Experimental Benchmarks on Accelerator-Driven System at Kyoto University Critical Assembly

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Background and Purpose

Background

- An original concept of ADS for producing energy and transmuting MA and LLFP
  - Nuclear transmutation and Energy amplifier system
- Outline and Roadmap of ADS study
  - Focus on analyses of reaction rates and subcriticality
  - Deterministic methodology of ADS experiments
- ADS research activities in Japan
  - JAEA: TEF facilities in J-PARC
  - KURRI: ADS experiments with KUCA+FFAG (100 MeV protons) accelerator

Purpose

- Conduct feasibility study on ADS, relating energy amplifier and nuclear transmutation
- Investigate neutron characteristics of ADS through the experiments and the accuracy of numerical (MCNP) analyses

Roadmap of ADS for nuclear transmutation

Power

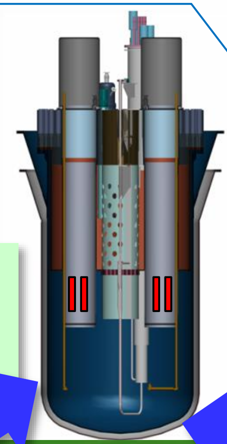
Demonstration

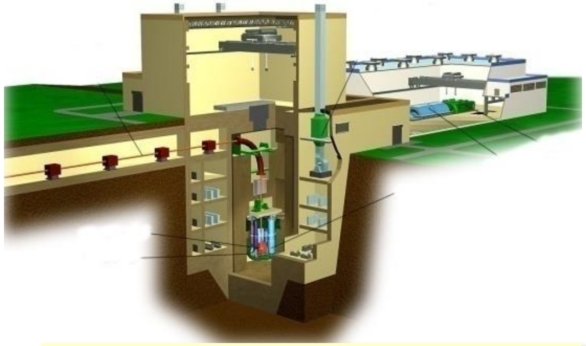
Principle

Concept

ADS tech. w/o MA fuel (Pb-Bi core, Accelerator, Operation experiences)

MYRRHA in Belgium
- ~2.4 MW-beam, 50~100 MWth
- Demonstration of ADS tech.
- Fuel irradiation





Actual ADS plant
- 30 MW-beam, 800 MWth
- MA nucl. trans. of 10 LWR plants

TEF of J-PARC in Japan
- Pb-Bi target exp.
- Reactor physics exp. (MA in kg order)
- R&D of basic and eng.

R&D of
- Reactor physics of MA fuel
- Target materials

②ADS plant R&D of engineering feasibility

- **High-reliability of accelerator**
- **Control of subcriticality**
- **Removal system of heat decay**

Reactor Physics Exps. at KUCA

①KUCA-FFAG: Reactor Physics Exp.

