Recent Experimental Results of the Accelerator Driven System with a Sub-critical Nuclear Reactor (ADS) Program

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Outline

ADS : Accelerator Driven (nuclear transmutation) System
KURNS : Institute for Integrated Radiation and Nuclear Science, Kyoto University
MA : Minor Actinide

- Spent fuel issue
- ADS* for transmutation
- Experimental facilities for basic ADS study at KURNS**
  - Sub-critical core : Kyoto University Critical Assembly (KUCA)
  - Proton driver : Fixed Field Alternating gradient (FFA) synchrotron
- Setup for MA*** transmutation experiments
  - Core setup
  - Beam characteristics
- Results
- Conclusion

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Spent fuel issue

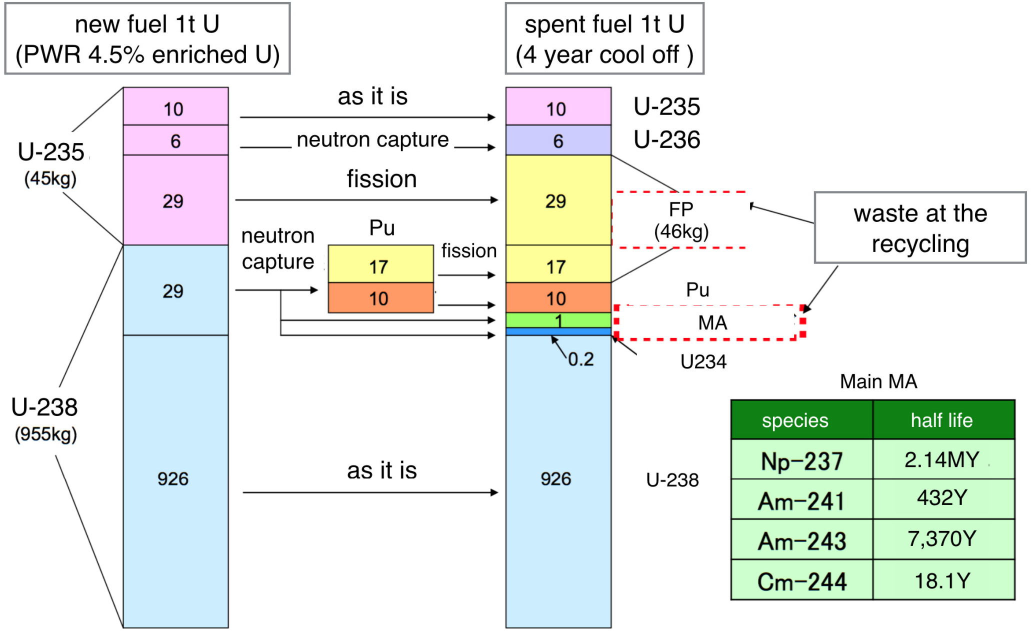
Spent fuel : urgent worldwide issue.

Japan : 17,000 ton spent fuel (2014 April)

1 GW class LWR x 1 year → 20 ton spent fuel

Forecast 2030 :
Assume 15% of electricity demand (20 GW) is covered by nuclear power.

Spent fuel : 400 ton / year

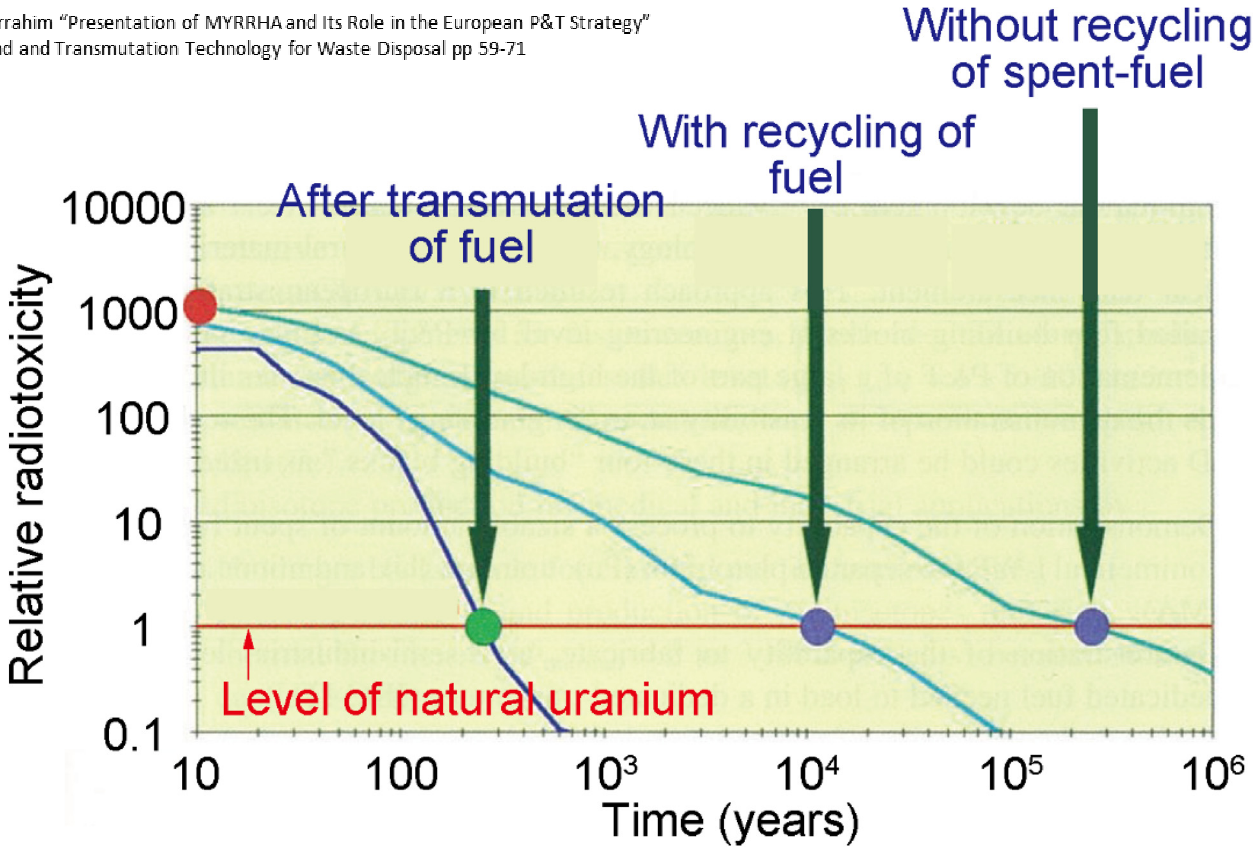


Main MA

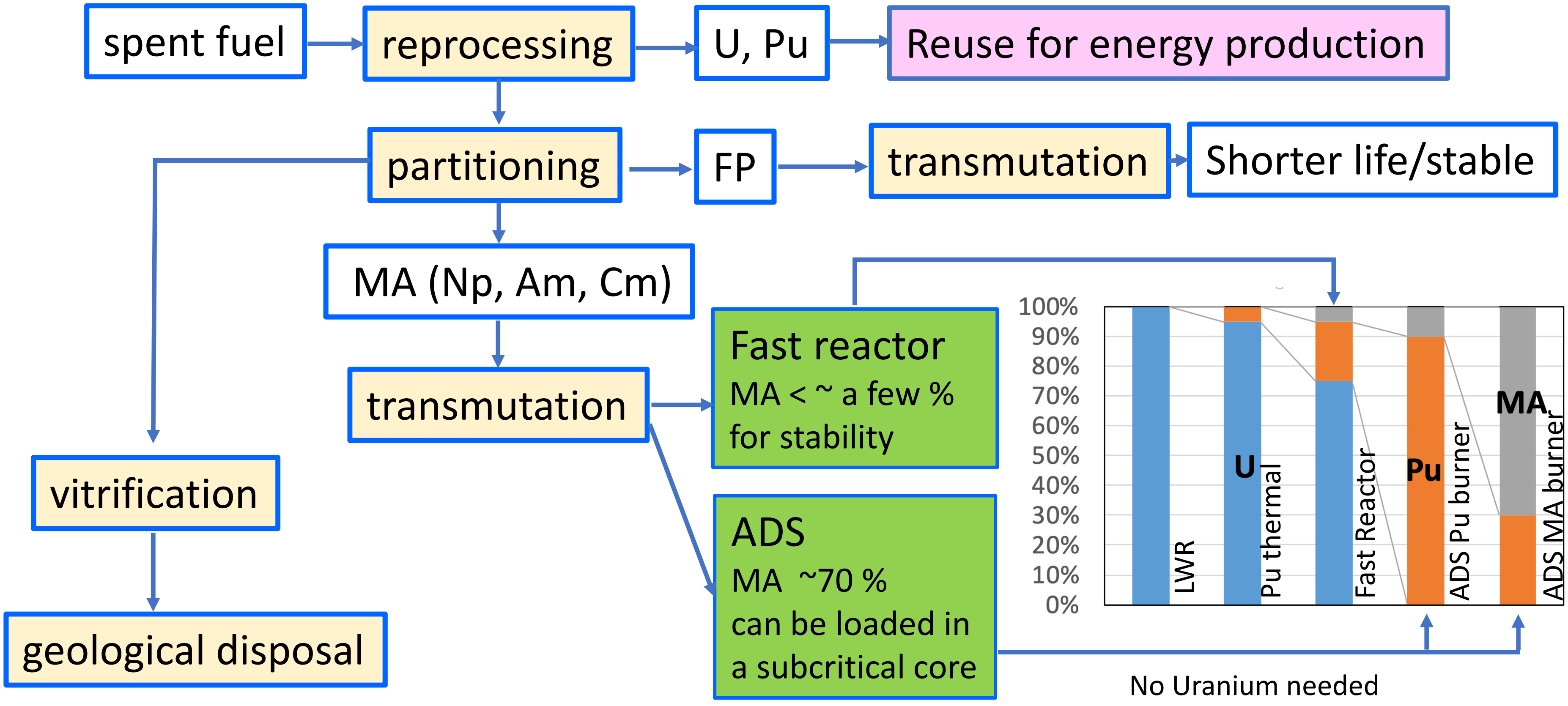
species	half life
Np−237	2.14MY
Am−241	432Y
Am−243	7,370Y
Cm−244	18.1Y

Decay of radio-active toxicity

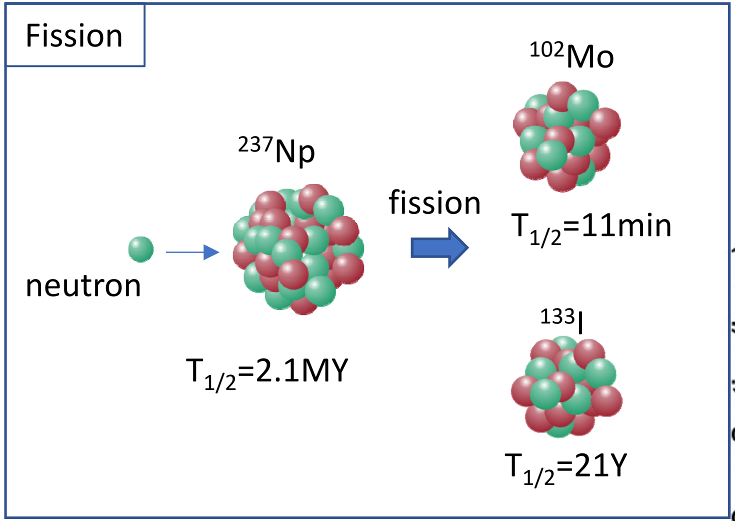
Hamid Aït Abderrahim "Presentation of MYRRHA and Its Role in the European P&T Strategy"
Nuclear Back-end and Transmutation Technology for Waste Disposal pp 59-71

