Benchmark Experiments of Accelerator Driven Systems (ADS) in Kyoto University Critical Assembly (KUCA)

C. H. Pyeon, T. Misawa, H. Unesaki,
K. Mishima and S. Shiroya
(Kyoto University Research Reactor Institute, Japan)

Contents

- Background and Purpose
- A plan of ADSR (Kart & Lab. Project):
  Accelerator Driven Subcritical Reactor (ADSR) in
  Kyoto University Critical Assembly (KUCA) by using
  Fixed Field Alternating Gradient (FFAG) Accelerator
- Neutron spectrum experiments by Foil activation method
  - 14MeV neutron experiment (Pulsed neutron generator)
  - High-energy proton experiment (FFAG accelerator)
- ADS collaboration research in Japan
- IAEA benchmark problem
- Summary

Background

- ADS Research and Development:
  producing energy and transmuting minor actinides and long-lived fission products

- A neutron source in next generation of KURRI and introduction of a new accelerator

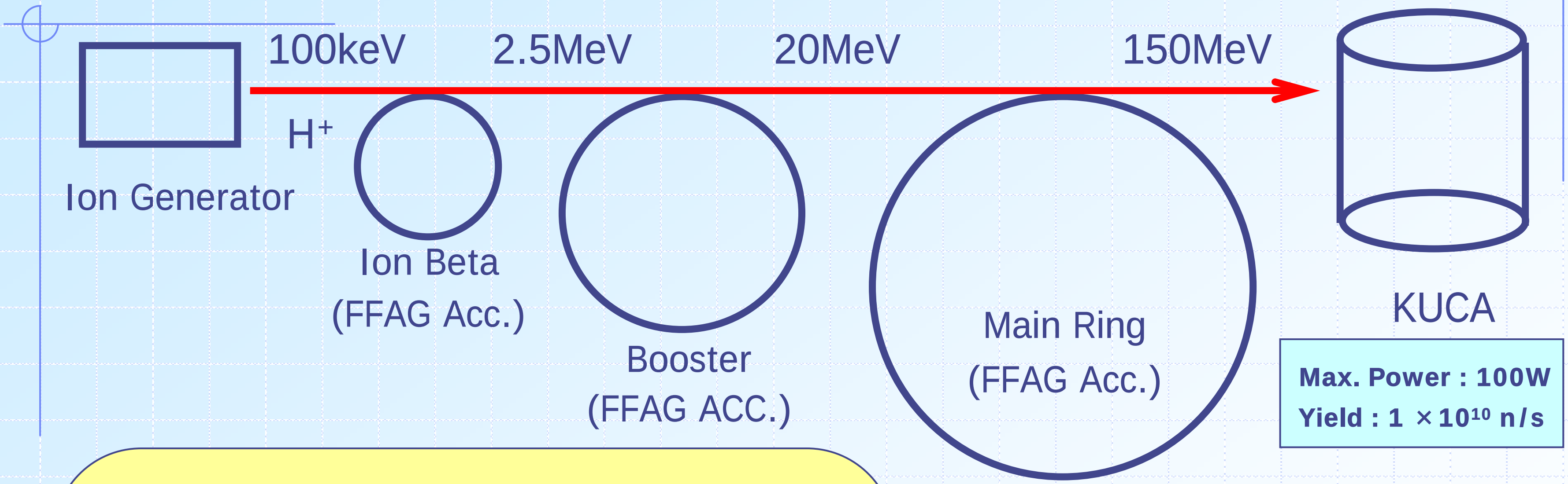
- Injection of 150MeV proton beam into KUCA core (with Tungsten (W) target) on Aug. 2007

- Investigation of main characteristics of ADSR using KUCA core with 14MeV pulsed neutrons generator

Purpose

- Conduct feasibility study of ADSR in KURRI as Energy Amplifier System
- Examine subcritical neutronic characteristics through experiments in KUCA (KUCA A core + 14MeV pulsed neutron generator)
- Assess neutronic characteristics for 14MeV neutrons by MCNP analyses with nuclear data libraries
- Establish measurement techniques
  - Reaction rate distribution, Neutron spectrum, etc.
  - Subcriticality, Neutron multiplication, Neutron decay constant

FFAG Accelerator



Main parameters in the FFAG accelerator

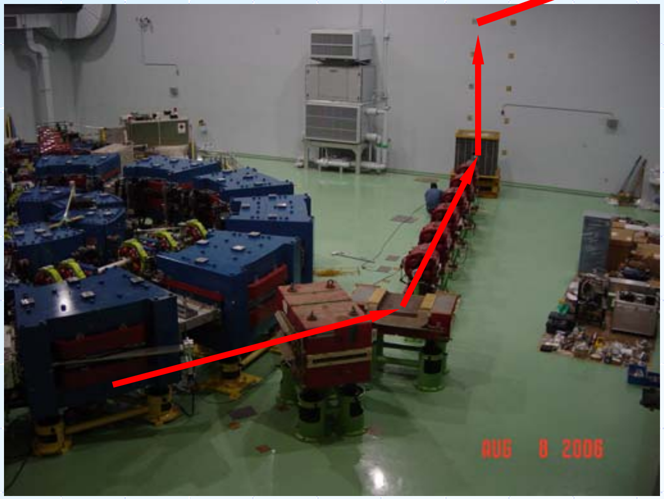
# of sectors	12
Energy	2.5 - 150MeV
Repetition rate	120Hz
Average beam current	1nA
Rf frequency	1.5 - 4.6MHz
Field index	7.5
Closed orbit radius	4.4 - 5.3m