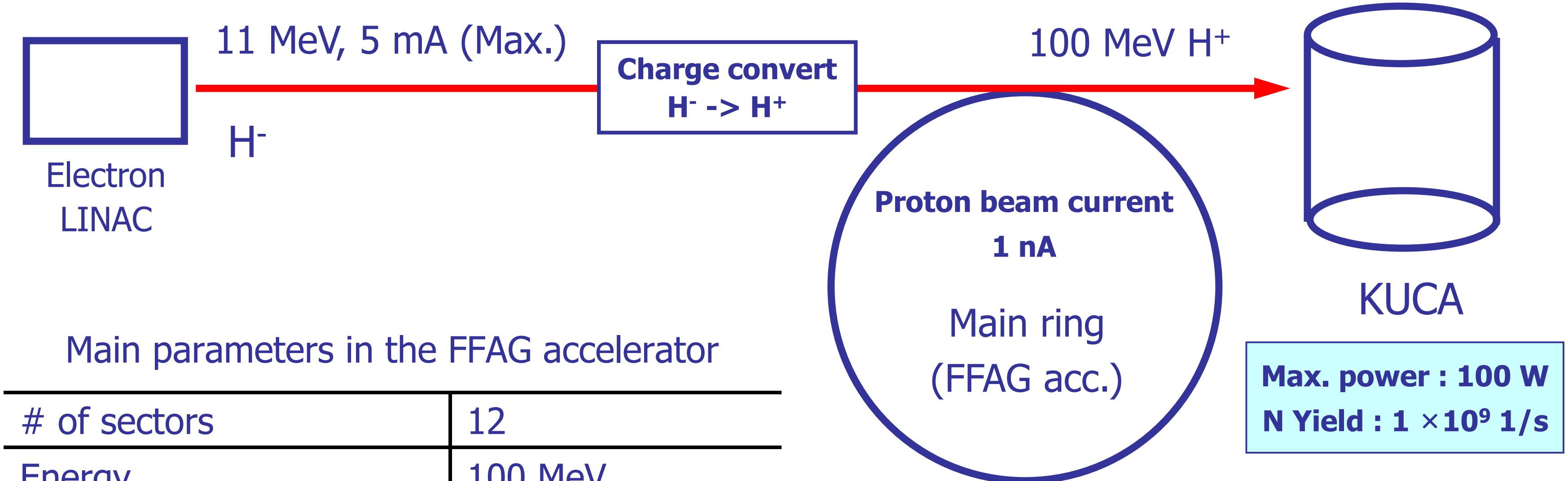
2016 | 2020 | 2025 | Future

Experimental facilities in the world

Table Specification of ADS facilities in the world

Project or Facility	Country	Fuel	Reflector or Coolant	Spectrum	Accelerator (target)	Power	Remarks
MUSE	France	MOX	Na	Fast	14 MeV – n	Zero	Finished
YALINA	Belarus	LEU	Solid metal	Fast & Thermal	14 MeV – n	Zero	Finished
VENUS-F	Belgium	LEU (MOX)	Pb	Fast	14 MeV – n	Zero	Being
KUCA	Japan	HEU	Polyethylene (Gr, Pb & Pb-Bi)	Thermal	14 MeV – n 100 MeV – p (W, Pb-Bi…)	Zero	Being
CLEAR-1	China	UO_2	Pb	Fast	14 MeV – n	Zero	Planned
TEF	Japan	LEU (Pu) + MA	Pb-Bi	Fast	400 MeV – p (Pb-Bi)	500 Wth	Planned
MYRRHA	Belgium	MOX + MA	Pb-Bi	Fast	600 MeV – p (Pb-Bi)	100 MWth	Planned

ADS composition in KURRI

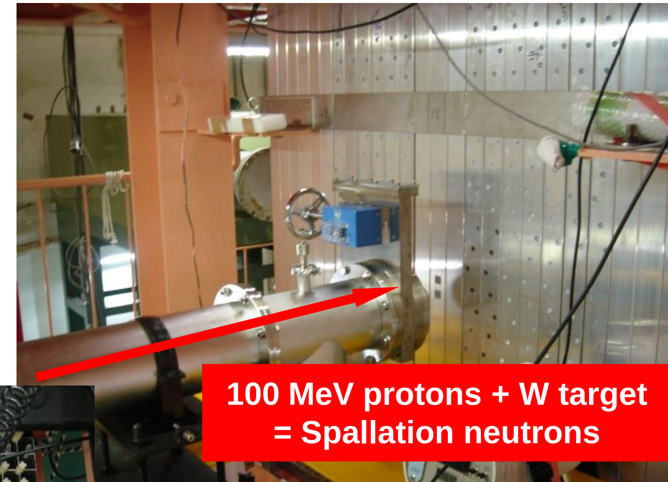


Main parameters in the FFAG accelerator

# of sectors	12
Energy	100 MeV
Repetition rate	20 Hz
Average beam current	1 nA
Width	50 ns
Field index	7.5
Closed orbit radius	4.4 - 5.3 m

ADS composition at KUCA

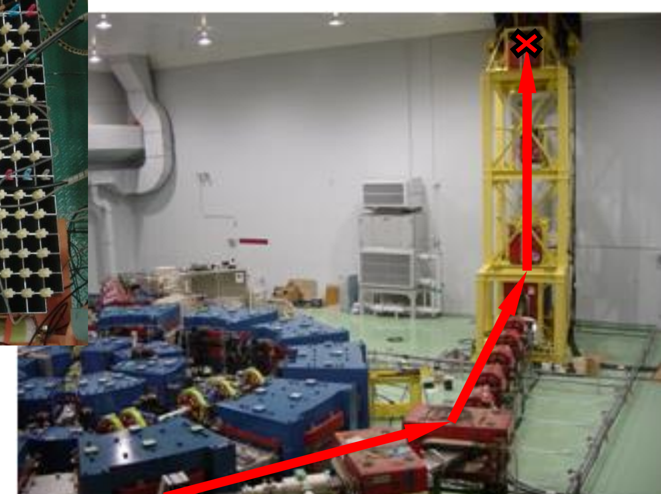
Beam line of D



Beam line of protons

KUCA core

Pulsed neutron generator



FFAG accelerator

KUCA core (Solid-moderated core)