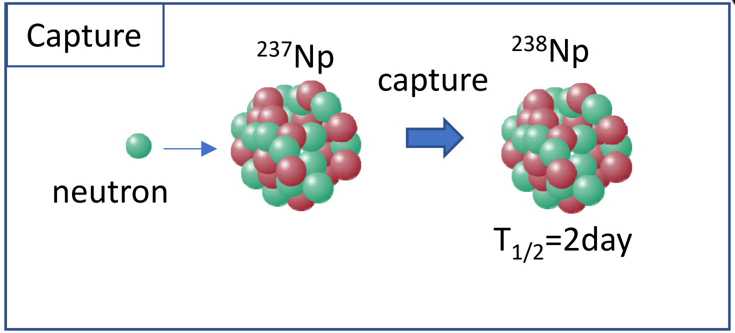


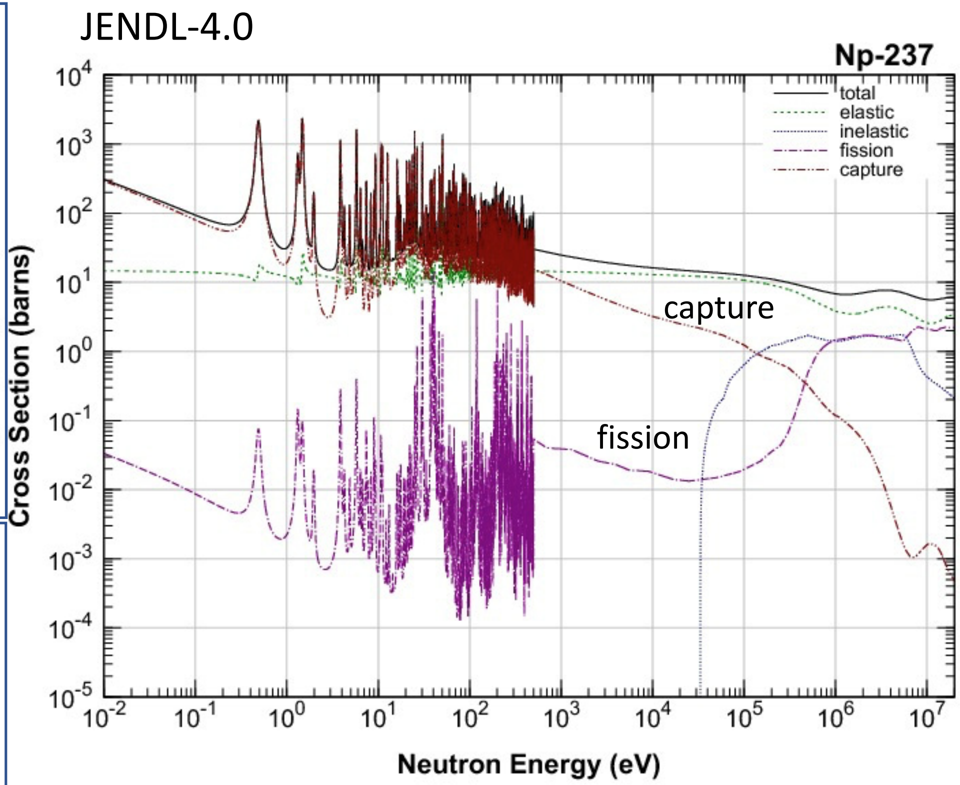
How do we solve this problem?



MA transmutation using neutrons







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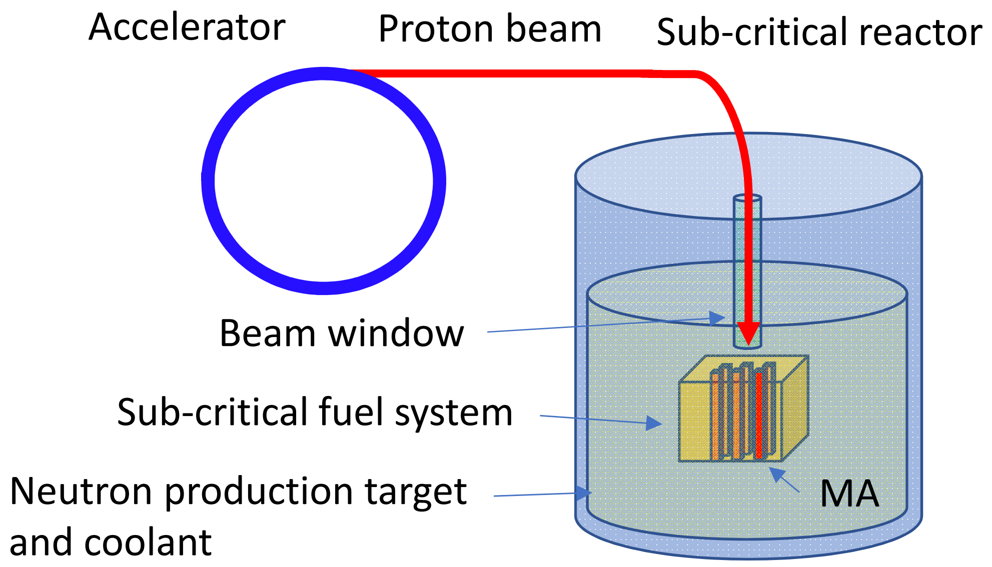
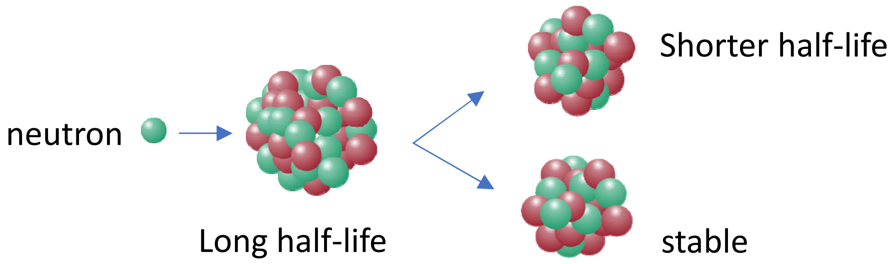
Concept of ADS

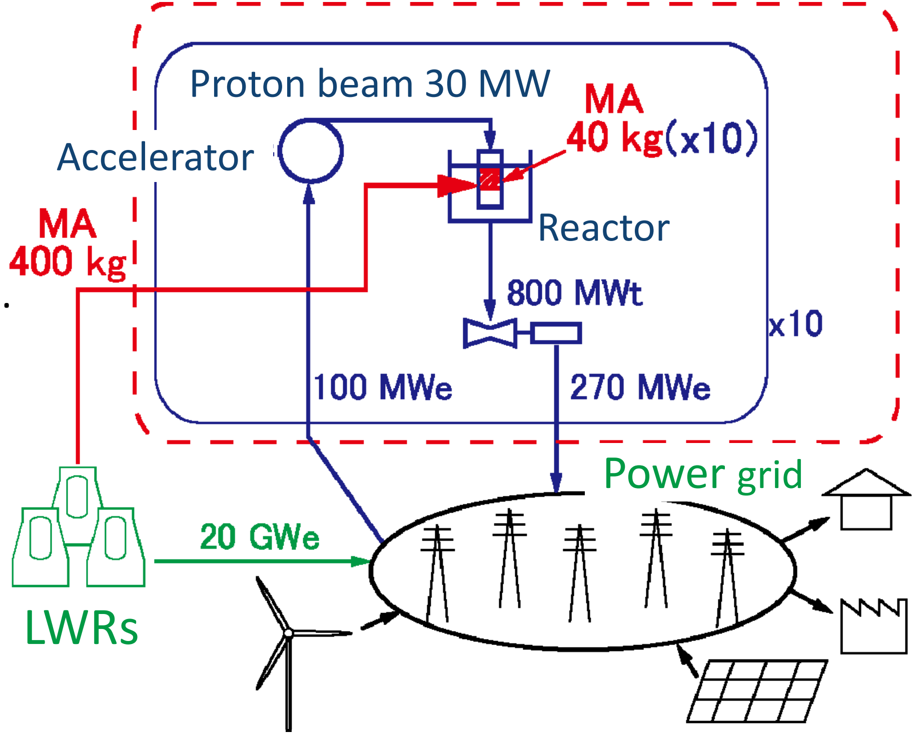




1. Accelerator sends the proton beams (0.8 – 1.5 GeV) to the sub-critical reactor through the beam window.
2. The beam hits the liquid-metal target e.g. Pb-Bi which plays a role of circulating coolant as well as neutron production target.
3. Protons hitting the target cause the spallation reaction and generate numbers of neutrons.
4. Neutrons generated at the target cause the fission chain reaction inside the fuel system.
5. Neutrons transmute MAs into stable or shorter-life material.

Power flow of ADS

1. Accelerator generates 30 MW beam.
2. Reactor amplifies beam power.
3. Thermal output of the reactor ~800MWt
4. MA loaded in the core is transmuted.
5. Thermal power of 800 MWt will be converted to the electric power of 270 MWe.
6. Electric power of 100 MWe out of 270MWe will be used for the accelerator complex.
7. The rest of electric power i.e. 170 MWe will be returned to the power grid.



Characteristics of ADS

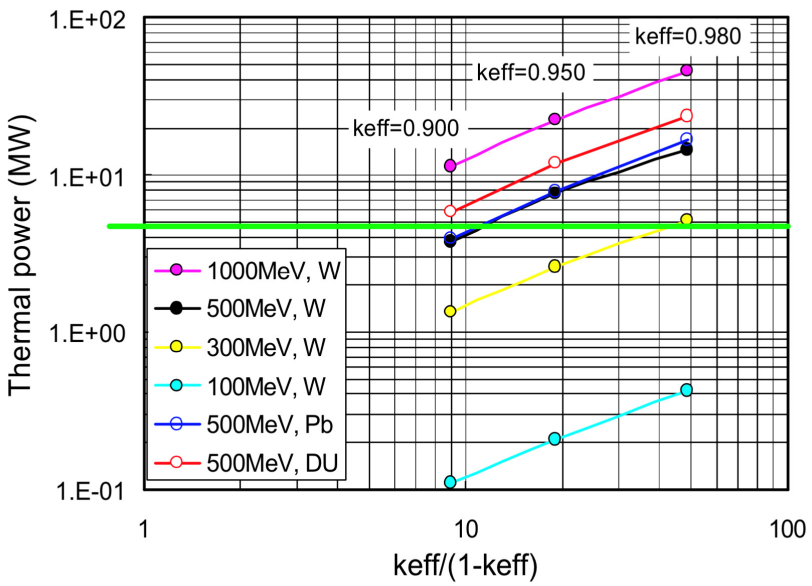
On of the caracteristics of ADS is that output power of the nuclear reactor can be controlled by changing the beam power from the accelerator. Output power P from the sub-critical reactor is expressed as

$$P \sim \frac{S}{1 - k_{\text{eff}}}$$

S: power of neutron source, which can be adjusted by changing the beam energy and/or current of the proton driver.

k_{eff} : Effective multiplication factor, which is determined by the control rods and other parameters of the fuel system.

$$k_{\text{eff}} = \frac{\text{Production rate of neutrons}}{\text{Annihilation rate of neutrons}}$$