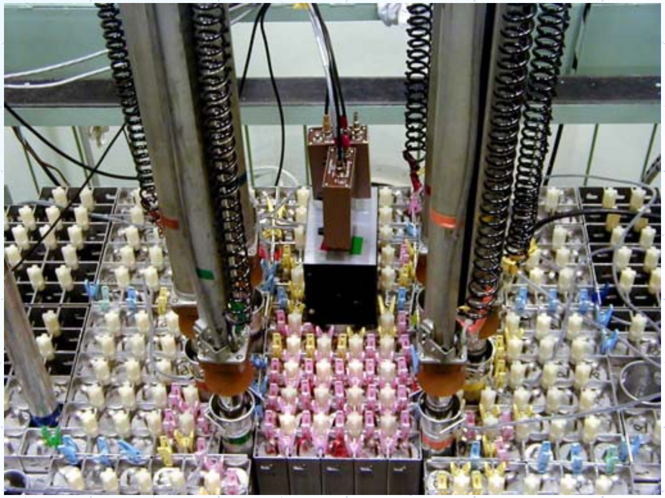
KUCA A-core & FFAG Accelerator

FFAG Accelerator

KUCA A core

Beam Line

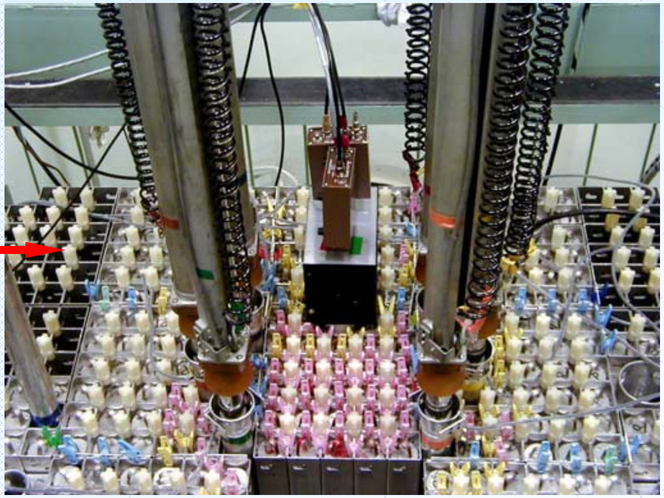




KUCA A-core & 14MeV D-T Accelerator

Tritium Target

Beam Injection



KUCA A-core

Cockcroft-Walton type Accelerator

✧ **Accelerator (D-T reactions)**
- 14MeV Pulsed Neutrons
- Yield: 1×10^9 n/s, Intensity: 0.5mA

✧ **Critical Assembly**
- Highly enriched ^{235}U
- Polyethylene Reflector & Moderator
- Thermal neutron field

KUCA A-core (with Neutron guide)

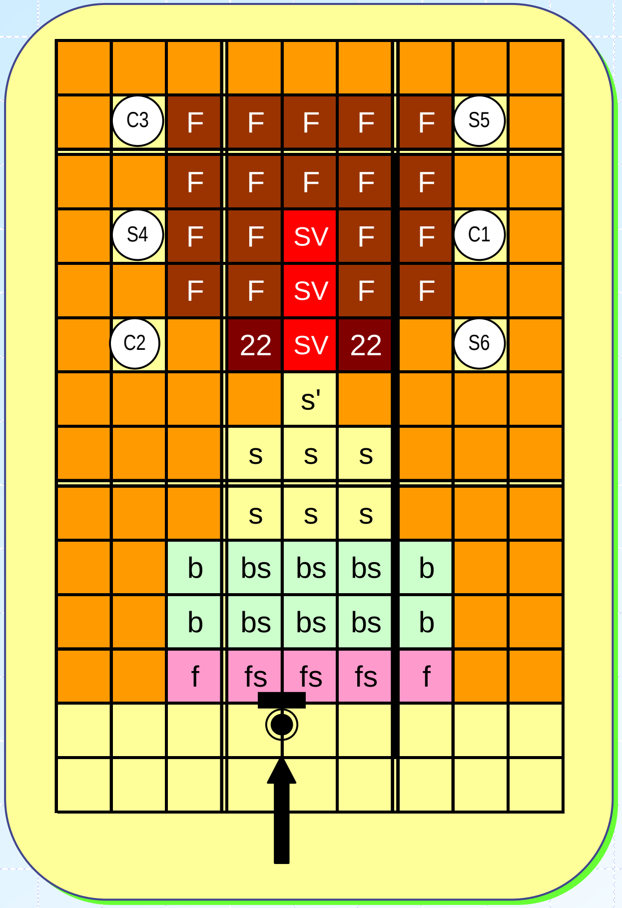


Fig. KUCA A-core with neutron guide

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

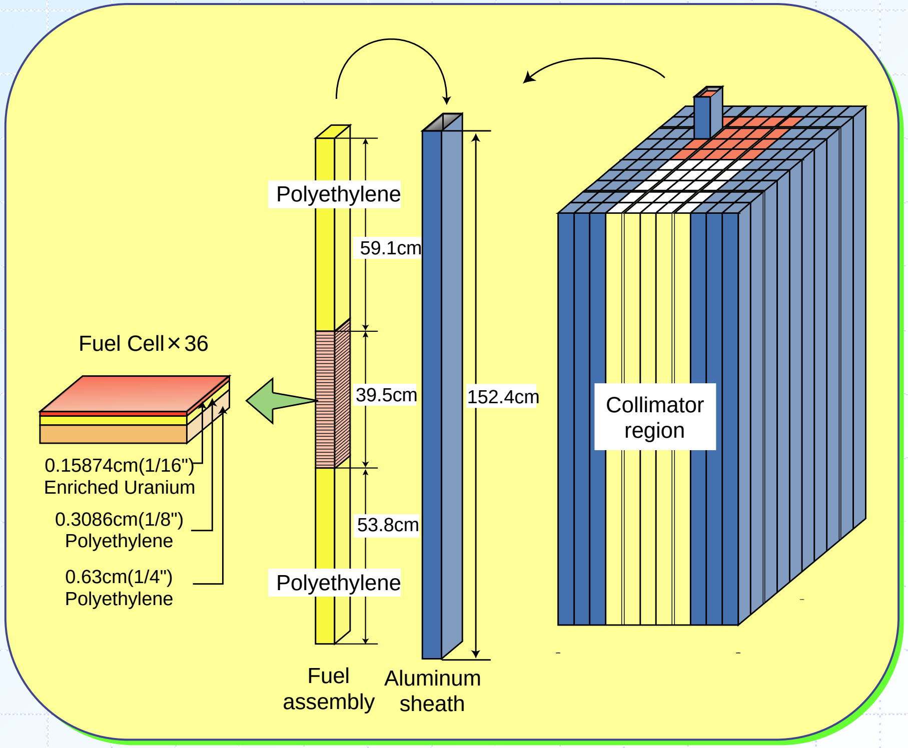


Fig. Image of KUCA A-core and fuel assembly loaded

C. H. Pyeon, KURRI, Japan

Neutron Spectrum Experiments by 14MeV Neutrons

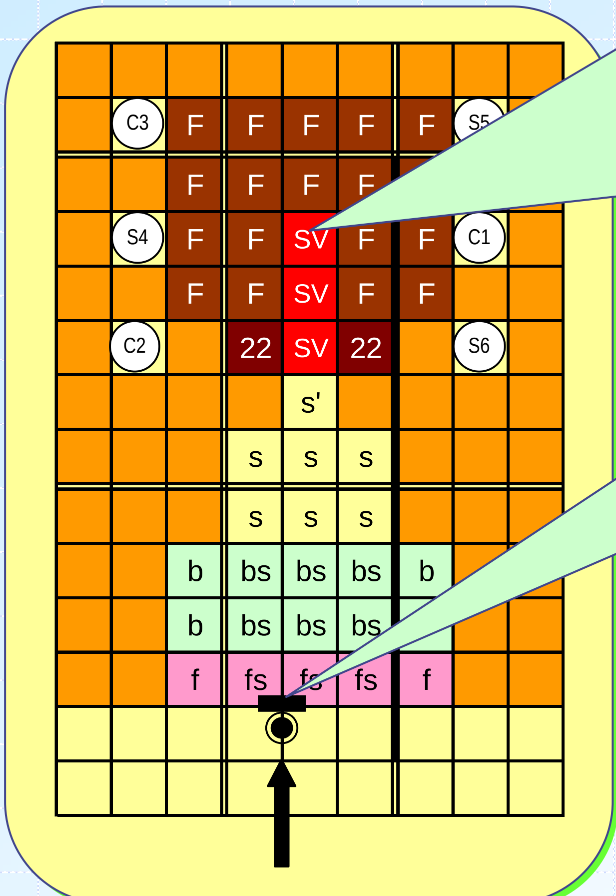


Fig. KUCA A-core with neutron guide

Table Activation foils with threshold energy and size

Reaction	Threshold [MeV]	Size [mm³]
^{115}In (n, n') ^{115m}In	0.32	45×45×3
^{56}Fe (n, p) ^{56}Mn	2.97	45×45×5
^{27}Al (n, α) ^{24}Na	3.25	45×45×5
^{92}Nb (n, 2n) ^{92m}Nb	9.05	45×45×2
^{197}Au (n, γ) ^{198}Au	Normalization	1ϕ×0.05