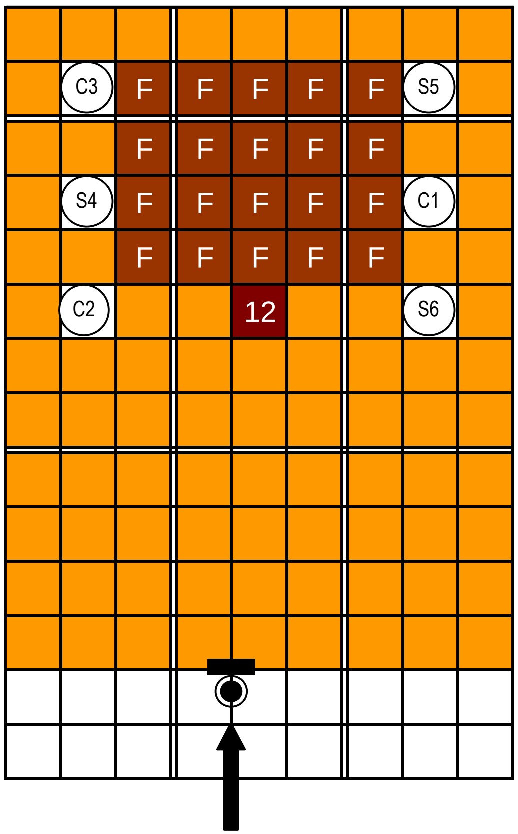


Fig. KUCA core

- KUCA core -
A solid-moderated and -reflected core

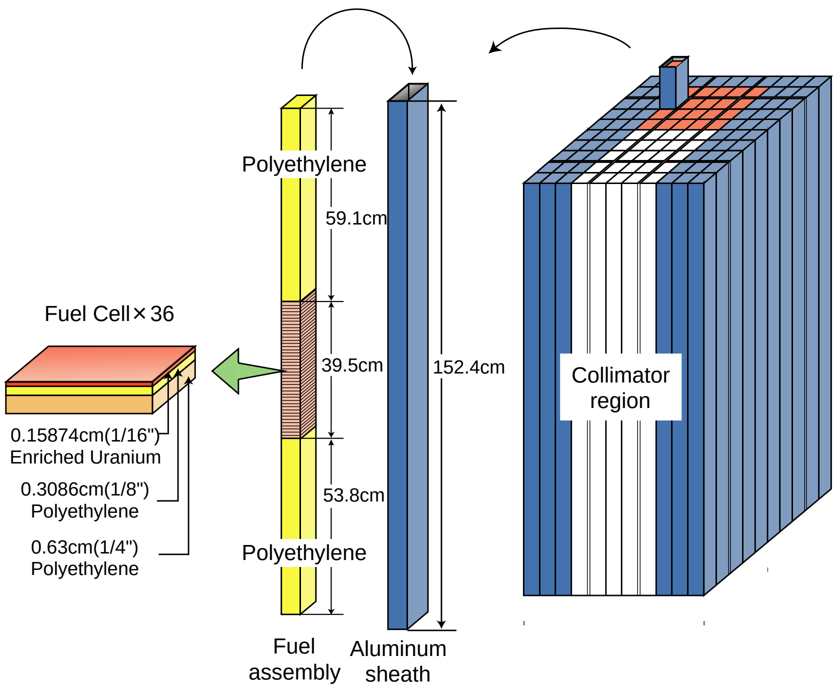


Fig. Image of KUCA core and fuel assembly loaded

^{235}U-loaded ADS experiments with 14 MeV neutrons

(IAEA ADS CRP in 2007 to 2011)

- Subcriticality measurements
- Neutron spectrum (Activation foils)
- Reaction rates (M and k-source)

C. H. Pyeon, *et al.*, *J. Nucl. Sci. Technol.*, **44**, 1368 (2007).
C. H. Pyeon, *et al.*, *J. Nucl. Sci. Technol.*, **45**, 1171 (2008).
C. H. Pyeon, *et al.*, *J. Nucl. Sci. Technol.*, **46**, 965 (2009).
H. Shahbunder, *et al.*, *Ann. Nucl. Energy*, **37**, 592 (2010).
H. Taninaka, *et al.*, *J. Nucl. Sci. Technol.*, **47**, 376 (2010).
H. Shahbunder, *et al.*, *Ann. Nucl. Energy*, **37**, 1214 (2010).
H. Shahbunder, *et al.*, *Ann. Nucl. Energy*, **37**, 1785 (2010).
H. Taninaka, *et al.*, *J. Nucl. Sci. Technol.*, **48**, 873 (2011).
H. Taninaka, *et al.*, *J. Nucl. Sci. Technol.*, **48**, 1272 (2011).
C. H. Pyeon, *et al.*, *Ann. Nucl. Energy*, **40**, 229 (2012).
A. Sakon, *et al.*, *J. Nucl. Sci. Technol.*, **50**, 481 (2013).
A. Sakon, *et al.*, *J. Nucl. Sci. Technol.*, **51**, 116 (2014).
A. Sakon, *et al.*, *J. Nucl. Sci. Technol.*, **52**, 204 (2015).

^{235}U-loaded ADS experiments with 100 MeV protons

(IAEA ADS CW from 2016 to 2019)

