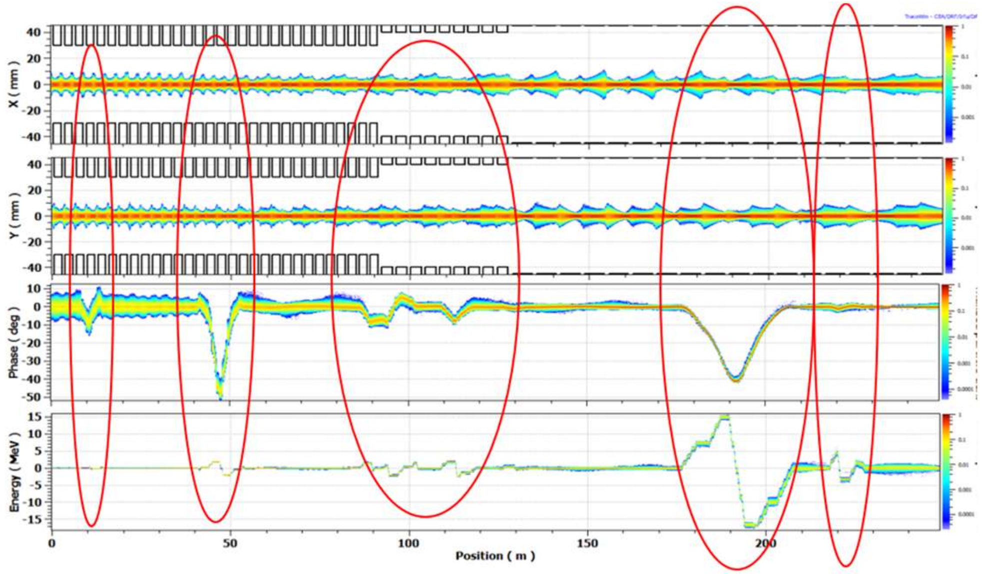
[1] A. Gatera, et al, “MYRRHA-MINERVA Injector Status and Commissioning” ,HB’21.



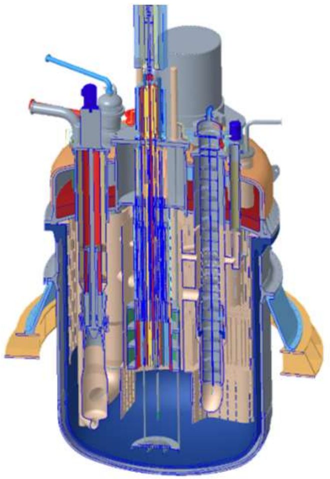
Courtesy of Minerva team.

# Other activities

Cryomodule development in collaboration with IJCLab (France) . See MOPOGE020 , TUPOJO023, TUPOPA016 , TUPOGE04, and THP0GE04.




Fault-recovery scenarios. Multiplies failures compensations. F. Bouly, Accelerator Driven system & High power linacs, JUAS 2022. See TUPORI004.



Reactor design completed, 2020.

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

cnrs IN2P3

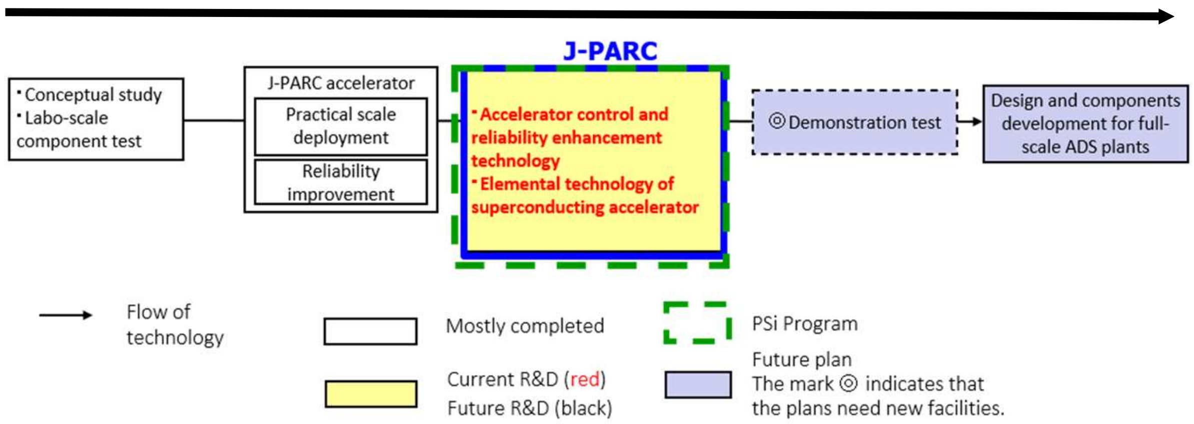
SRF prototyping.