✧ **Irradiation**
- Positions: Core center and Target
- Method: Foil activation method
- Irradiation time: 3 to 6 hrs

✧ **Subcriticality**
- 0.87, 1.23, 1.75%Δk/k

✧ **MCNP-4C2 and ENDF/B-VI.2**

Reaction Rates Evaluation

Table Comparison of measured reaction rates with calculated ones

Core	Threshold [MeV]	C/E (0.87%Δk/k)	C/E (1.23%Δk/k)	C/E (1.75%Δk/k)
^{115}In	0.32	2.31 ± 0.05	2.22 ± 0.05	2.10 ± 0.05
^{56}Fe	2.97	0.14 ± 0.01	0.17 ± 0.01	0.20 ± 0.01
^{27}Al	3.25	1.10 ± 0.03	1.05 ± 0.03	0.92 ± 0.03
^{93}Nb	9.05	None	0.10 ± 0.01	None

Reaction rates evaluation

- Good: ^{27}Al within 10% error regardless of subcriticality
- Large discrepancy: ^{115}In, ^{56}Fe and ^{93}Nb
- Relationship between C/E value and subcriticality

Target	C/E
^{115}In	4.50 ± 0.13
^{56}Fe	0.88 ± 0.02
^{27}Al	1.26 ± 0.04
^{93}Nb	1.29 ± 0.04

Unfolding Evaluation

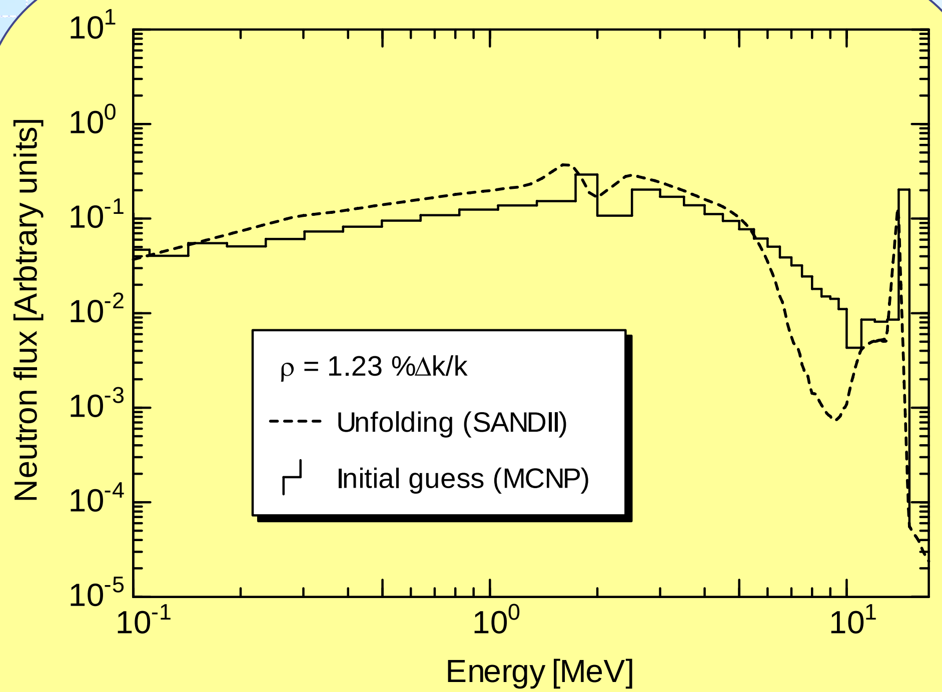


Fig. Comparison of unfolding with initial guess

Numerical analyses

- **Unfolding by SANDII (based on measured reaction rates)**
- **Initial guess by MCNP (ENDF/B-VI.2)**

