

Neutron Radiography

2017. 5. 17

문명국

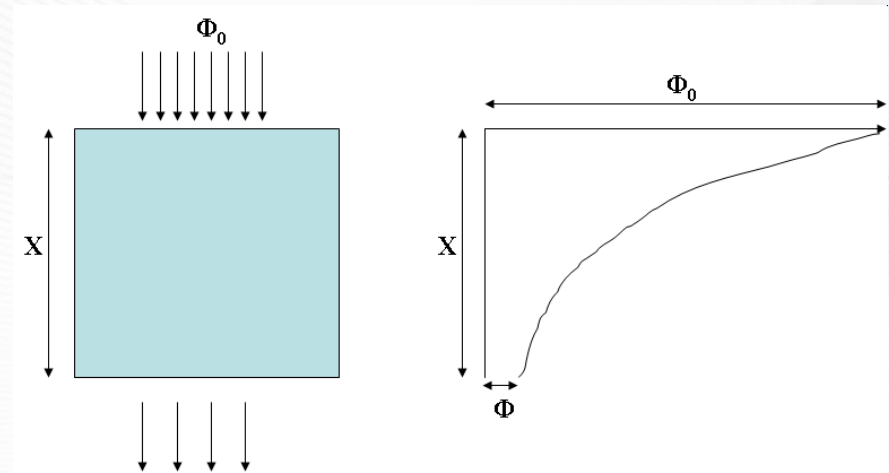
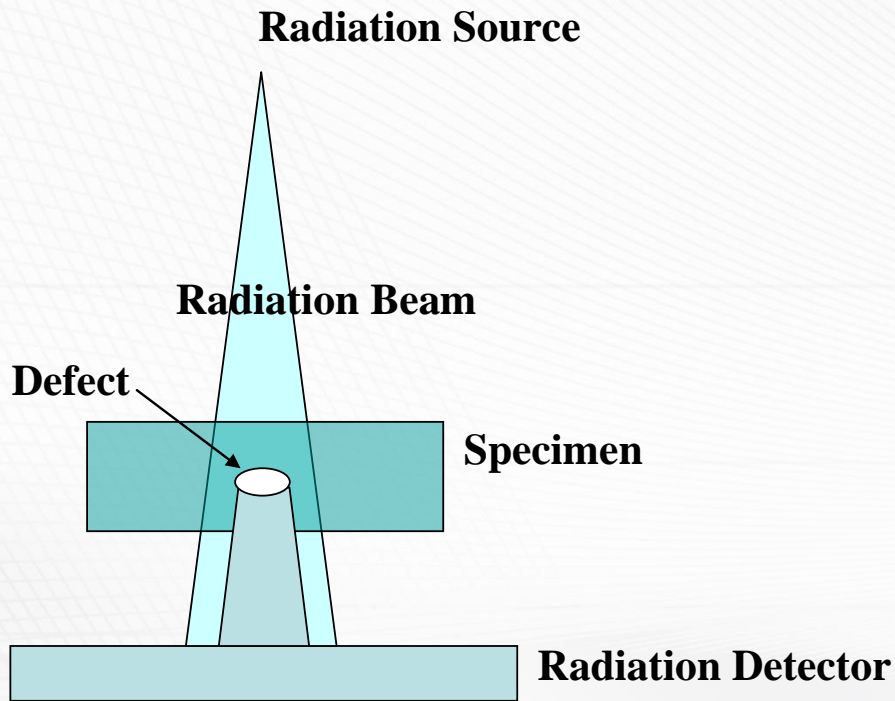
중성자과학연구센터