C. H. Pyeon, *et al.*, *J. Nucl. Sci. Technol.*, **46**, 1091 (2009).

C. H. Pyeon, *et al.*, *J. Nucl. Sci. Technol.*, **47**, 1090 (2010).

J. Y. Lim, *et al.*, *Sci. Technol. Nucl. Install.*, **2012**, 395878, 9 pages, (2012).

Y. Takahashi, *et al.*, *Ann. Nucl. Energy*, **54**, 162 (2013).

T. Yagi, *et al.*, *Appl. Radiat. Isot.*, **72**, 11 (2013).

C. H. Pyeon, *et al.*, *Nucl. Eng. Technol.*, **45**, 81 (2013).

C. H. Pyeon, *et al.*, *Prog. Nucl. Energy*, **82**, 22 (2015).

C. H. Pyeon, *et al.*, *Nucl. Technol.*, **192**, 181 (2015).

M. Yamanaka, *et al.*, *Nucl. Sci. Eng.*, **184**, 551 (2016).

M. Yamanaka, *et al.*, *J. Nucl. Sci. Technol.*, (2017). [in print]

H. Iwamoto, *et al.*, *J. Nucl. Sci. Technol.*, (2017). [in print]

C. H. Pyeon, et al., *Ann. Nucl. Energy*, (2017). [to be accepted]

^{235}U-ADS: Source spectrum of target

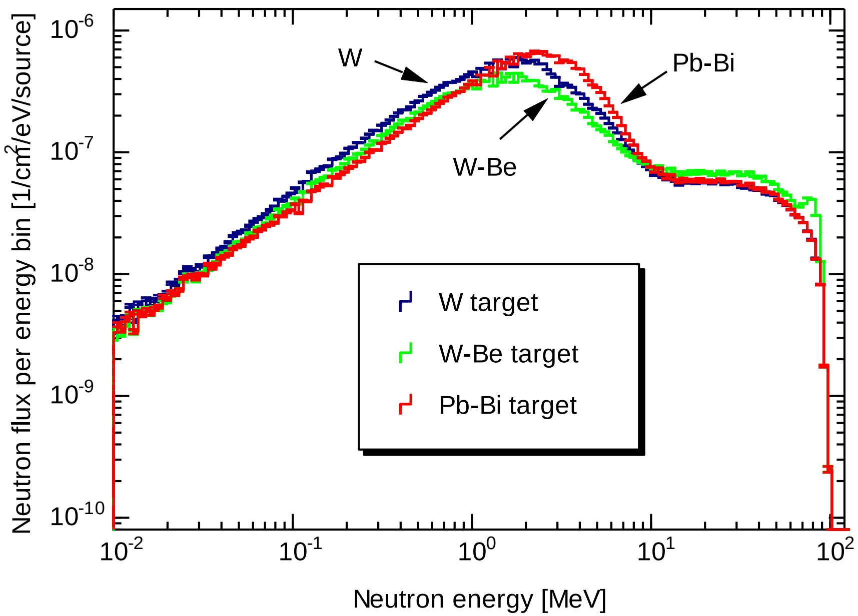


Fig. Neutron spectrum of injection of 100 MeV protons into heavy metal target

- Spectrum of spallation neutrons (100 MeV proton injection)
  - W, W-Be and Pb-Bi targets
  - Almost same

Source: C. H. Pyeon, *et al.*, *Nucl. Technol.*, **192**, 181 (2015).

- Very unique peak ranging between 85 and 100 MeV neutrons (for 100 MeV proton injection)

-> How about influences on neutron characteristics in the core?

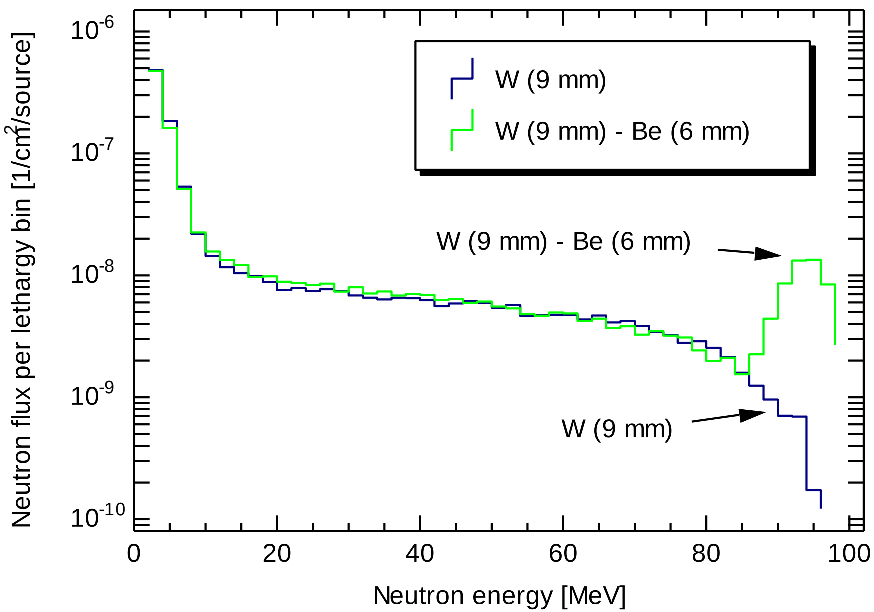


Fig. Comparison between neutron spectra of W and W-Be targets

Static: Neutron multiplication

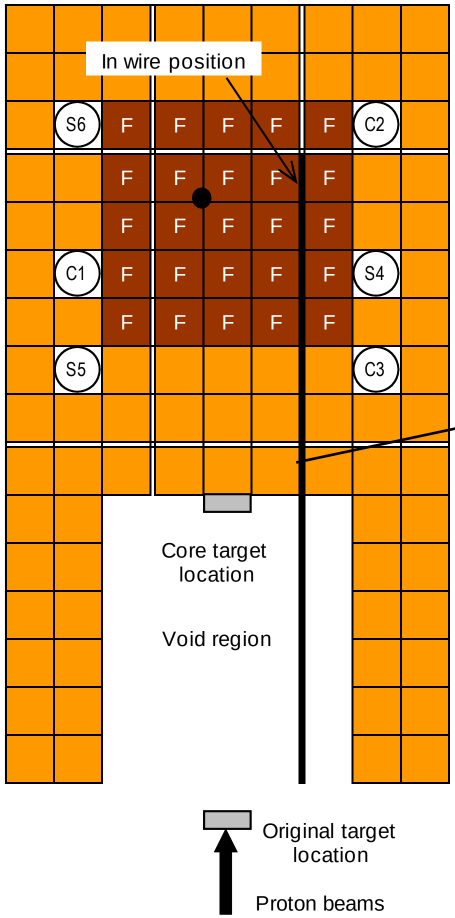


Fig. Core configuration of ^{235}U-PE core (**100 MeV protons**)