Good evaluation by unfolding analyses based on measured reaction rates

Neutron Spectrum Experiments at FFAG accelerator

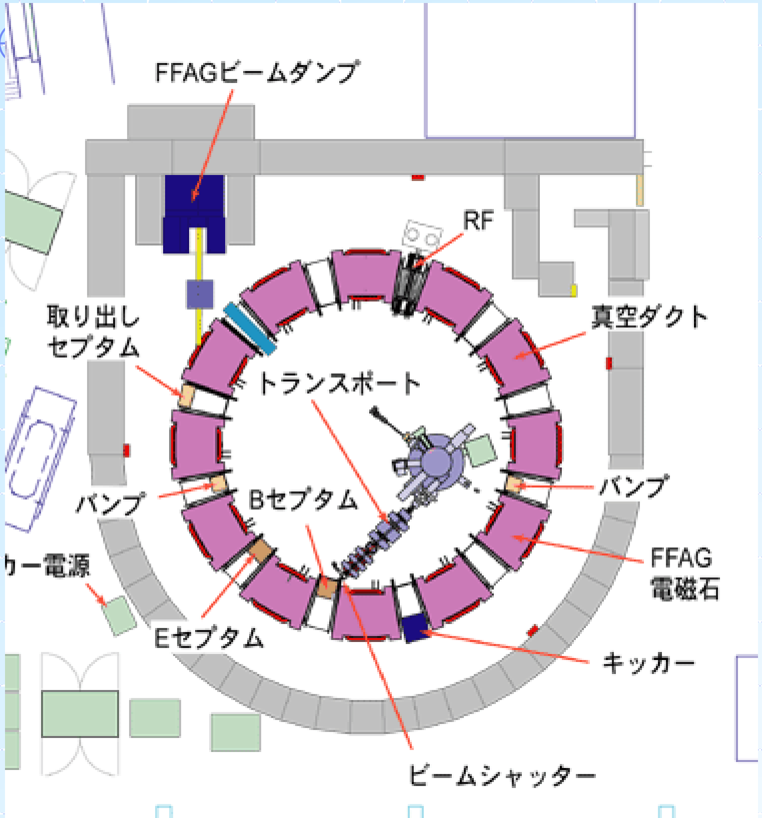
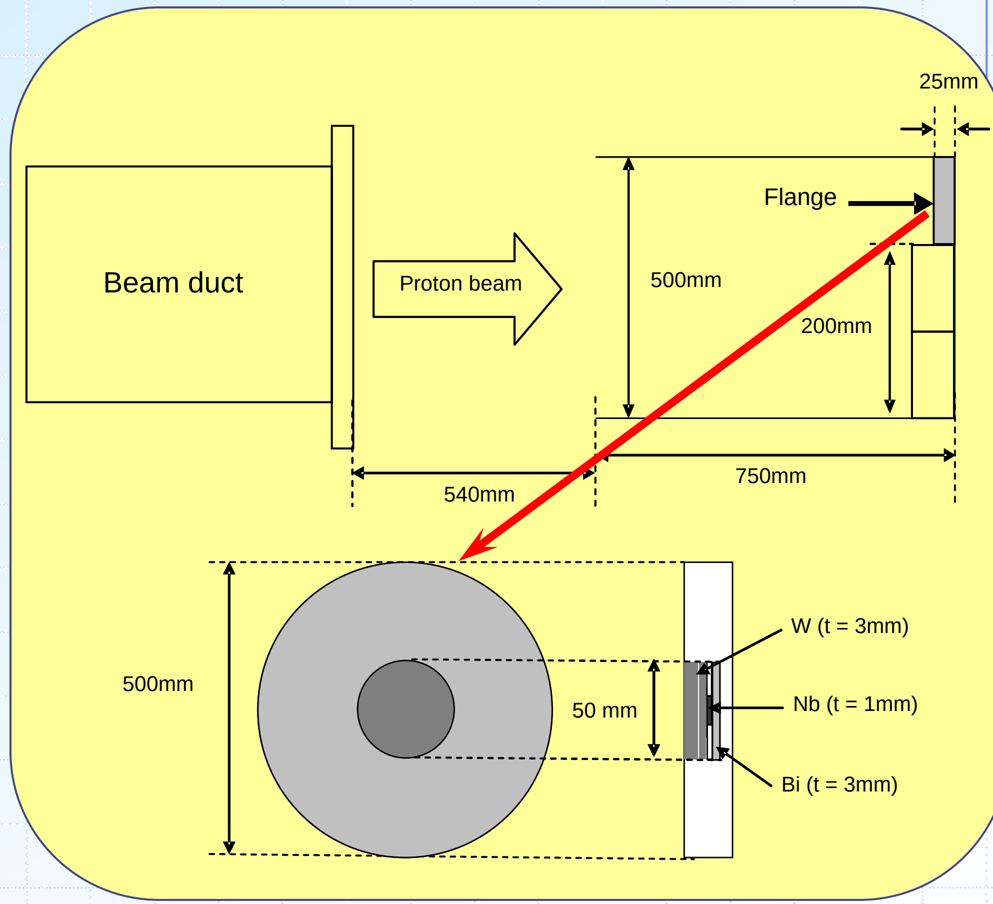


Fig. Top view of PoP FFAG acc. (KEK)



- Proton beam (At beam dump: 70MeV, 0.4n)
- ^{184}W target and ^{93}Nb (Norm. factor of neutron generation)
- ^{209}Bi Threshold Energy (15 to 90MeV): ^{209}Bi (n, xn) $^{210-x}$Bi (x=3 to 12)

C. H. Pyeon, KURRI, Japan

Neutrons and Protons Estimation

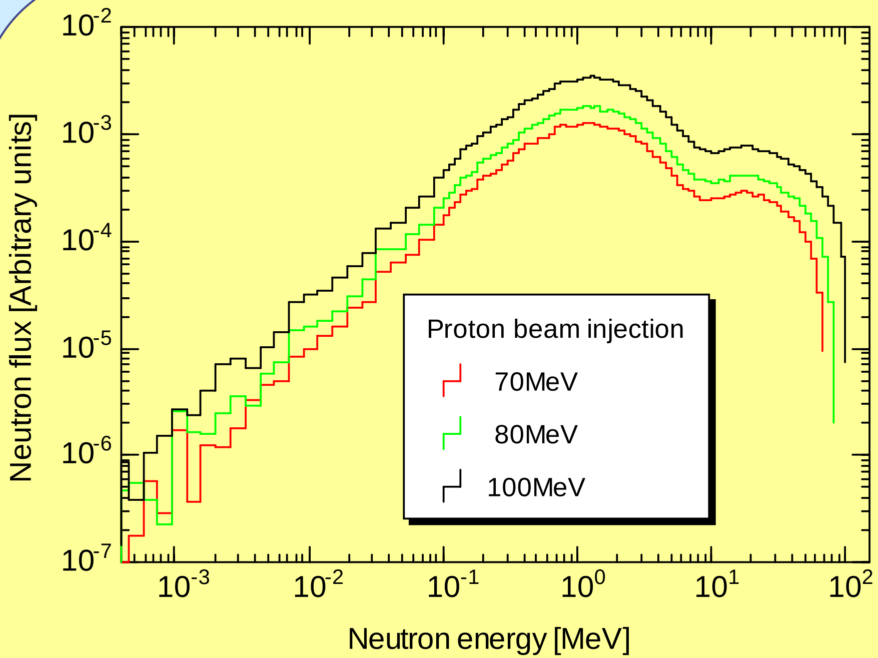


Fig. Calculated neutron spectrum evaluated by MCNPX

- **About 60MeV neutron generation by about 70MeV proton injection onto ^{184}W**
- **Useful foil of ^{209}Bi covering wide range of threshold energy**

Table Measured reaction rates obtained at FFAG acc.

Reaction	Threshold [MeV]	Measured reaction rate
^{209}Bi (n,3n) ^{207}Bi	14.42	-
^{209}Bi (n,4n) ^{206}Bi	22.55	$(1.51 \pm 0.01) \times 10^{5}$
^{209}Bi (n,5n) ^{205}Bi	29.62	$(1.01 \pm 0.03) \times 10^{5}$
^{209}Bi (n,6n) ^{204}Bi	38.13	$(2.37 \pm 0.02) \times 10^{4}$
^{209}Bi (n,7n) ^{203}Bi	45.37	$(6.35 \pm 0.16) \times 10^{3}$
^{209}Bi (n,8n) ^{202}Bi	54.24	$(2.74 \pm 0.07) \times 10^{2}$
^{209}Bi (n,9n) ^{201}Bi	61.69	-
^{209}Bi (n,10n) ^{200}Bi	70.89	-
^{209}Bi (n,11n) ^{199}Bi	78.47	-
^{209}Bi (n,12n) ^{198}Bi	87.94	-