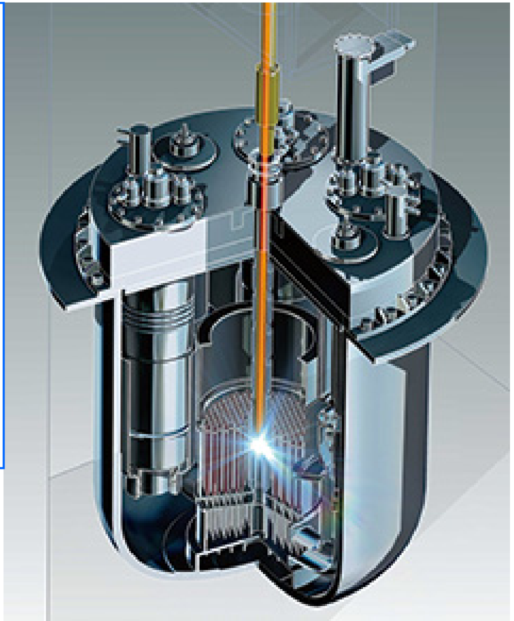
$k_{\text{eff}} > 1$: Supercritical

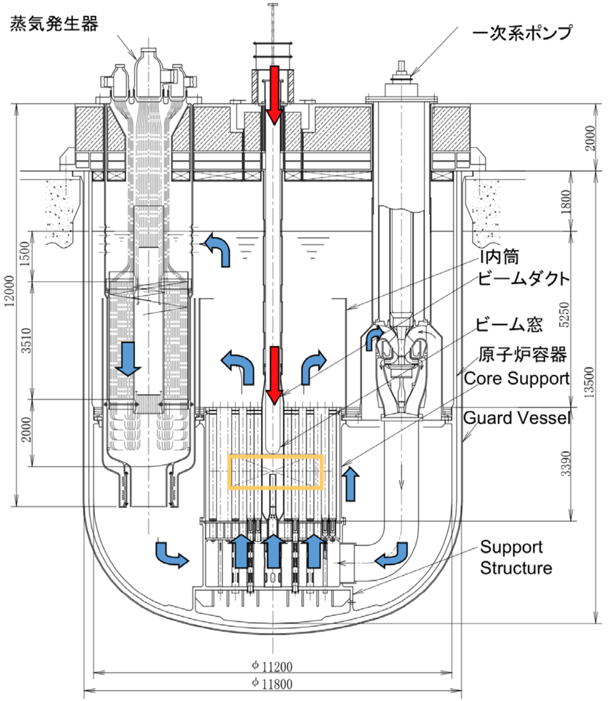
$k_{\text{eff}} = 1$: critical

$k_{\text{eff}} < 1$: Subcritical

Design example of ADS by JAEA

- Proton beam : 1.5GeV
- Beam power : ~30MW
- Spallation target : LBE
- Coolant : LBE
- Subcriticality : $k_{eff} = 0.97$
- Thermal output : 800MWt





K. Tsujimoto, H.Oigawa, K.Kikuchi, et. al, "Feasibility of Lead-Bismuth-Cooled accelerator-Driven System for Minor-Actinide Transmutation", *Nucl. Tech.* 161, 315-328 (2008).

LBE: Lead-Bismuth Eutectic

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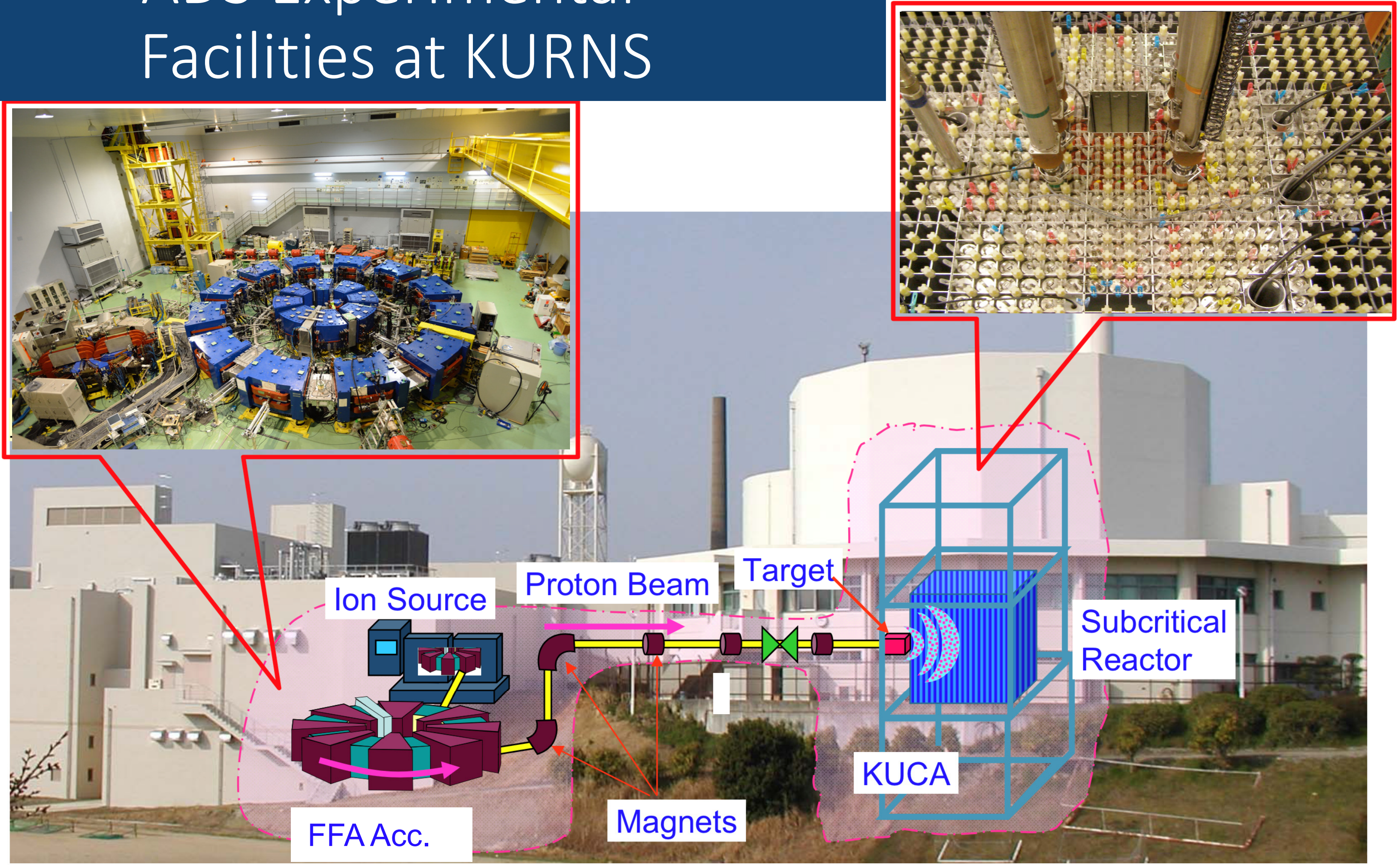
ADS Experimental Facilities at KURNS



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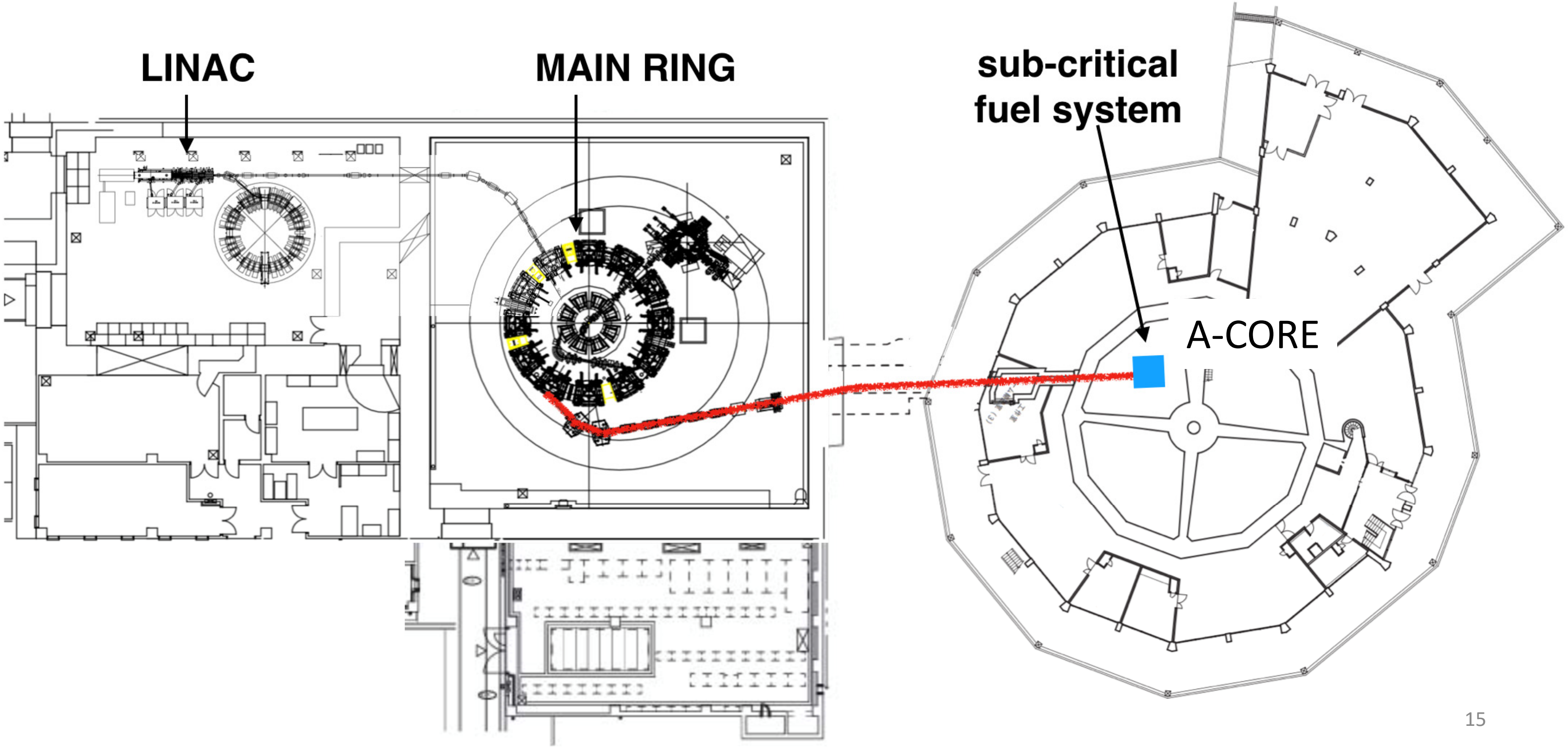
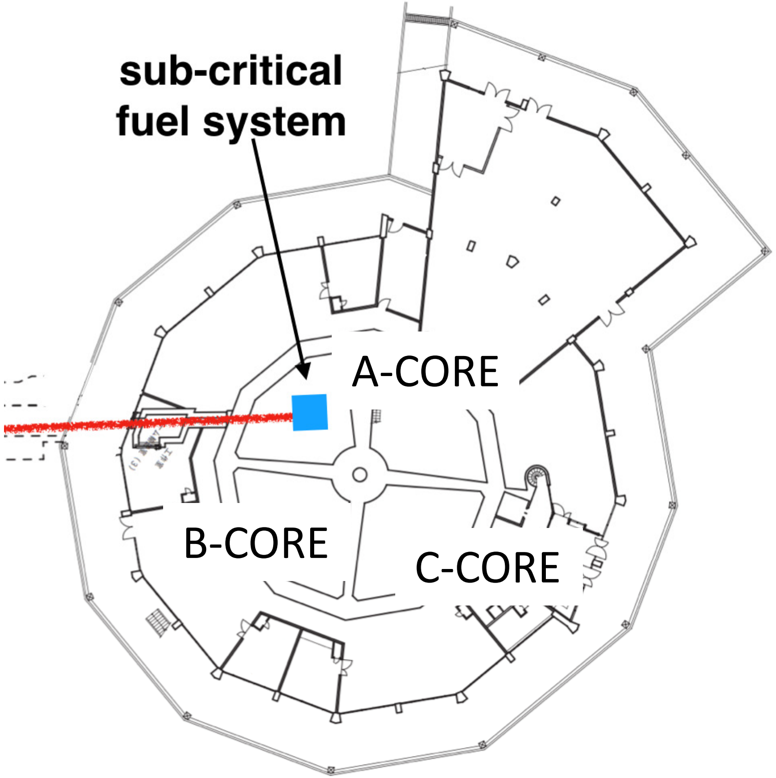


ADS Experimental Facilities at KURNS

Characteristics of KUCA
Output power ~10 W

Designed for reactor physics

three critical assemblies :
  i. A & B cores
    Polyethylene Mod./Ref.
  ii. C core
    H_2O Mod./Ref.