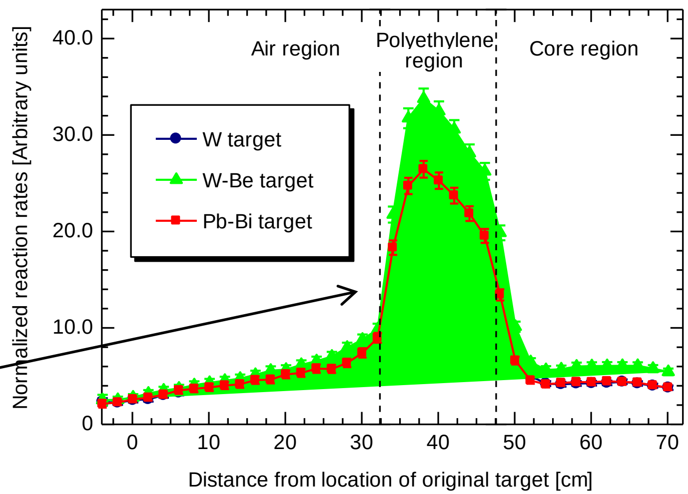


Fig. Measured reaction rate distribution (M and k-source study)

Table Comparison between measured and calculated M values (Subcritical level: 2,657 pcm)

Target	Calculation	Experiment	C/E value
W	1.73 ± 0.01	1.85 ± 0.02	0.93 ± 0.01
W-Be	2.29 ± 0.01	2.36 ± 0.03	0.97 ± 0.01
Pb-Bi	1.95 ± 0.01	1.94 ± 0.02	1.01 ± 0.01

Source: C. H. Pyeon, *et al.*, *Nucl. Technol.*, **192**, 181 (2015).

^{232}Th-loaded ADS experiments with 14 MeV neutrons or 100 MeV protons

(IAEA ADS CW from 2013 and 2014)

C. H. Pyeon, *et al.*, *Ann. Nucl. Energy*, **38**, 2298 (2011).
C. H. Pyeon, *et al.*, *Nucl. Sci. Eng.*, **177**, 156 (2014).
M. Yamanaka, *et al.*, *Nucl. Sci. Eng.*, **183**, 96 (2016).

Exp. benchmarks on Th-loaded ADS

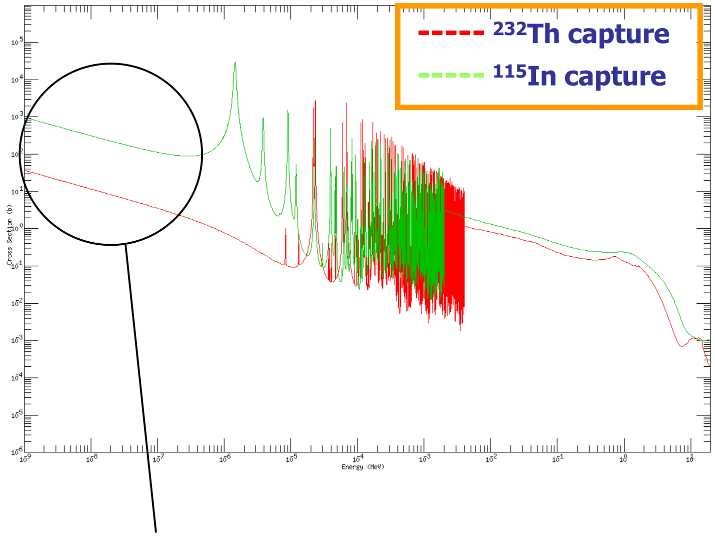


Fig. Proportionality of X secs. of ^{232}Th and ^{115}In in thermal neutron range

- Measurement (Foil activation method)

- **Source**:
  14 MeV neutrons -> ^{93}Nb(n, 2n)^{92m}Nb (9 MeV threshold)
  100 MeV protons -> ^{115}In(n, n')^{115m}In (0.3 MeV threshold)
- **Core**: In capture (~ Th capture; Proportionality) -> ^{115}In(n, γ)^{116m}In reactions