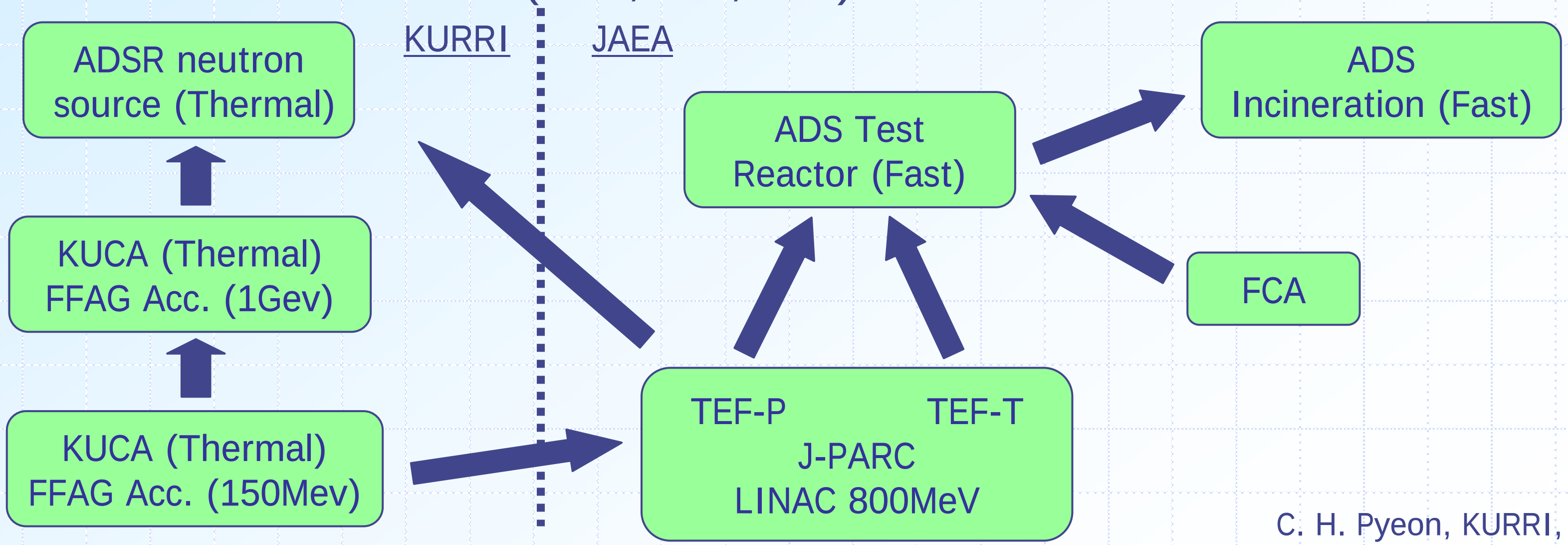
ADS Collaboration Research in Japan

- KURRI (Kart & Lab. project): KUCA, FFAG Accelerator

  Thermal neutron field → Energy amplifier system
- JAEA (J-PARC project): FCA, TEF-P, TEF-T

  Fast neutron field → Nuclear Transmutation
- User and support group: Tohoku Univ., Nagoya Univ., Kinki Univ., etc.

✓ Subcriticality measurement (Noise method, NSM method, etc.)
✓ Neutronic characteristics (Neutron flux, Neutron spectrum, etc.)
✓ Nuclear Transmutation (MAs, FPs, etc.)



IAEA Benchmark Problem

- Phase I: Static experiments (14MeV neutrons)
  Reaction rates distribution, Neutron spectrum, Reactivity
- Phase II: Kinetic experiments (14MeV neutrons)
  Neutron multiplication, Subcriticality measurement method
  (Rossi-α, Feynman-α, Pulsed neutrons and
  Neutron source multiplication (NSM) methods)
- Phase III: Static and Dynamic experiments (150MeV protons)
  Above topics, γ-ray distribution, Power monitoring, etc.

- Fuel: Highly enriched ^{235}U, ^{232}Th, Natural Uranium
- Reflector: Polyethylene, Graphite, Aluminum, Beryllium
- Core: Any combinations of Fuel & Reflector

Publish KUCA benchmark problem in a near future

Summary

- ADSR project (Kart & Lab. project) in KURRI
  - Energy amplifier system by ADSR
- Neutron spectrum experiments of ADSR
  - 14MeV pulsed neutrons in KUCA
    - Reaction rates evaluation: Good results by foil activation method
    - Unfolding evaluation: Feasibility of SANDII code
  - High-energy protons from FFAG accelerator
    - About 60MeV neutron generation by about 70MeV proton injection onto ^{184}W target
    - Useful activation foil of ^{209}Bi covering wide range of threshold
- From 14MeV neutron results, very important and valuable information, for 150MeV proton analyses

KUCA A-core

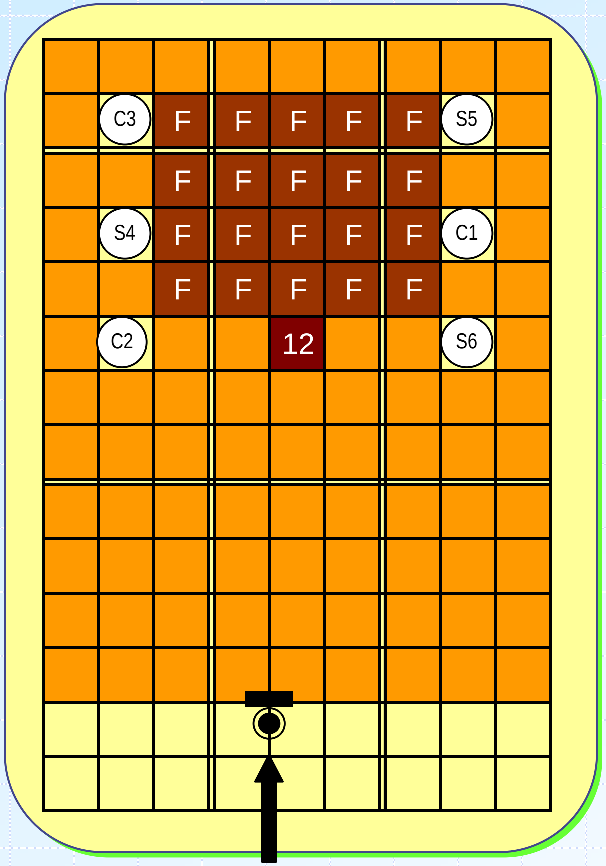


Fig. KUCA A-core (Reference core)