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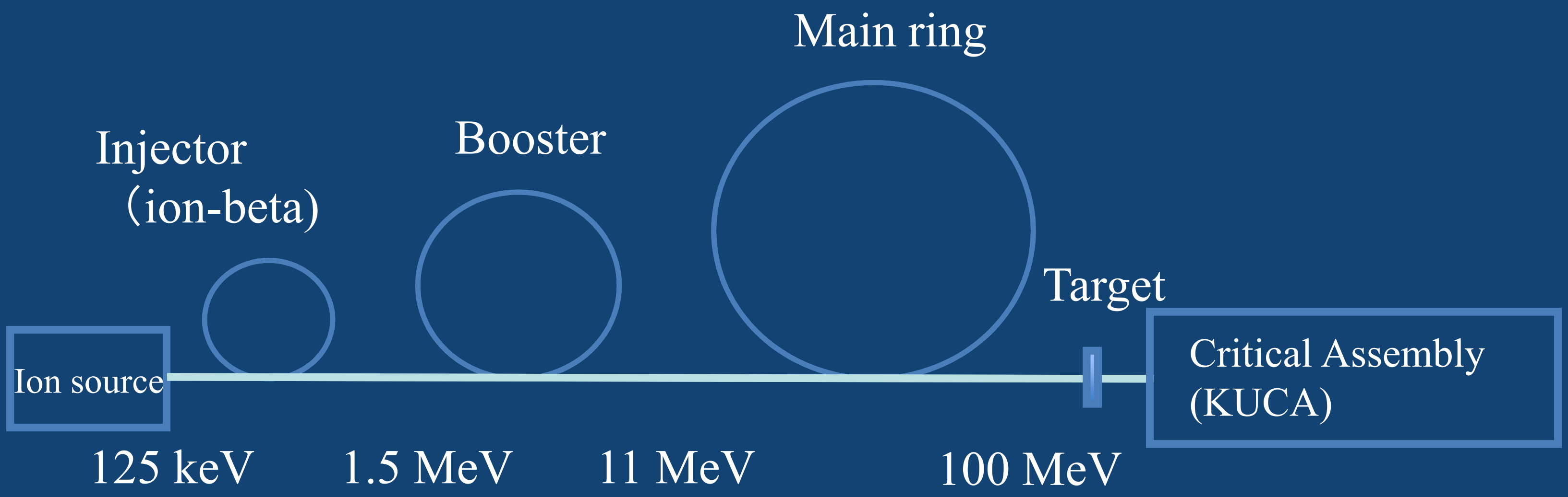
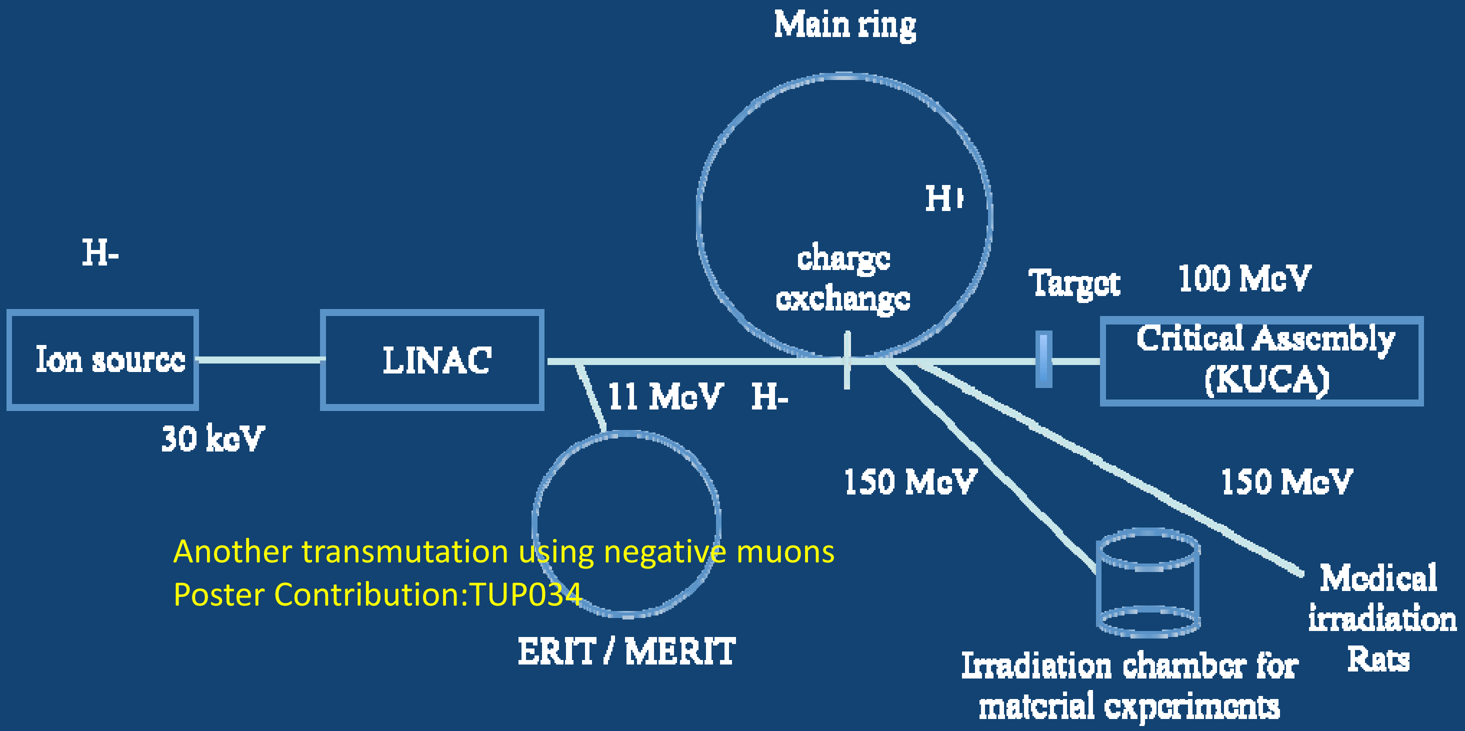
FFA – KUCA ADS facility schematic diagram



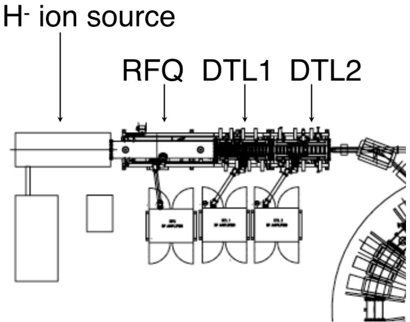
FFA – KUCA ADS facility schematic diagram (2011 -)