R&D CW amplifiers.

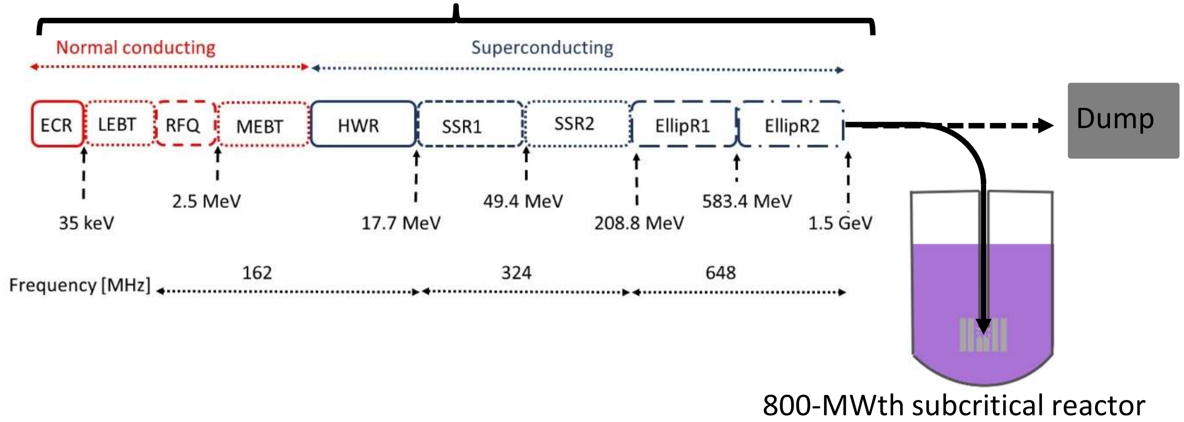
Courtesy of MYRRHA/MINERVA project.

# 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 |

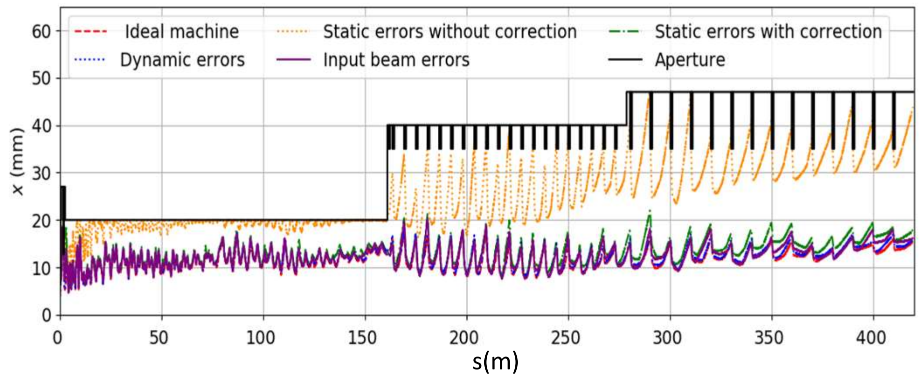



JAEA's simplify roadmap for ADS Accelerator.