- KUCA A-core -

A solid-moderated and reflected core

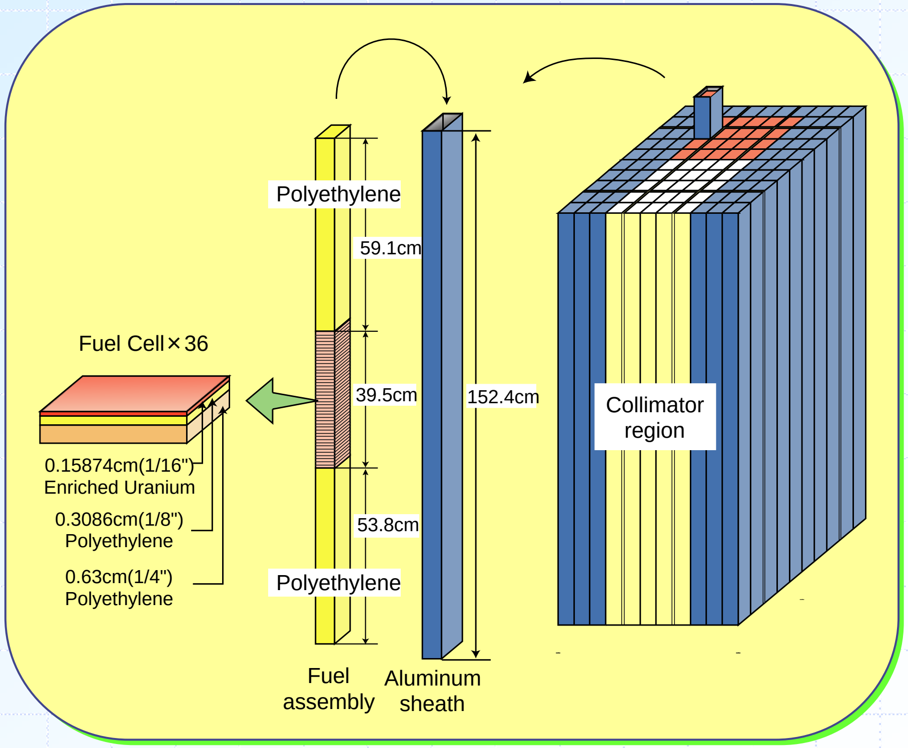


Fig. Image of KUCA A-core and fuel assembly loaded

C. H. Pyeon, KURRI, Japan

Static Experiments

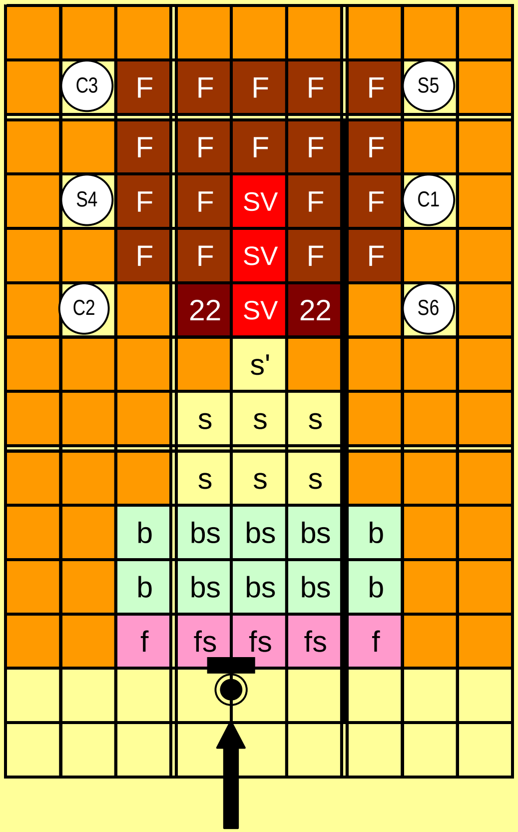


Fig. KUCA A-core with collimator and beam duct.

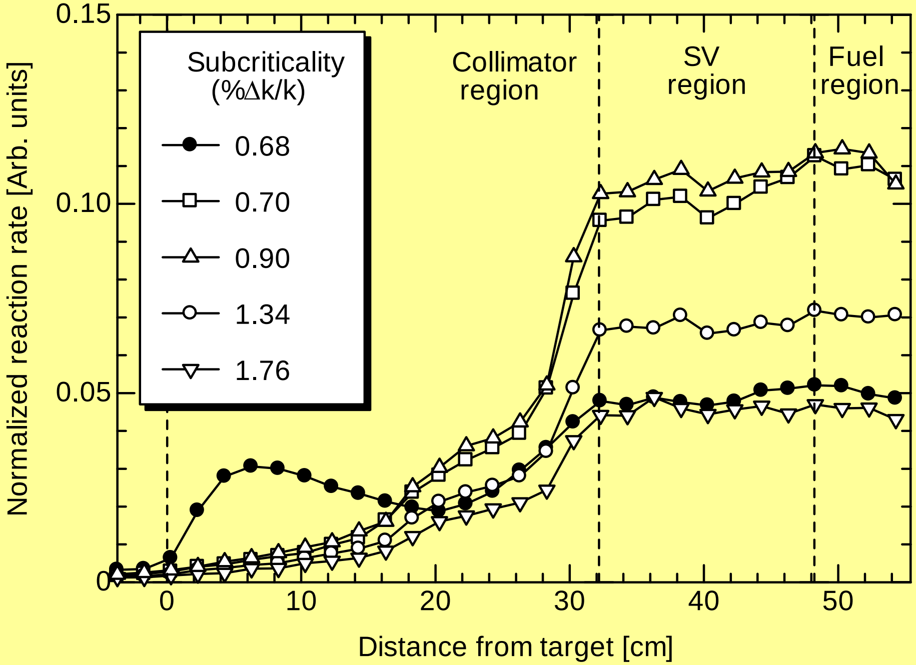


Fig. Measured Indium reaction rates distribution.

Reaction rates distribution (Foil activation method)

- ✓ Measure ^{115}In (n, γ) ^{116m}In (Exp. error: 5%)
- ✓ Examine effects on subcriticality, configuration
- ✓ Optimize collimator and beam duct

C. H. Pyeon, KURRI, Japan

MCNP Analyses for Static Experiments

Table Comparison of measured subcriticality with calculated one.

Experiment (%Δk/k)	MCNP (JENDL-3.3) (%Δk/k)	MCNP (ENDF/B-VI.2) (%Δk/k)
-0.68±0.04	-0.68 (1.4%)	-0.67 (1.8%)
-0.89±0.05	-0.98 (5.7%)	-0.91 (3.5%)
-1.34±0.07	-1.35 (0.3%)	-1.40 (3.9%)
-1.76±0.09	-1.71 (2.9%)	-1.72 (2.4%)

( ): Relative difference, Cal. error: 0.03%Δk/k

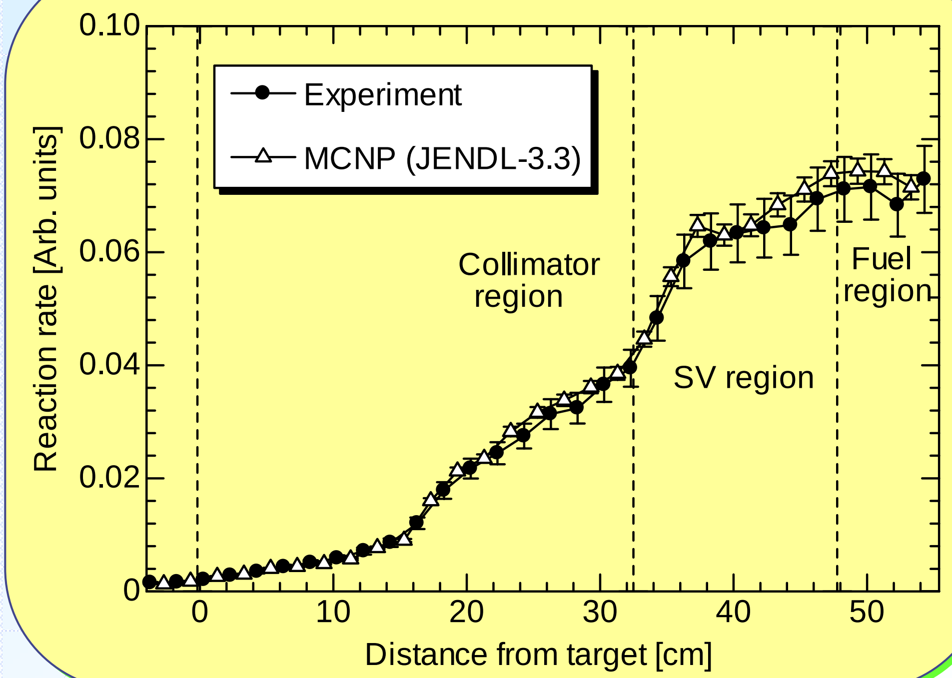


Fig. Comparison of measured In reaction rates distribution with calculated one.