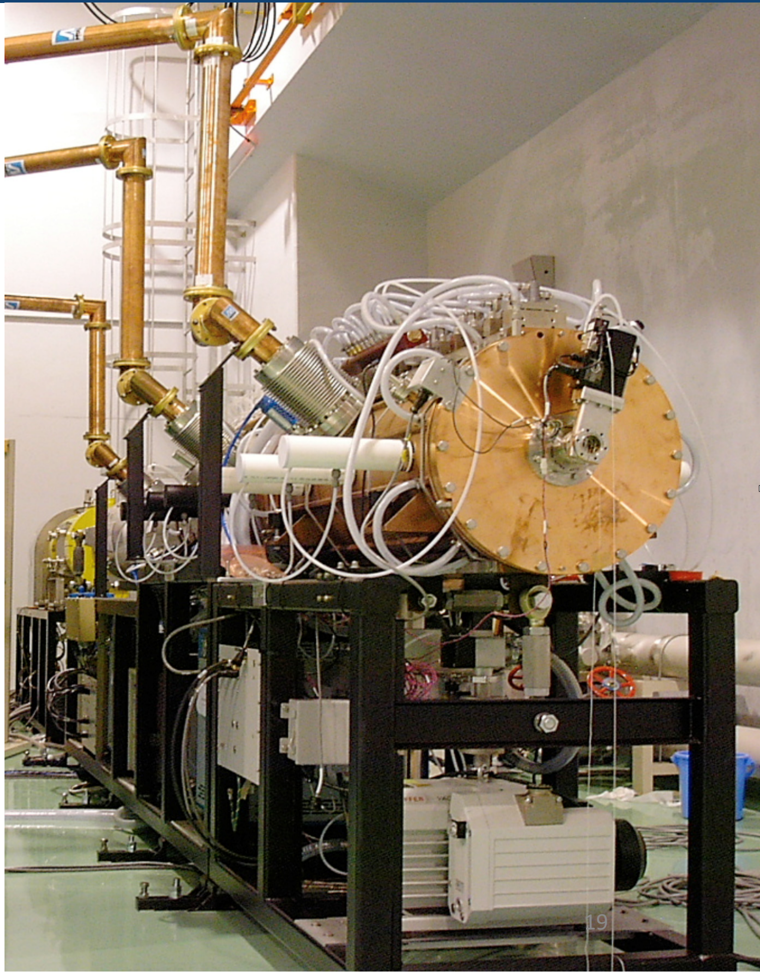


Another transmutation using negative muons
Poster Contribution:TUP034

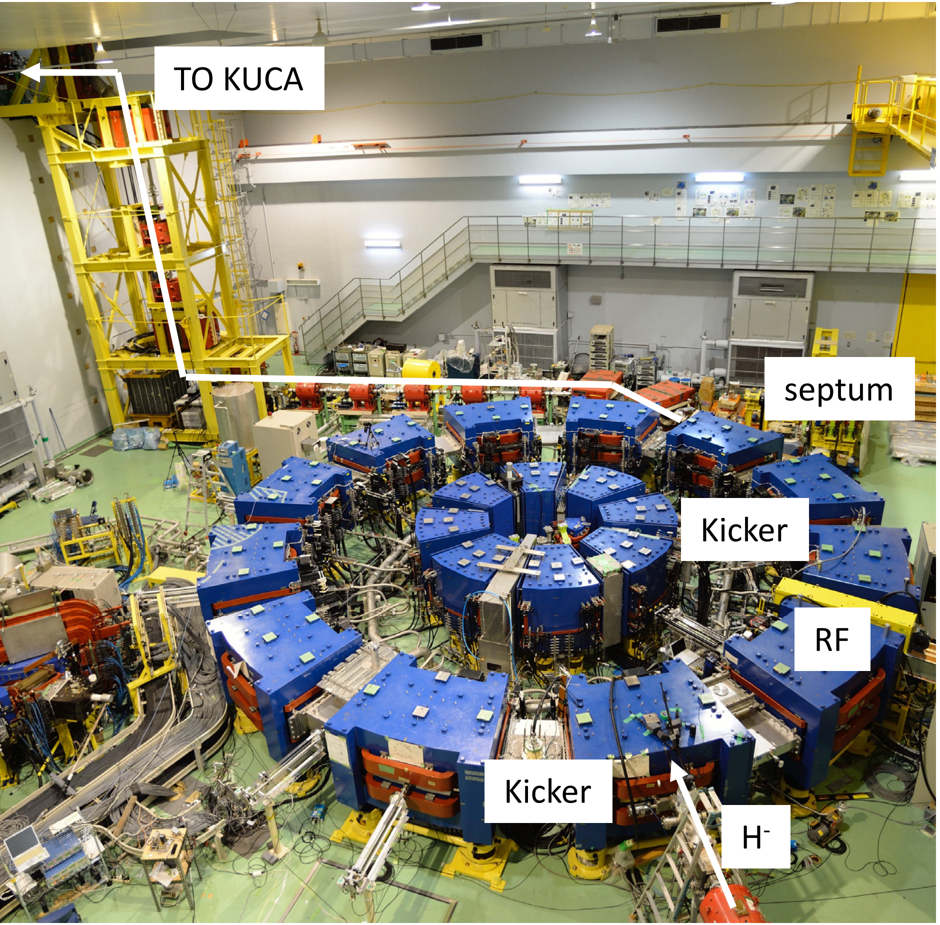
Injector LINAC

Beam species	: H-
Injection energy	: 30 keV
Extraction energy	: 11 MeV
Beam Pulse width(MAX)	: 100 μsec
Peak Curr.(MAX)	: ~5 mA
	: ~3.12*1012[ppp]
rep. rate	: 1Hz~200Hz
Rf frequency	: 425 MHz
Power supply	: tube (triode YU176A)



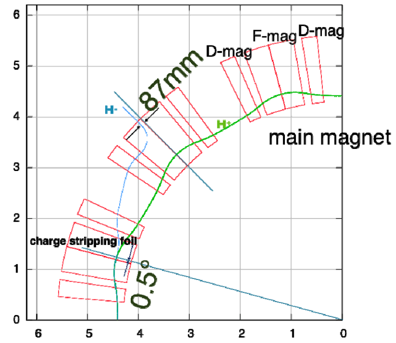


MAIN RING

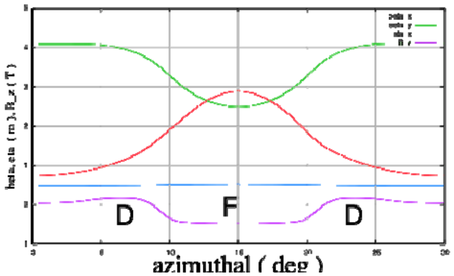


Beam species : proton
Injection energy : 11 MeV
Extraction energy : 150 (100) MeV
Beam current : 1 nA (safety reg.)
Lattice structure : 12-cell DFD
Field index k : 7.5
Average orbit radii : 4.52 – 5.12 m

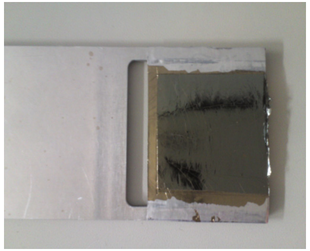
Beam injection



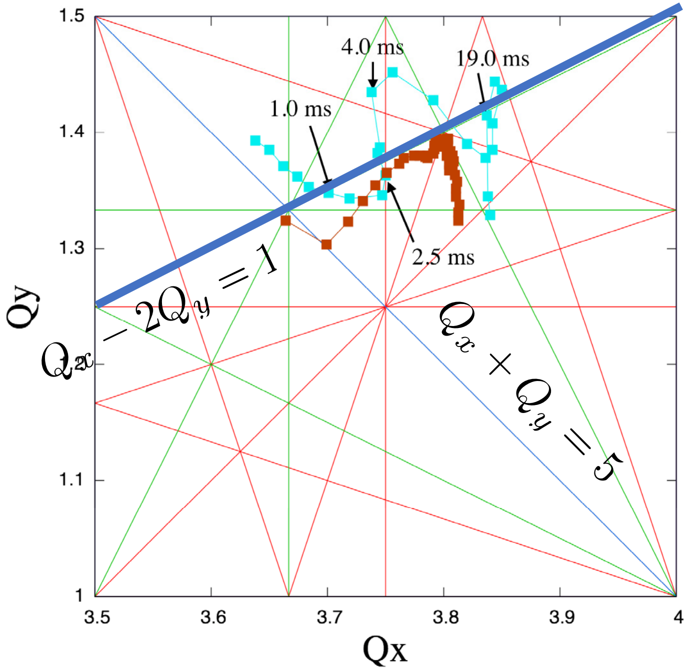
Betatron functions



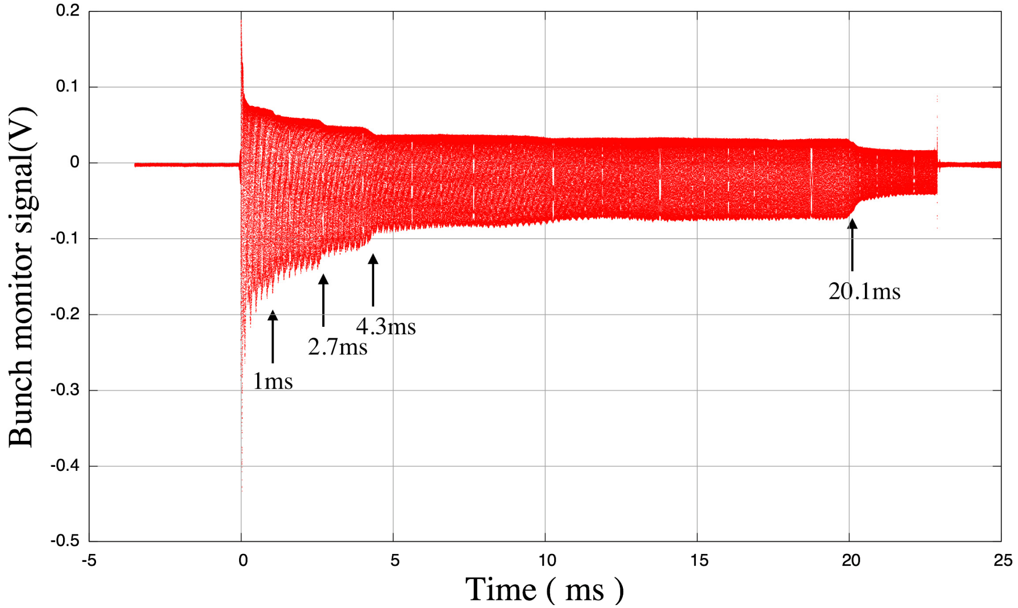
Charge stripping foil



MAIN RING tune excursion

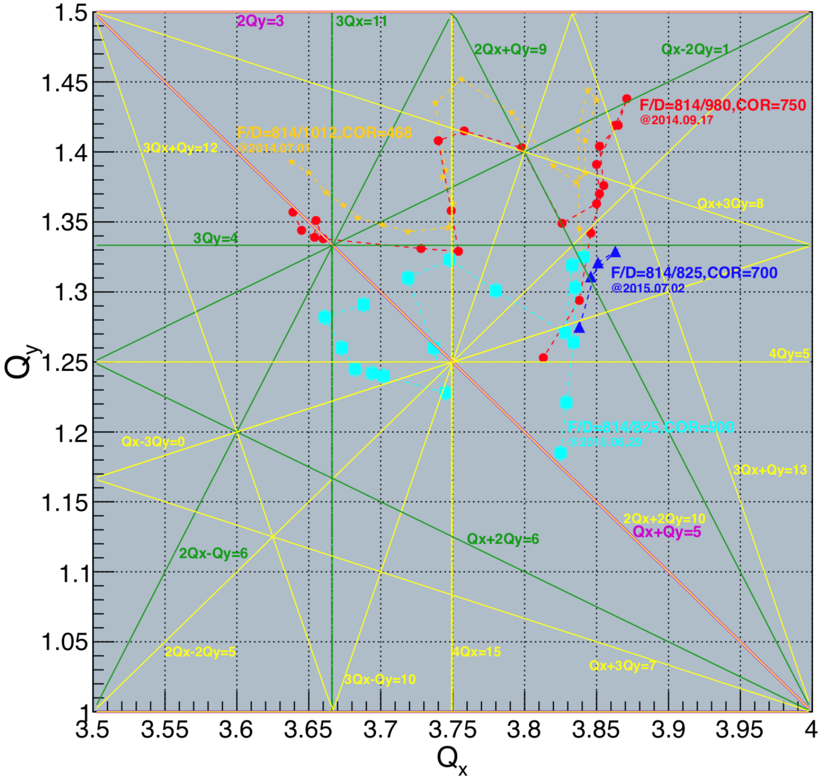


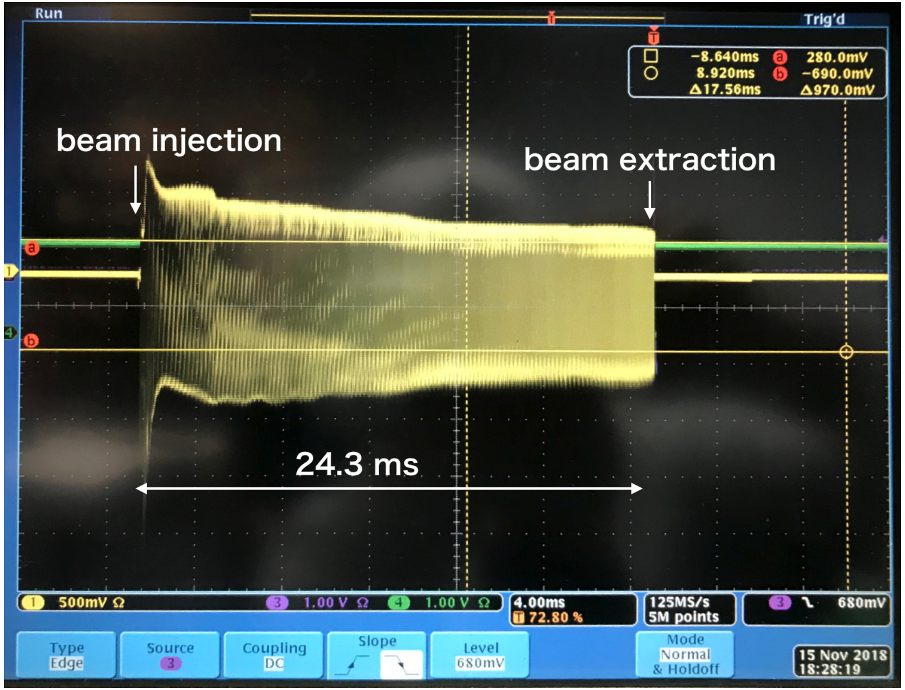
MAIN RING tune footprints.
Blue: measured
Brown: simulated



MAIN RING bunch monitor signal.