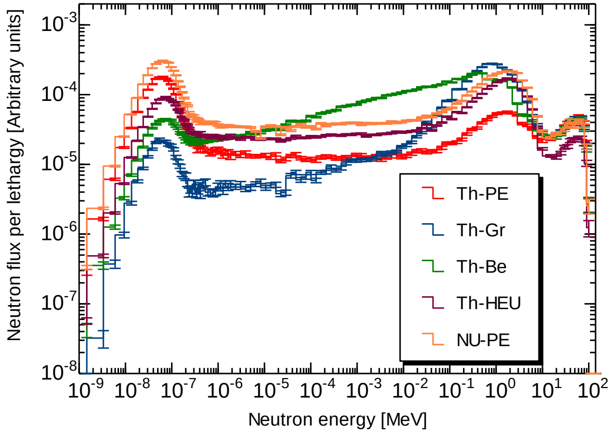


Fig. Neutron spectrum in injection of **100 MeV protons**

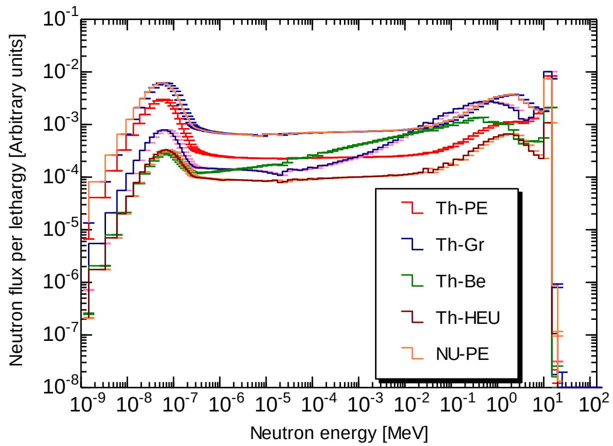
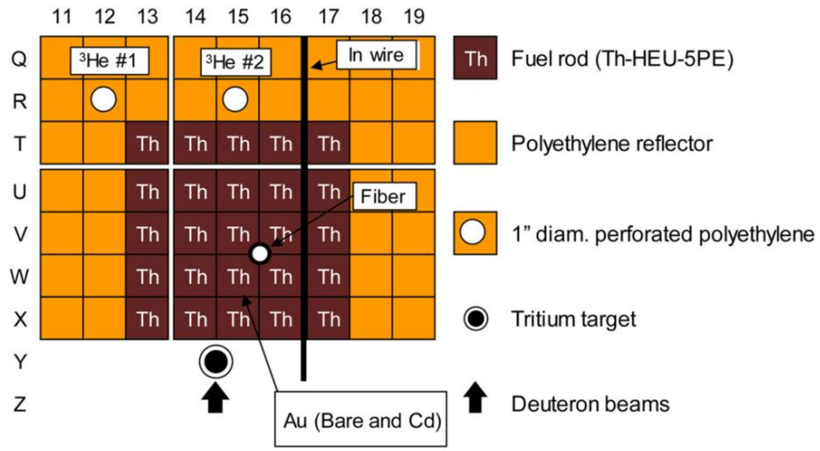


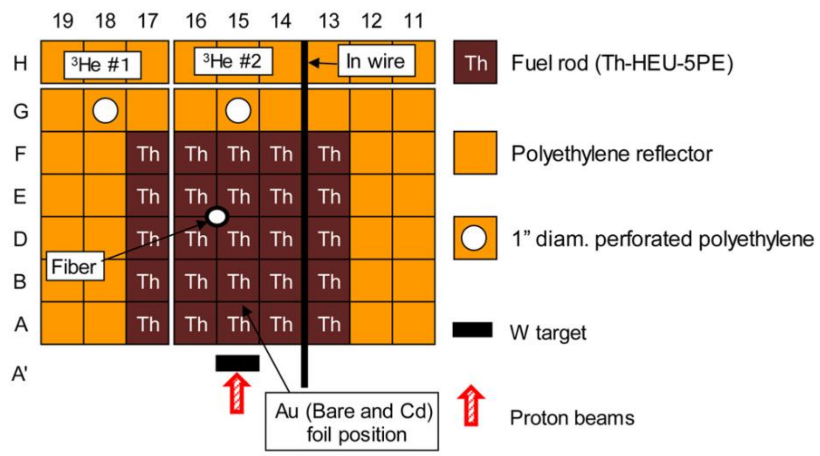
Fig. Neutron spectrum in injection of **14 MeV neutrons**

Source: C. H. Pyeon, *et al.*, *Nucl. Technol.*, **177**, 156 (2014).

Profile on ^{232}Th capture reaction rates



(a) ^{232}Th-loaded core with 14 MeV neutrons



(b) ^{232}Th-loaded core with 100 MeV protons (W target)

Fig. Core configuration of ^{232}Th-loaded core

Source: M. Yamanaka, *et al.*, *Nucl. Sci. Eng.*, **183**, 96 (2016).

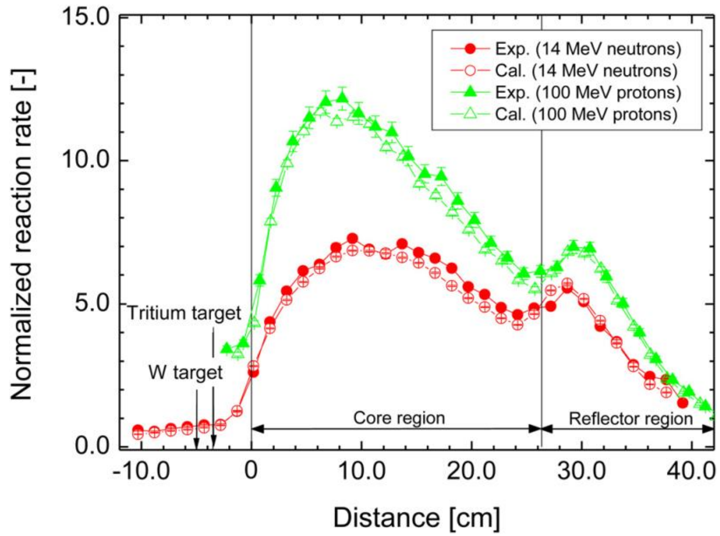


Fig. Measured ^{115}In (n, γ)^{116m}In reaction rates
(14 MeV neutrons vs. 100 MeV protons with W target)

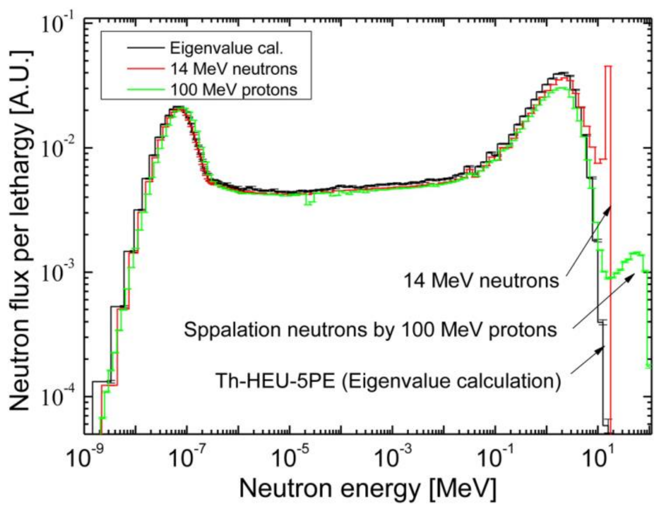


Fig. Comparison of neutron spectra

Kinetic parameters (^{232}Th-loaded ADS)