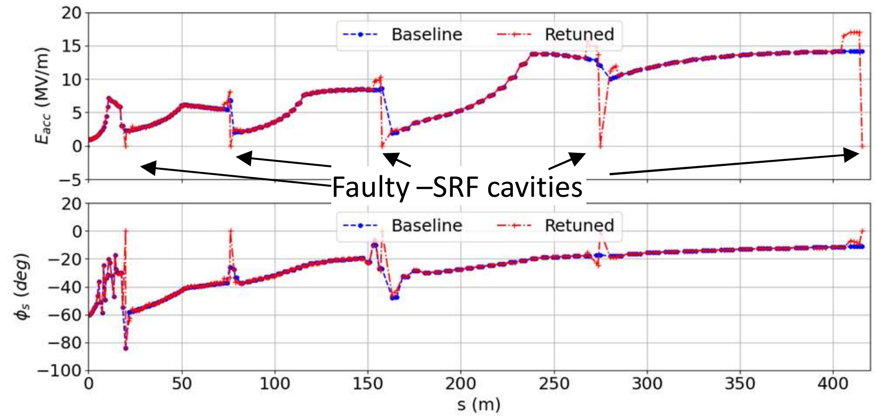



JAEA-ADS.

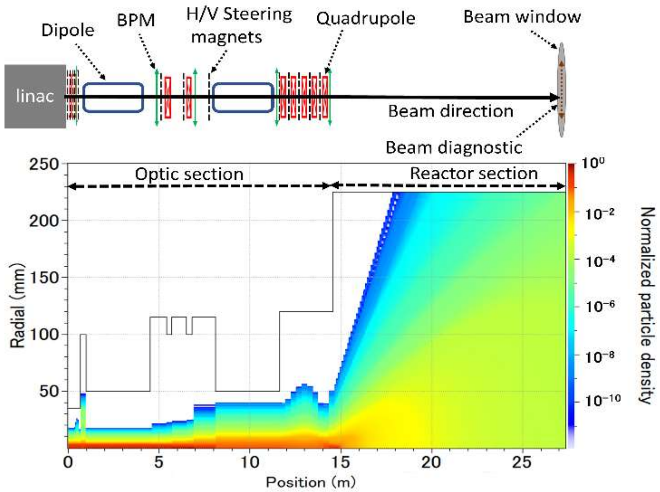
# Beam optics design



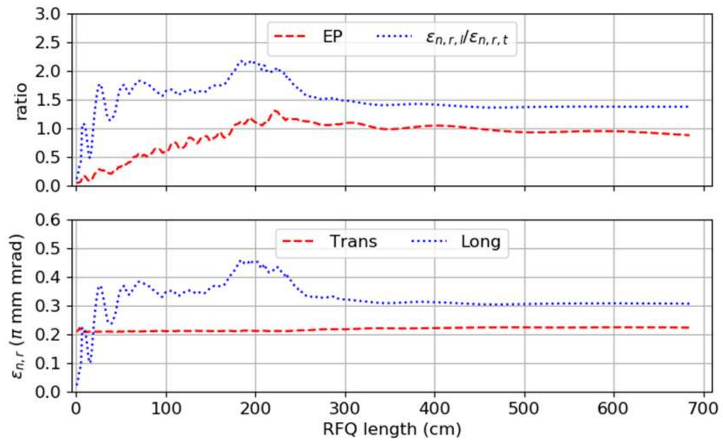

Robust optic design with a proper control of beam lost.
B. Yee-Rendon, et al. PRAB, **24**, 120101 (2021)




Fast beam recovery scenarios. Multiple element compensations.
B. Yee-Rendon, et al. PRAB, **25**,080101 (2022).




Beam transport to the target design. B. Yee-Rendon, et al, “Robust and compact design of a 30-MW beam transport line for an accelerator-driven subcritical system” to be presented at PASJ’22.



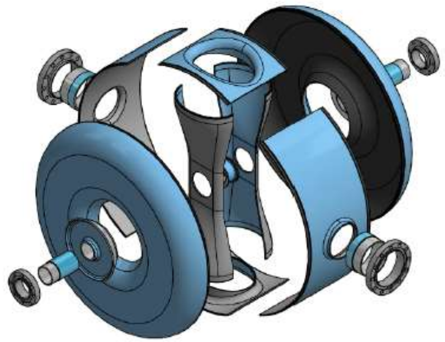

Equipartition RFQ. B. Yee-Rendon, et al, “Design and beam dynamics studies of an ADS RFQ based on equipartitioned beam scheme” to be presented at the PASJ’22.