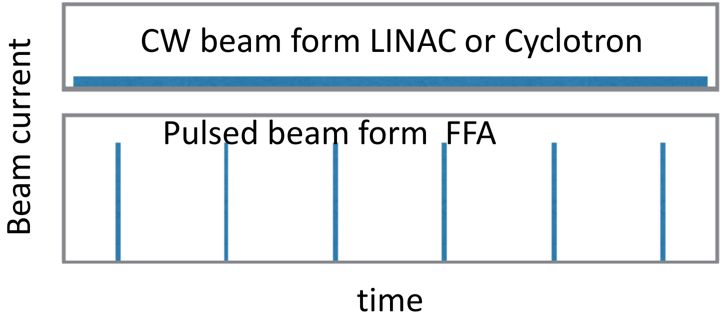
MAIN RING tune optimization





Bunch monitor signal with (F,D)=(814,814) A

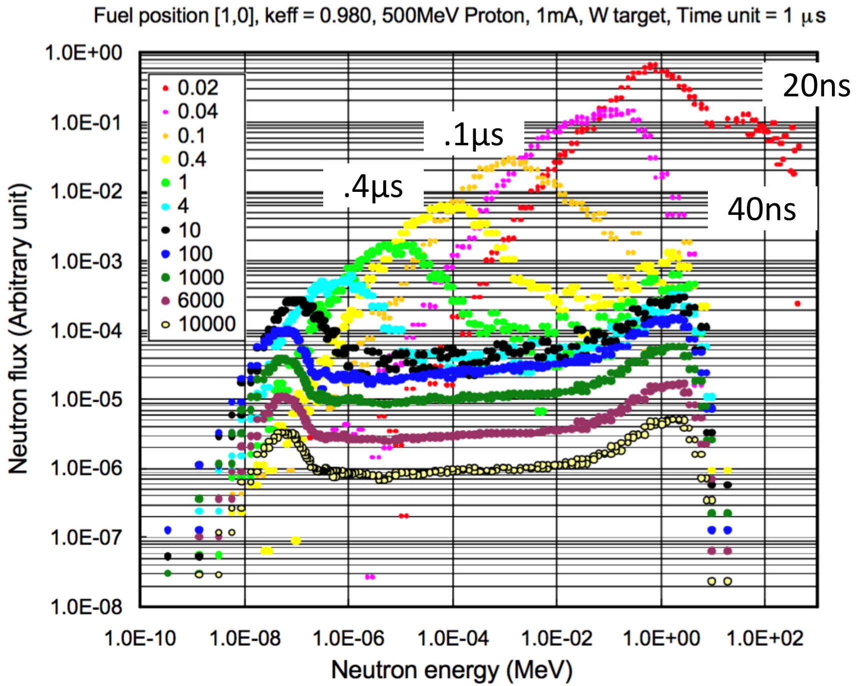
Advantage of pulsed beam



Average current only 1 nA
But peak power

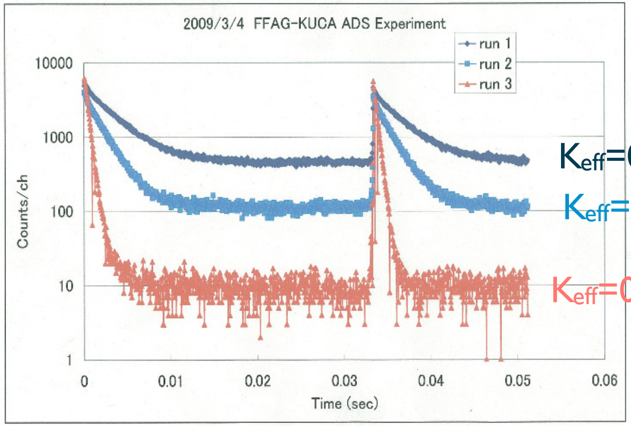
$$P_{peak} = \frac{100\ \text{MeV} \times 1\ \text{nA}}{100\ \text{ns} \times 20\ \text{Hz}} = .05\ \text{MW}$$

Dynamic characteristics of the core within 100 ns can be measured with extremely high instantaneous beam power.



Neutron energy spectrum in the core as a function of time measured from the beam hitting the target.

First ADS experiment in the world March, 2009



$K_{eff}=0.99$

$K_{eff}=0.96$

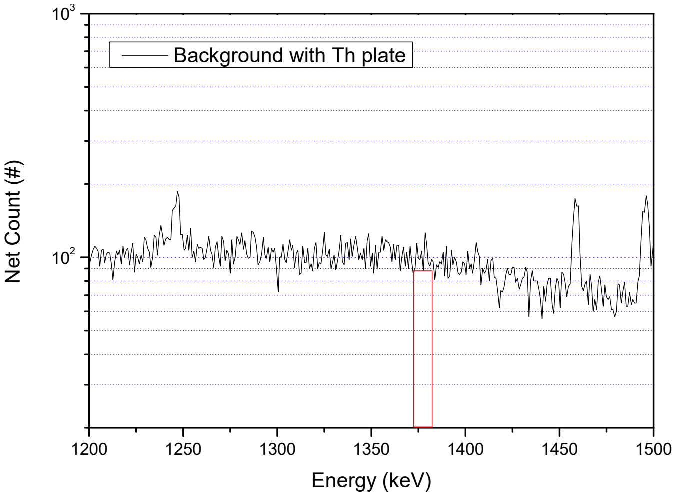
$K_{eff}=0.91$

Two components in the neutron counting rate: the fast component decaying exponentially and the slow component caused by delayed neutrons almost constant in time.
The presence of the delayed neutrons indicates that neutrons are generated through nuclear fission reaction inside the fuel system; it tends to have higher level with higher k_{eff} which means shallower subcriticality of the fuel system.

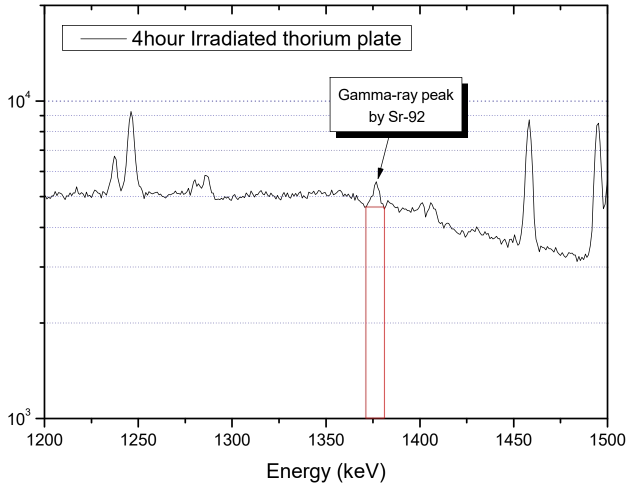
Thorium loaded core March, 2009

Th Plate Measurement by HFGe Detector

The existence of only Sr-92 was found with very small peak



<u>Count without Thorium Fuel Irradiation</u>



<u>Gamma peak by Sr-92 after Th Irradiation</u>

◆ **Proton Injection in Thorium Core**

- FFA Accelerator :
  100 MeV Protons
  30 Hz repetition rate
  ~30 pA intensity
  Tungsten target
  (80mm diameter, 10mm thick)

- KUCA A-Core with Th :
  Natural thorium metal fuel
  No moderator or Graphite moderator

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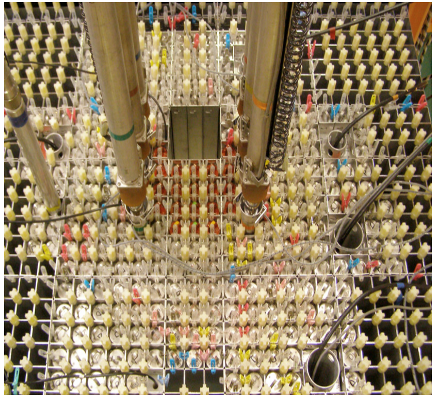
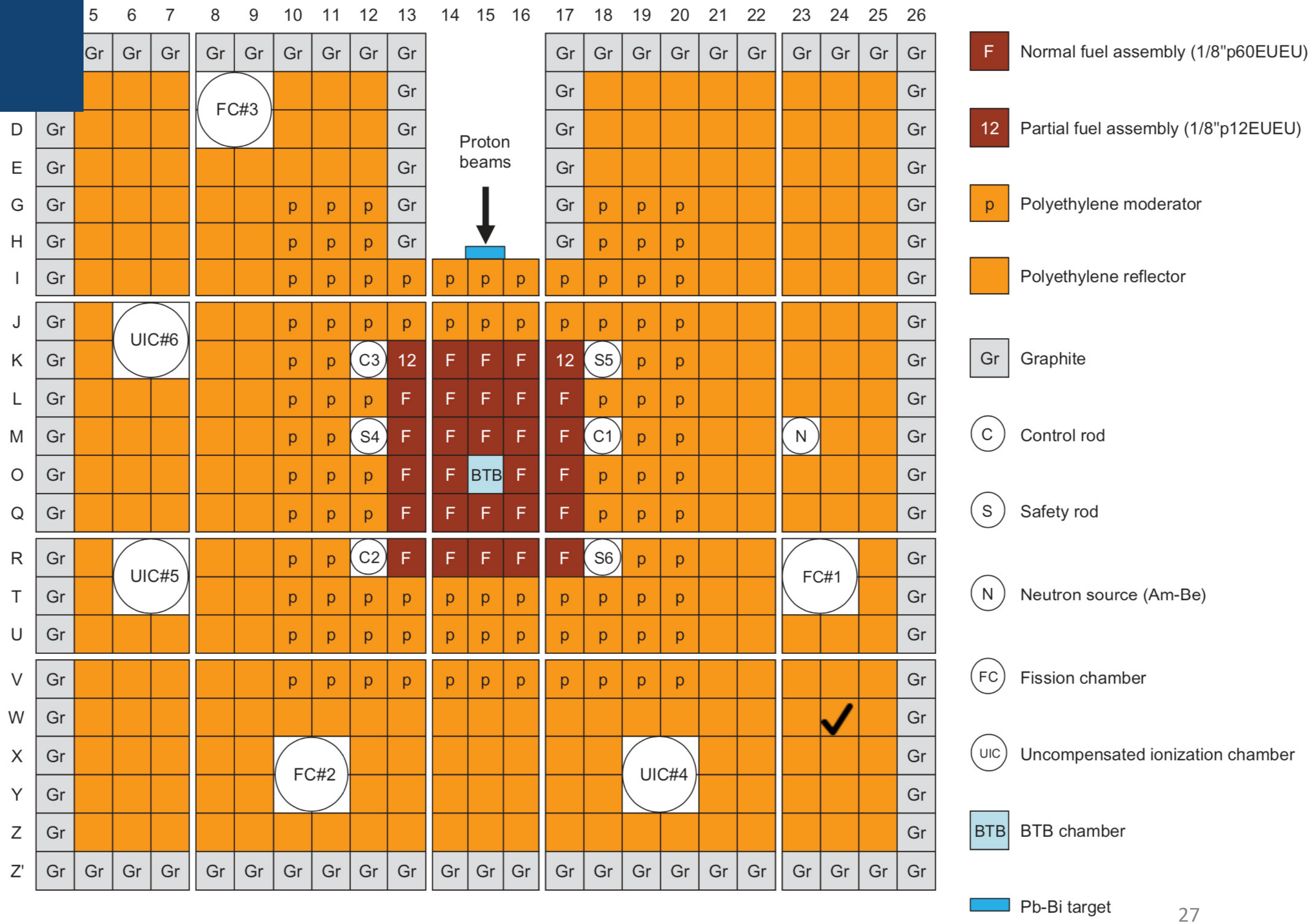
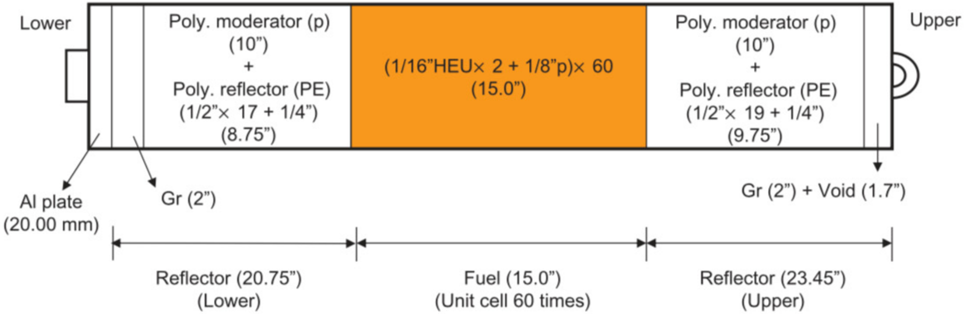
Core config.