MCNP eigenvalue and point source calculations

✓Good evaluation by MCNP within experimental error

Optical Fiber Detection System

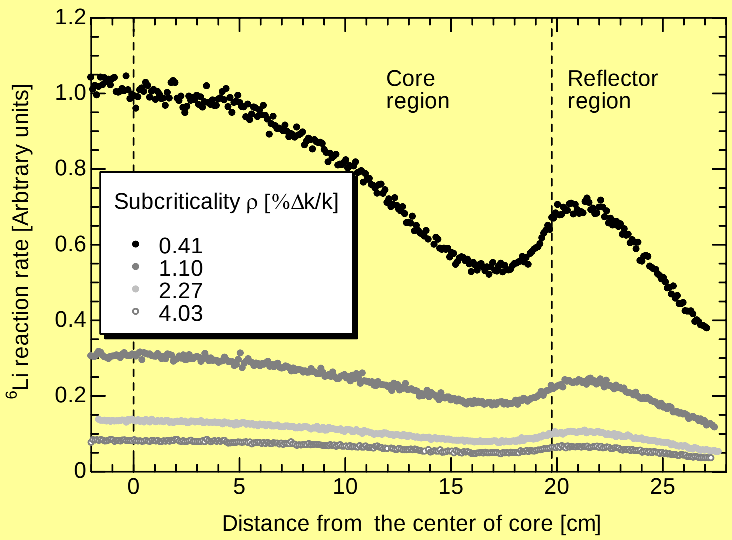


Fig. Li reaction rates by optical fiber detection system, along to subcriticality.

Area ratio method

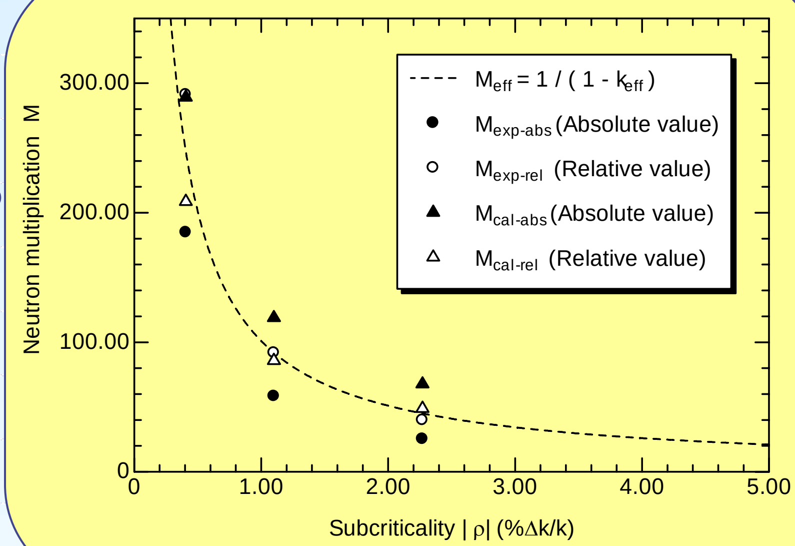
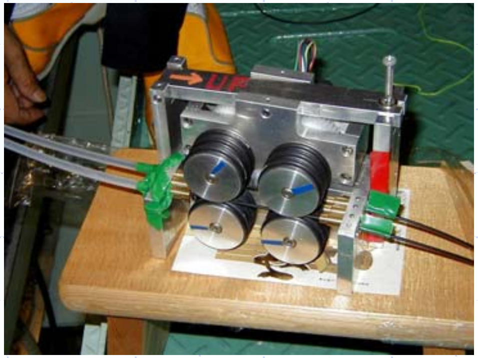


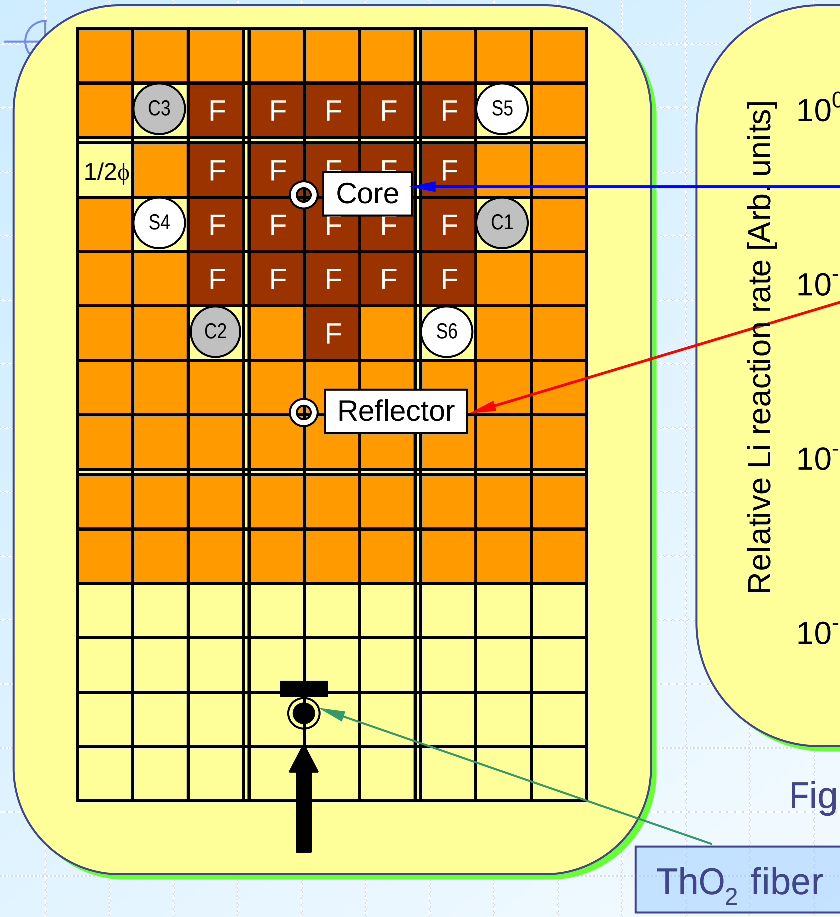
Fig. Neutron multiplication by Area ratio method applied to Li reaction rates.