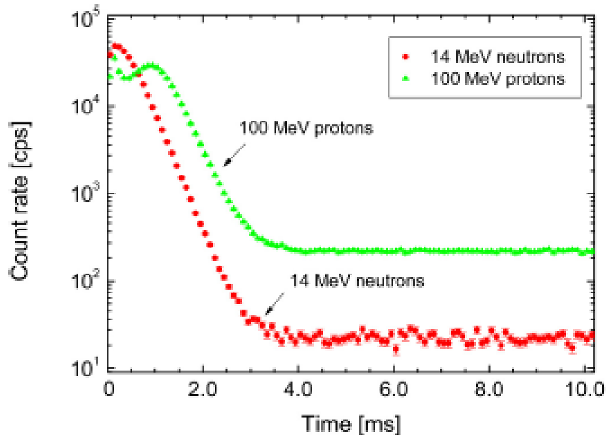


Fig. Time evolution of PNS method
(14 MeV neutrons vs. 100 MeV protons with W target)

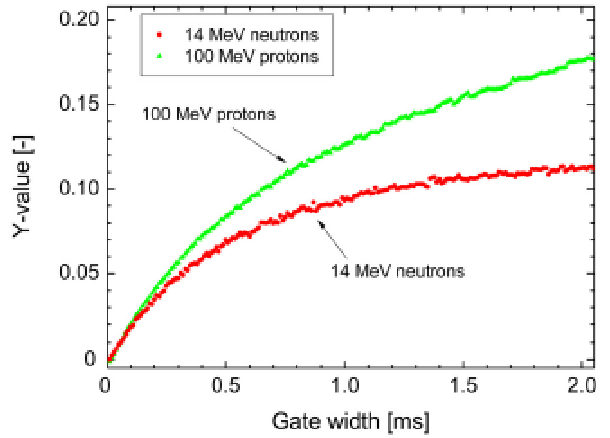


Fig. Noise data by Feynman-α method
(14 MeV neutrons vs. 100 MeV protons with W target)

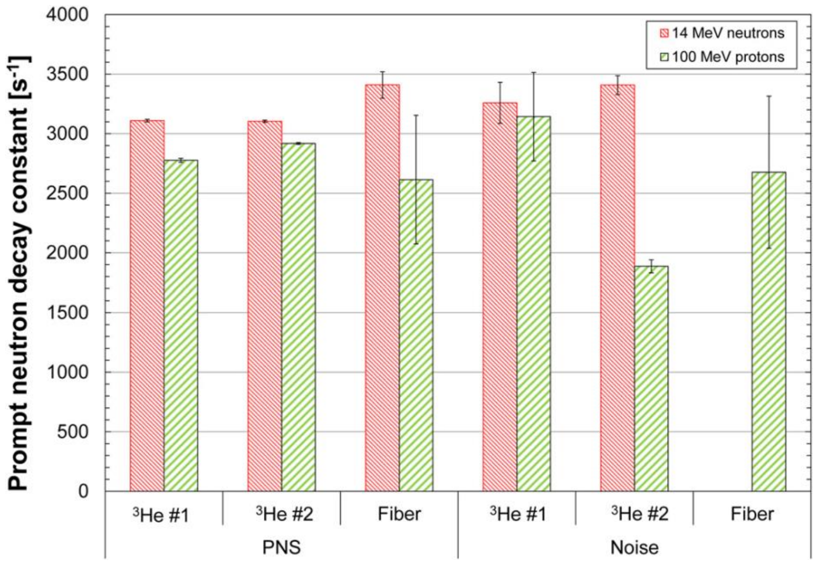


Fig. Comparison between a value by PNS and Feynman-α methods
(14 MeV neutrons vs. 100 MeV protons with W target)

Discussion issues

- Detector position dependency
- Neutron spectrum (External Source)
- Subcriticality measurement methods

Source: M. Yamanaka, *et al.*, *Nucl. Sci. Eng.*, **183**, 96 (2016).

Solid Pb-Bi Study
(collaboration with KUCA and JAEA)

C. H. Pyeon, *et al.*, *J. Nucl. Sci. Technol.*, **53**, 602 (2016).
C. H. Pyeon, *et al.*, *Nucl. Sci. Eng.*, (2017). [in print]

Uncertainties of Pb-Bi x-sec

- **Motivation**
  - Discrepancy between JENDL-3.3 and JENDL-4.0 of Pb-Bi x-sec.
    through numerical simulations of JAEA ADS model (Pb-Bi coolant model)
- **Experiments at KUCA (critical state)**
  - Sample worth (reactivity) of Pb plate in the critical state

Table Sample reactivity (C/E value) of Pb plates

Reactivity (pcm)	JENDL-3.3	JENDL-4.0	ENDF/B-VII.0	JEFF-3.1
94 ±7	1.63±0.13	1.13±0.10	0.79±0.08	0.89±0.09
110 ±6	1.53±0.10	1.07±0.08	0.85±0.07	0.97±0.07
145 ±6	1.65±0.08	1.12±0.06	0.94±0.05	1.00±0.05
156 ±7	1.76±0.08	1.13±0.06	0.94±0.05	0.98±0.05

Source: C. H. Pyeon, *et al.*, *J. Nucl. Sci. Technol.*, **53**, 602 (2016).