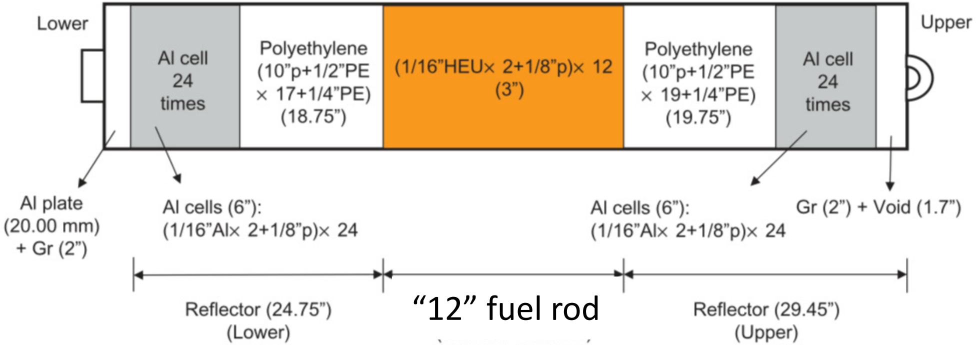


Proton beams
UIC#6
UIC#5
UIC#4
FC#1
FC#2
FC#3
BTB
F Normal fuel assembly (1/8"p60EUEU)
12 Partial fuel assembly (1/8"p12EUEU)
p Polyethylene moderator
Polyethylene reflector
Gr Graphite
C Control rod
S Safety rod
N Neutron source (Am-Be)
FC Fission chamber
UIC Uncompensated ionization chamber
BTB BTB chamber
Pb-Bi target

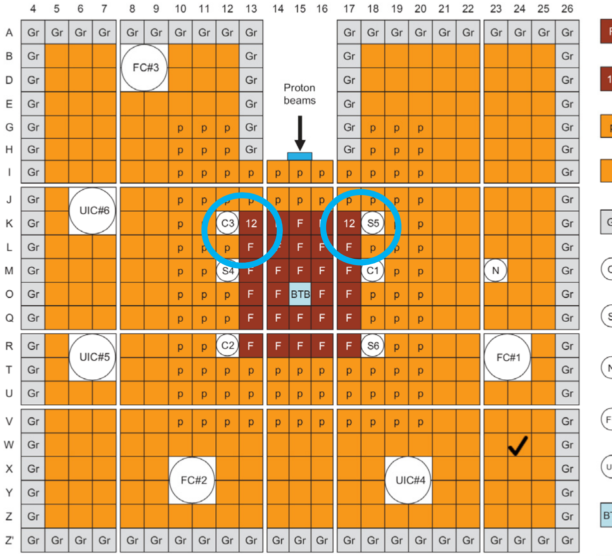
Fuel cell



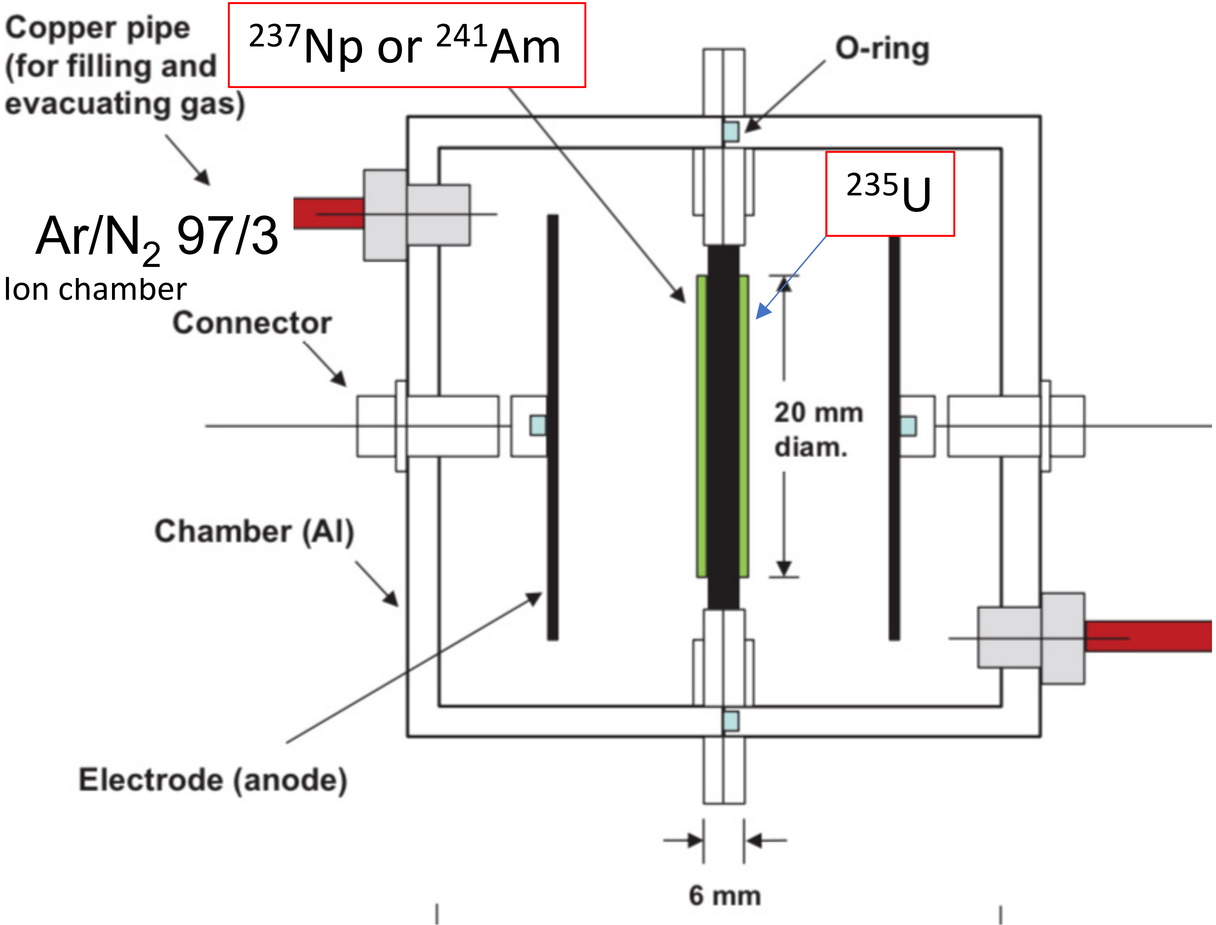
“F” fuel rod

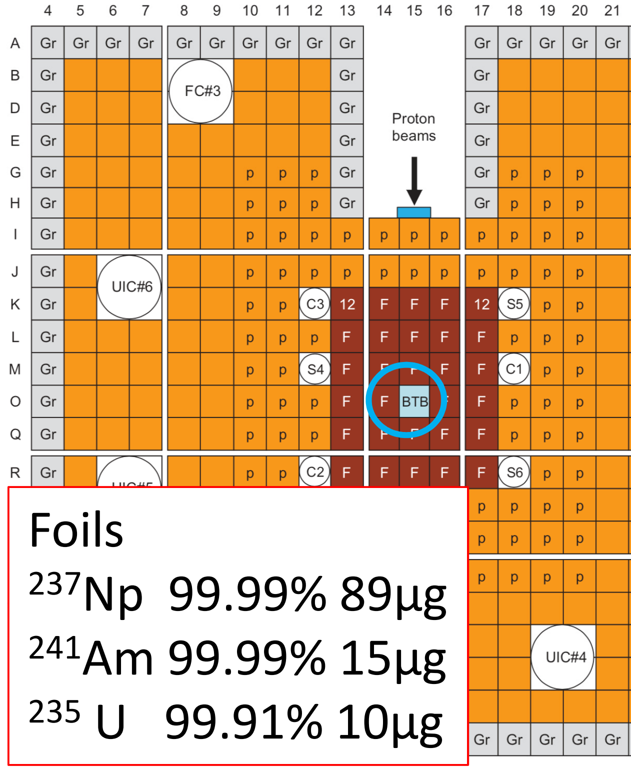


“12” fuel rod



BTB (Back-to-back fission chamber)





Foils

^{237}Np 99.99% 89µg

^{241}Am 99.99% 15µg

^{235}U 99.91% 10µg

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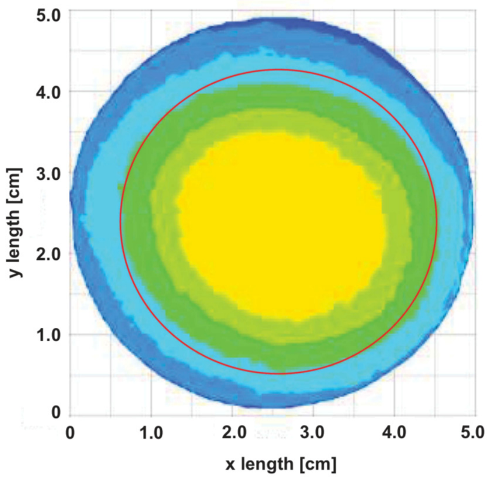
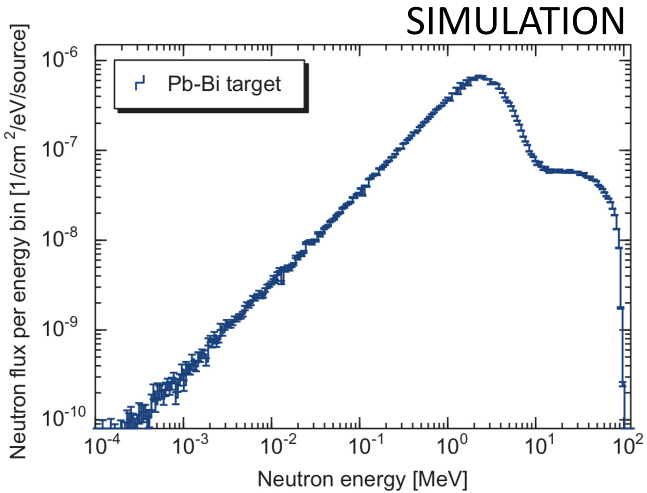
Proton beam profile and neutron energy spectrum at the target

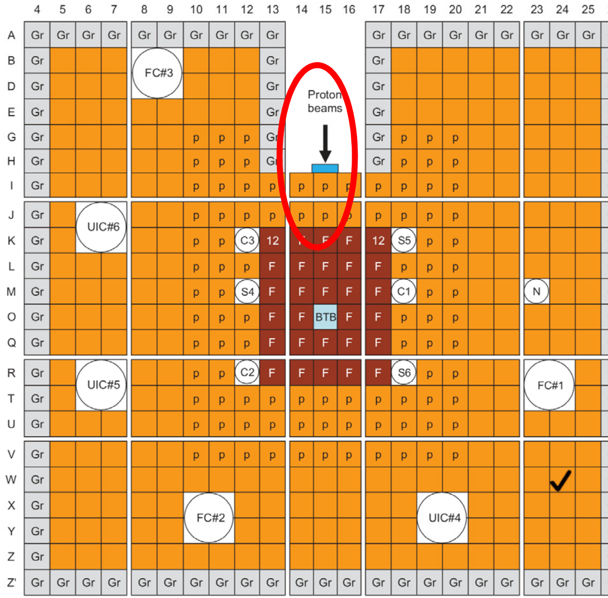


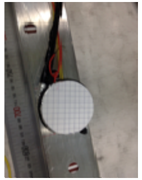
Proton beam profile at the Pb-Bi target measured by Gafchromic film.