# SRF prototyping

Prototyping Single Spoke Resonator (SSR) because:

- Common cavity for modern high-intensity proton.
- It will be the first SSR fabricated in Japan.
- To develop the expertise in superconducting cavities in JAEA/J-PARC.

The details were presented in MOPOGE014.

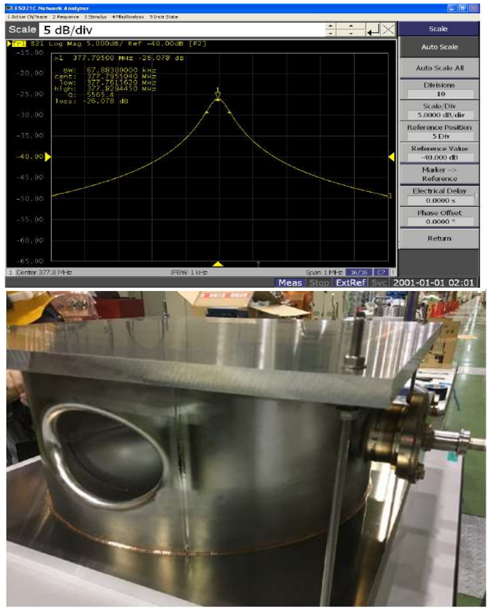


SSR prototype.

Table 1: Design Parameters of the Prototype Spoke Cavity

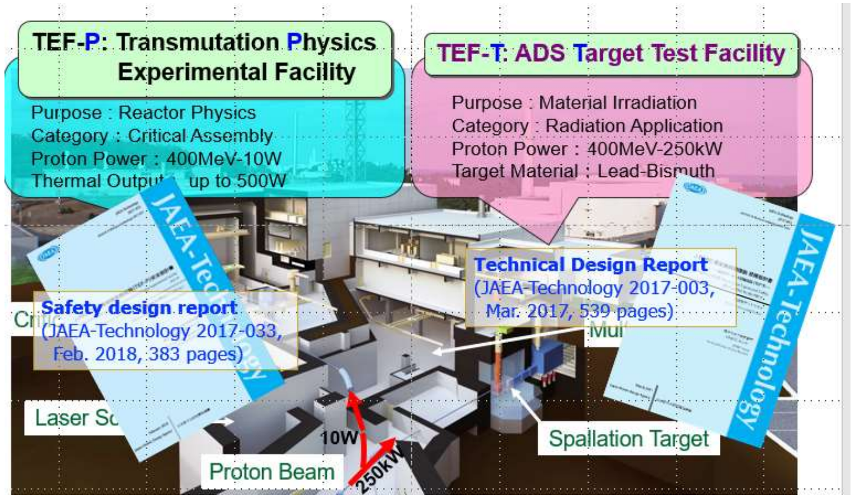
| Parameter | Value |
|---|---|
| $f_0$ | 324 MHz |
| $\beta_g$ | 0.188 |
| $\beta_{opt}$ | 0.24 |
| Beam aperture | 40 mm |
| Cavity diameter | ≈ 500 mm |
| Cavity length | 300 mm |
| $L_{eff} = \beta_{opt}\lambda$ | 222 mm |
| $G = Q_0 R_s$ | 90 Ω |
| $T(\beta_{opt}) = V_{acc}/V_0$ | 0.81 |
| $R_{sh}/Q_0 = V_{acc}^2/\omega W$ | 240 Ω |
| $E_{peak}/E_{acc}$ | 4.1 |
| $B_{peak}/E_{acc}$ | 7.1 mT/(MV/m) |

The body of the SSR prototype.