Upcoming experiments (Successive investigation)

- Sample worth of Bi and Pb-Bi plates in the critical state

MA irradiation in ADS (on Oct. 2017)

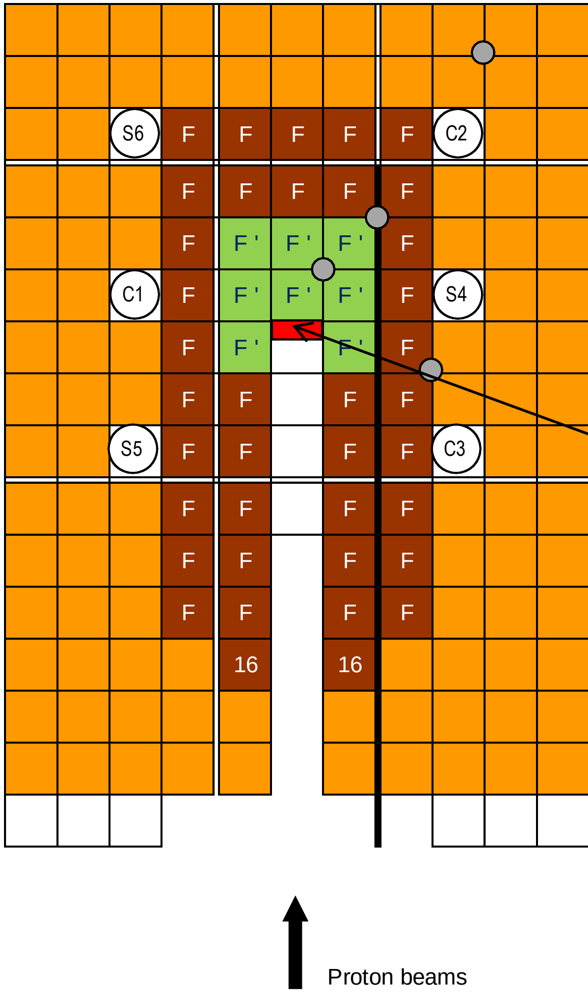


Fig. Core configuration of ^{235}U and Pb-Bi zoned core

Experimental settings

- ^{235}U and Pb-Bi zoned core
- 100 MeV protons and Pb-Bi target
- Back-To-Back Type Fission Chamber (**BTB fission chamber**)
- MA sample (^{237}Np and ^{241}Am)
  - ^{237}Np: Capture and fission
  - ^{241}Am: Fission
  - Reference: ^{235}U, ^{238}U or ^{197}Au

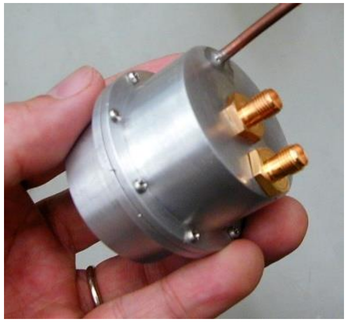


Fig. BTB fission chamber

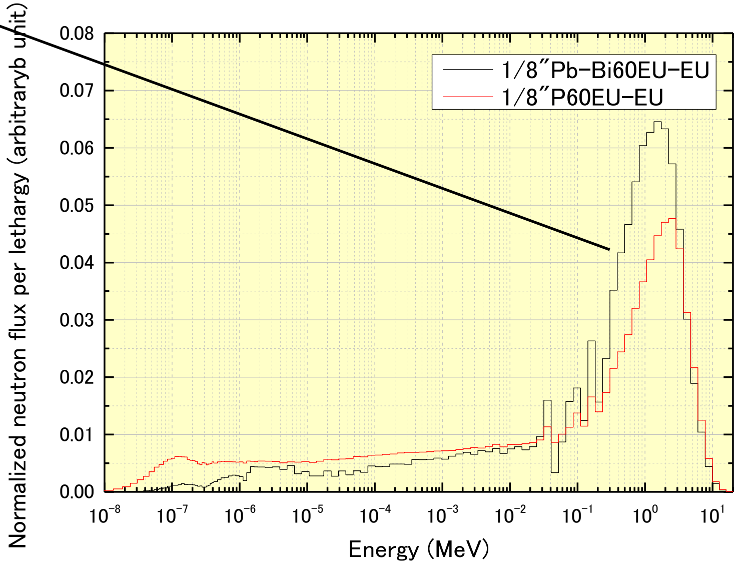


Fig. Neutron spectrum of core center in F' at 100 MeV proton injection onto Pb-Bi target

Summary

Current status

- **ADS research project in Kyoto Univ. Research Reactor Institute**
  - Application of ADS with high-energy protons to nuclear transmutation and energy amplifier system

- **Current status on ADS in the world**
  - Outline and roadmap of ADS
  - Research activities in Japan (JAEA and KURRI)

- **At KUCA, ^{235}U- and ^{232}Th-loaded ADS experiments**
  - Feasibility study on ADS with ^{235}U-loaded core and external sources
  - Preliminary study on ^{232}Th fission and capture reaction rates

Future plans

- Uncertainty analyses of Pb-Bi X-sec.
- MA irradiation at ADS with 100 MeV protons (Pb-Bi target)
- Analyses of ^{237}Np and ^{241}Am reaction rates
- Online monitoring of subcriticality by the PNS and Noise methods