6.3×10^9 protons/s
1.3×10^8 neutrons/s



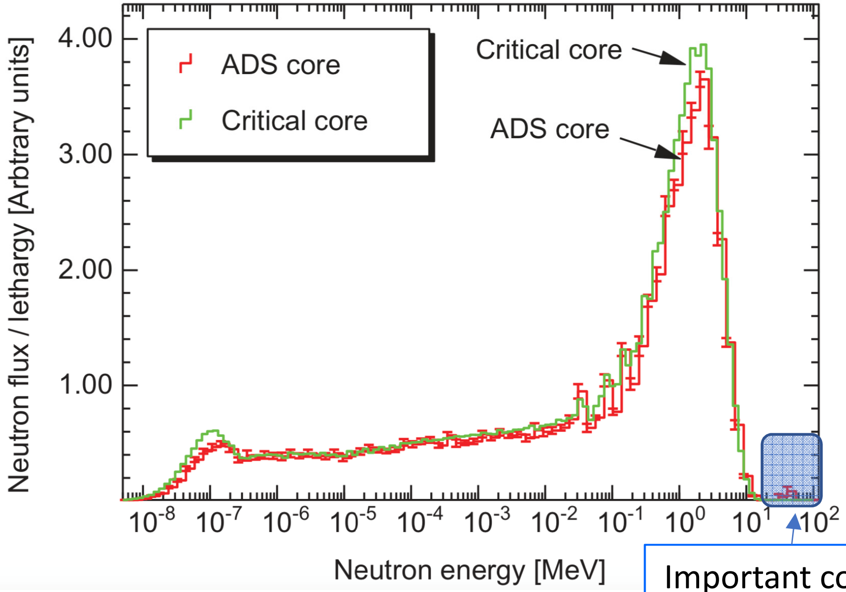
Neutron energy spectrum at the target calculated by PHITS, using the proton beam profile on the left.





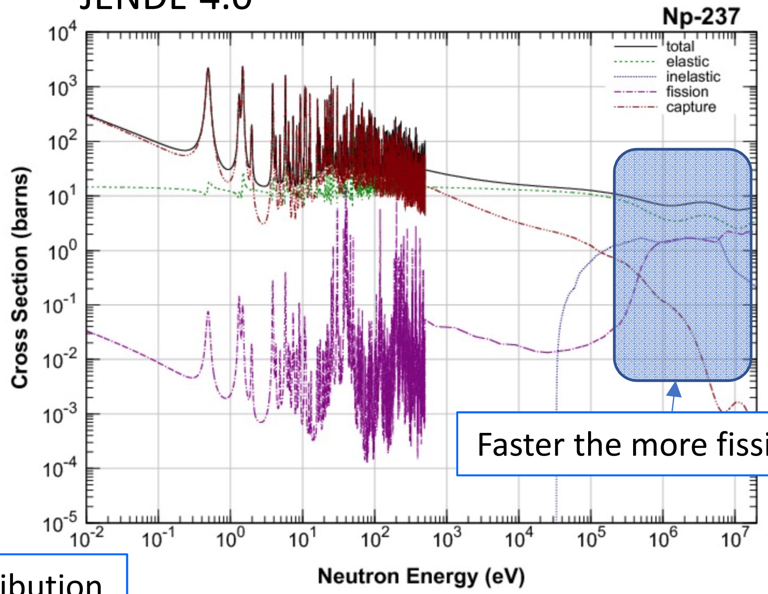
Neutron energy spectrum at the BTB

SIMULATION



Important contribution

JENDL-4.0



Faster the more fission

Neutron energy spectrum at the BTB calculated by PHITS, using the proton beam profile.

Neutron cross section by JENDL-4.0

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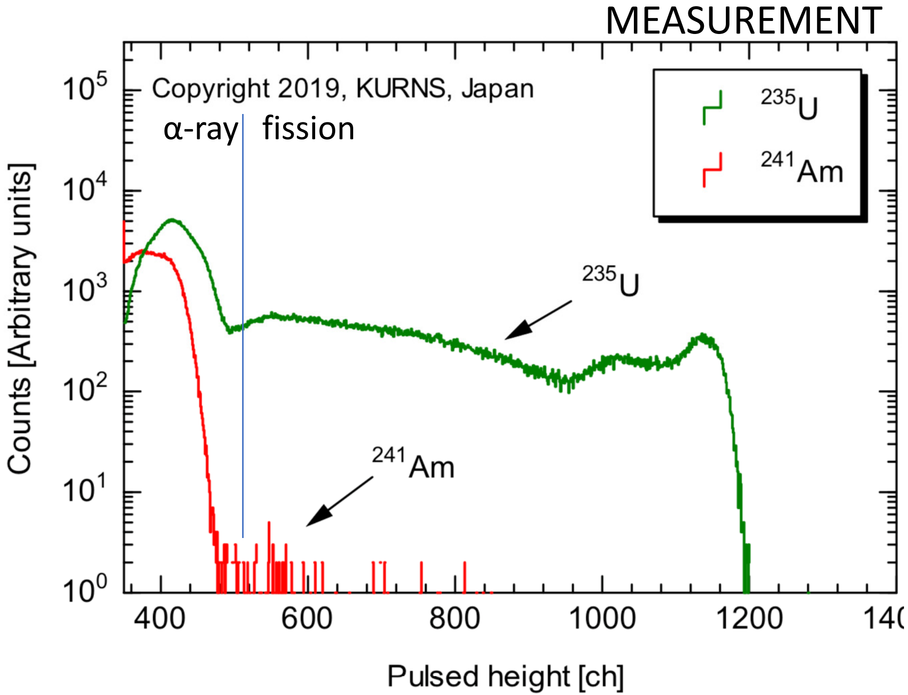
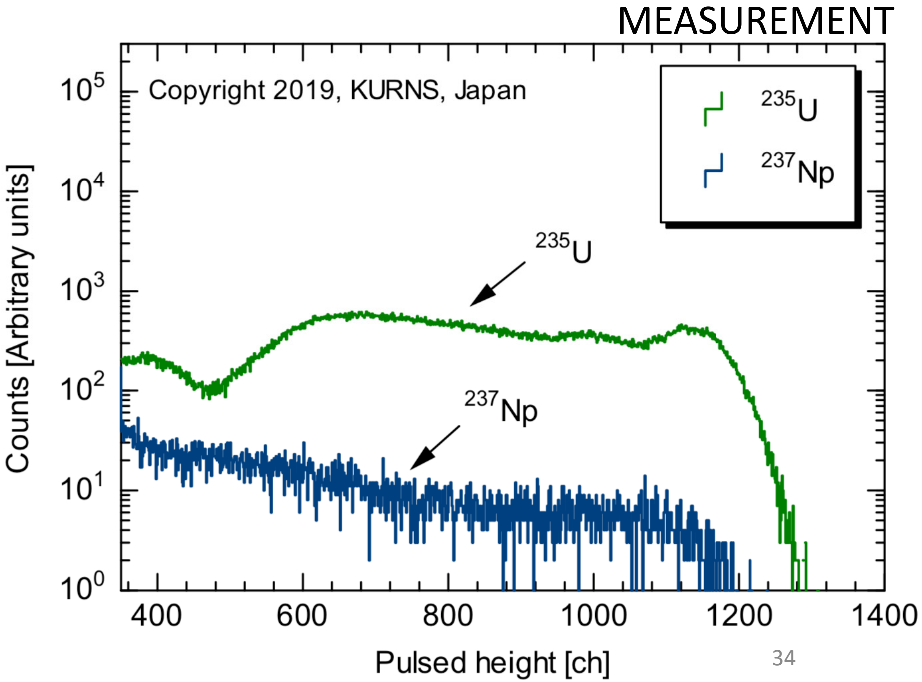
Fission reaction of ^{241}Am and ^{237}Np

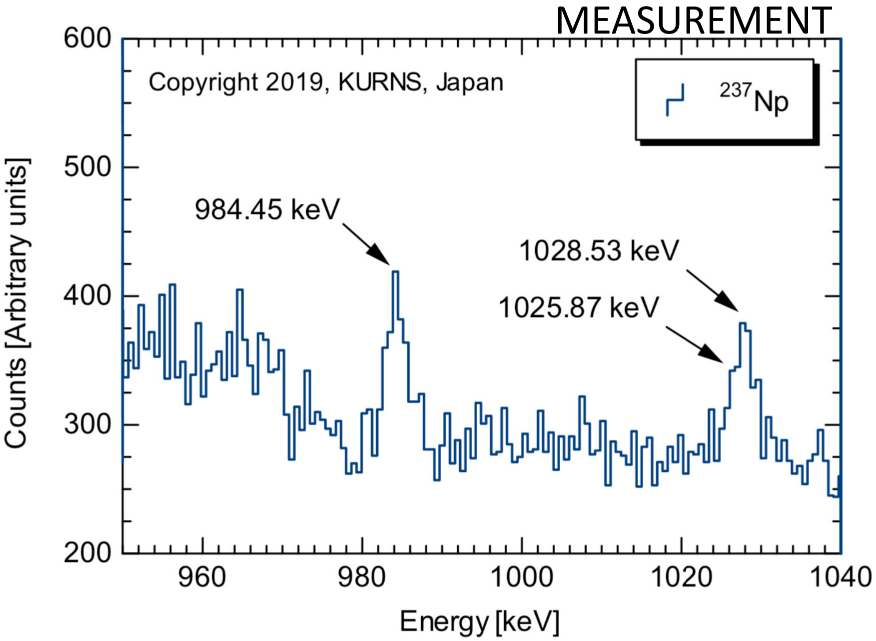
Np-237→Mo-102 + I-133

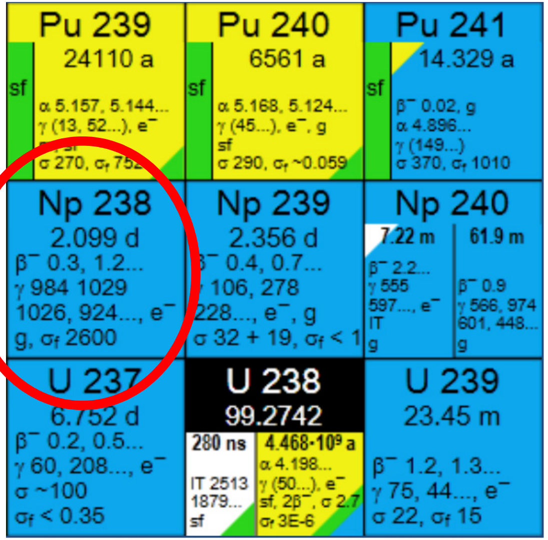




Capture reaction of ^{237}Np

n + ^{237}Np ⟶ ^{238}Np ⟶ (B decay(2.1 days)) ^{238}Pu





Conclusion

The world's first experiments for transmutation of minor actinide , ^{237}Np and ^{241}Am in the accelerator driven system have been accomplished at the Institute for Integrated Radiation and Nuclear Science, Kyoto University. The FFA accelerator complex played an important role as a proton driver.