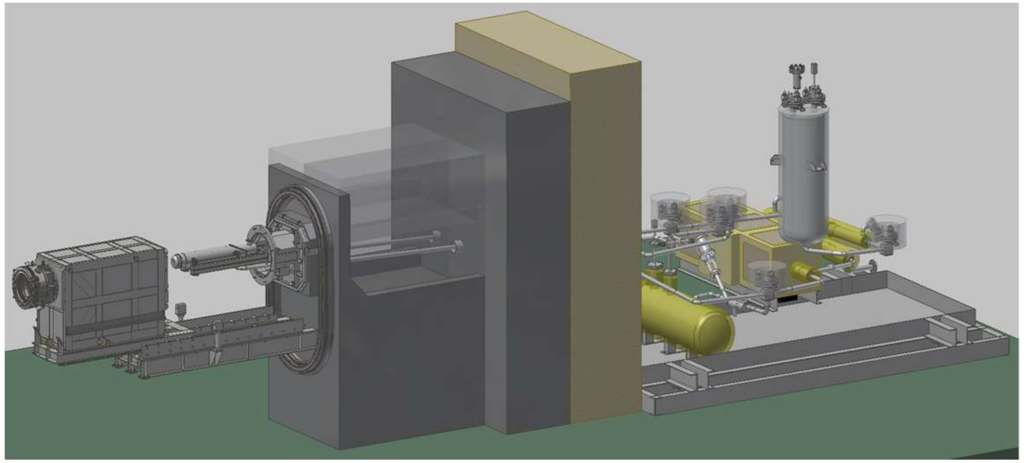



Frequency measurements of the SSR body.

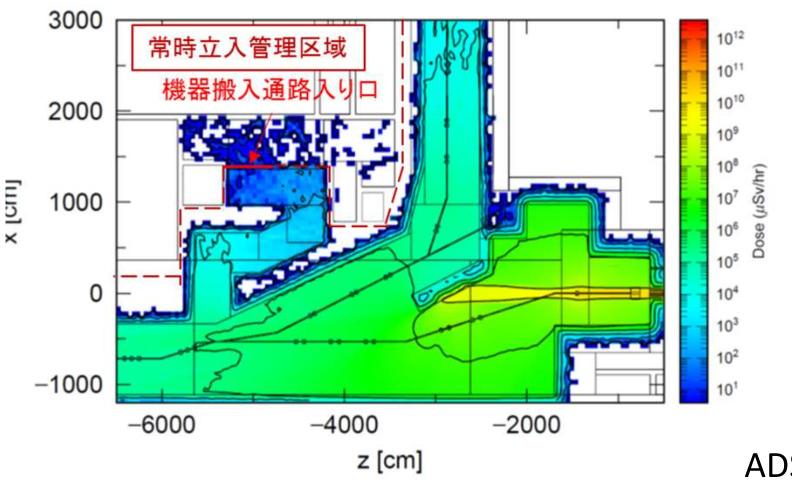
# Other activities



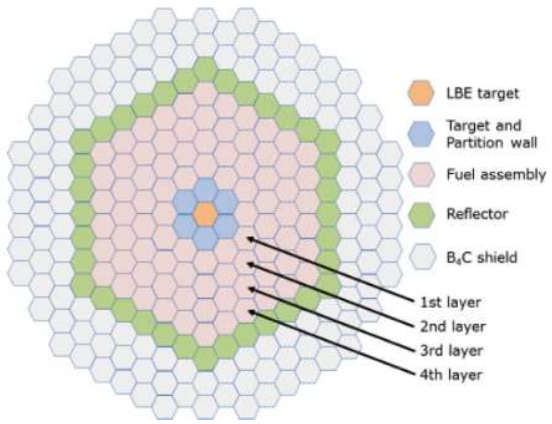

Transmutation Experimental facilities (TEF).



LBE target system.




Shielding calculations.




ADS calculation model. T. Sugawara, et al. Prog. Nucl. Energy.**106**,27-33 (2018).

Proton accelerator-driven Subcritical virtual system (PSi) Program:
Enhancing computer science.

Courtesy of JAEA Nuclear Transmutation.

# Summary

- ADS has become a promising choice to reduction of nuclear waste storage, clean energy (→ zero-emission goal).
- Transmutation has been one of the earliest motivations for the development of particle accelerators.
- ADS accelerators use the state-of-the-art of the high-power accelerator (SNS, PIP-II, ESS, Linac4).
- ADS will expand the barrier of high intensity by operating in the MW range with acceptable beam loss, high reliability, stability, and cost-effectiveness.
- For the development of ADS accelerators is necessary to have close international cooperation between laboratories around the world.

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