Optical fiber detection system

- LiF (ZnS): $^{6}Li\ (n, \alpha)$ reaction for thermal neutrons
- ThO_2 (ZnS): ^{232}Th fission reaction for fast neutrons



Dynamic Experiments (Optical fiber system)



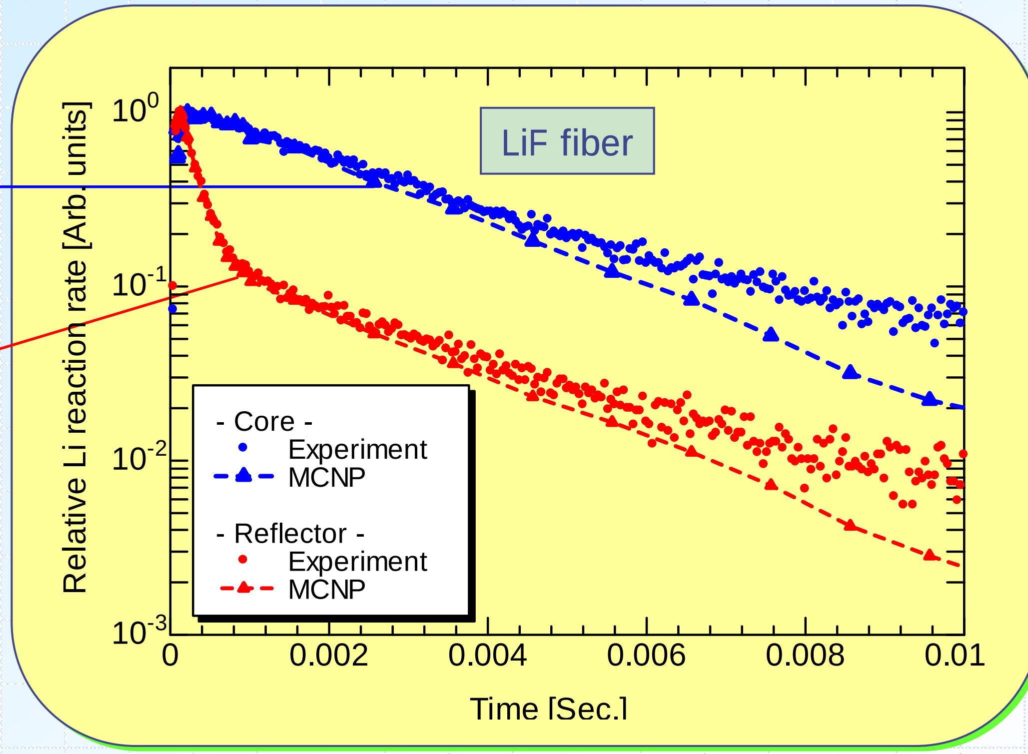


Fig. Measured neutron decay behavior by optical fiber detector system.

<u>Pulsed neutron method (PNM)</u>

- ✓ Good evaluation of subcriticality at both core and reflector positions
- ✓ Examine methodology and position dependency

C. H. Pyeon, KURRI, Japan

Subcriticality (Source Multiplication Method)

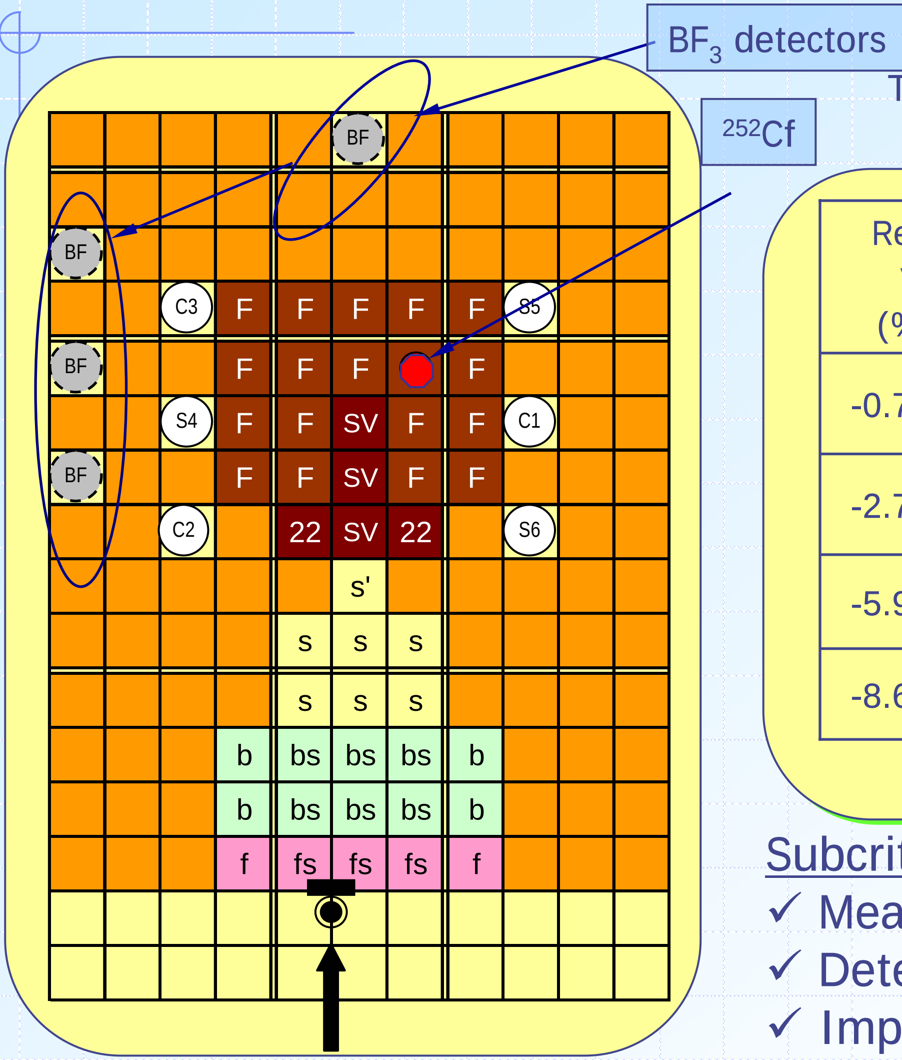


Table Comparison of measured subcriticality with calculated ones (with JENDL-3.3).

Ref. Exp. value (%Δk/k)	MCNP (%Δk/k)	Higher-mode SM method (%Δk/k)
-0.72±0.06	-0.69 (4.2%)	-0.67 (6.9%)
-2.72±0.22	-2.88 (5.9%)	-2.52 (7.4%)
-5.96±0.45	-6.44 (7.5%)	-5.19 (12.9%)
-8.66±0.69	-10.46 (20.8%)	-7.09 (18.1%)

( ): Relative difference, Cal. error: 0.03%Δk/k

Subcriticality (Source Multiplication method)

- ✓ Measurement technique
- ✓ Detector position dependency
- ✓ Improvement of precision and methodology

C. H. Pyeon, KURRI, Japan