한국원자력연구원

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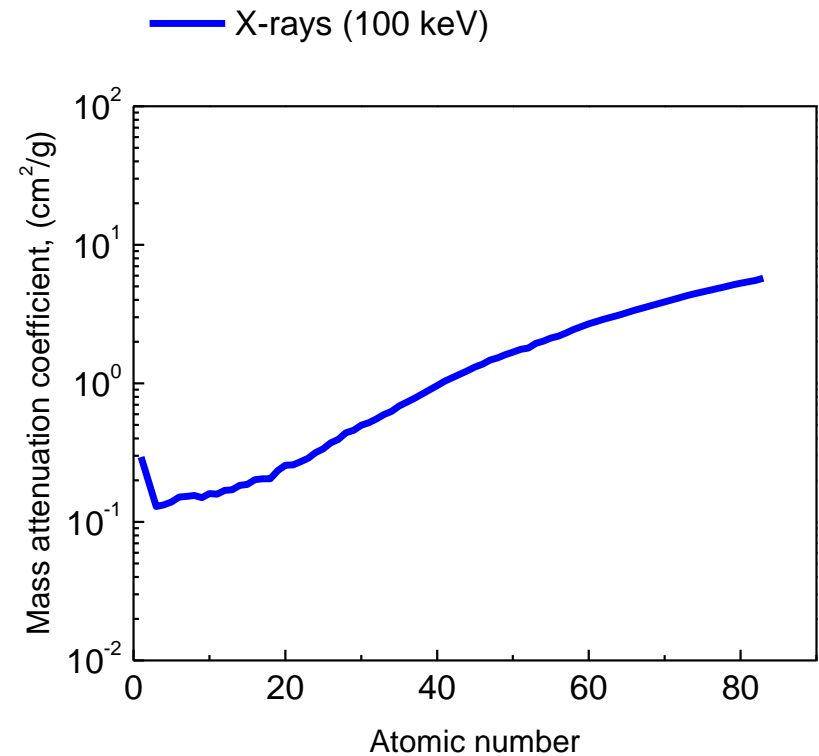
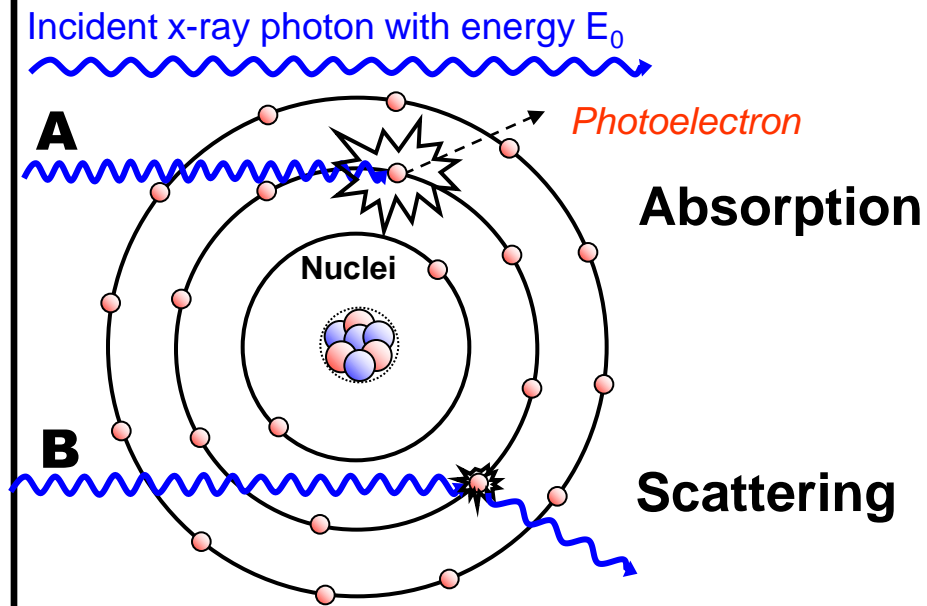
- ◆ **X-ray vs. Neutron**
- ◆ **Neutron Radiography @ HANARO**
- ◆ **On-site Neutron Radiography**
- ◆ **Conclusion and Perspective**

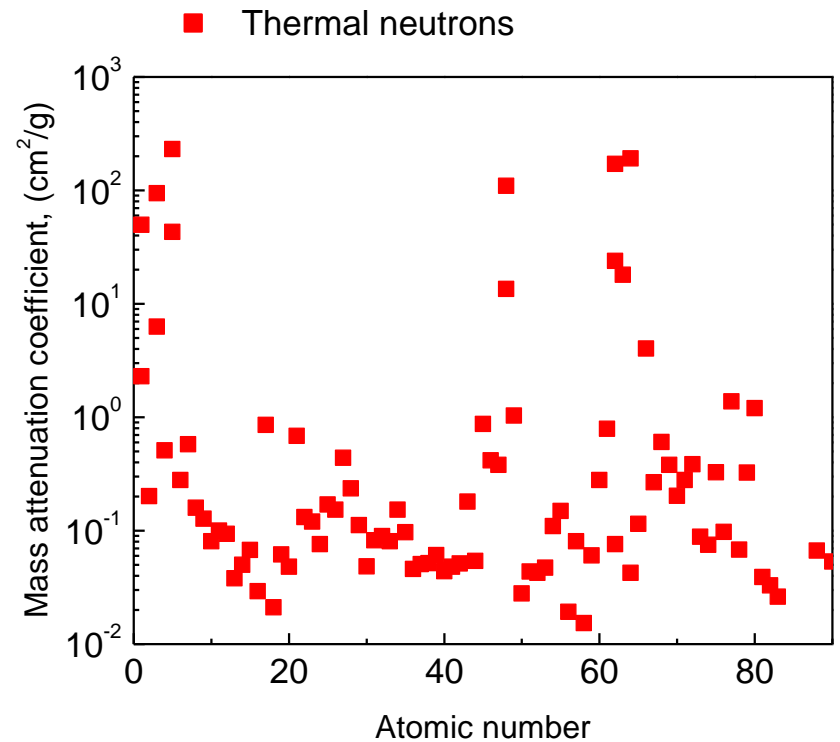
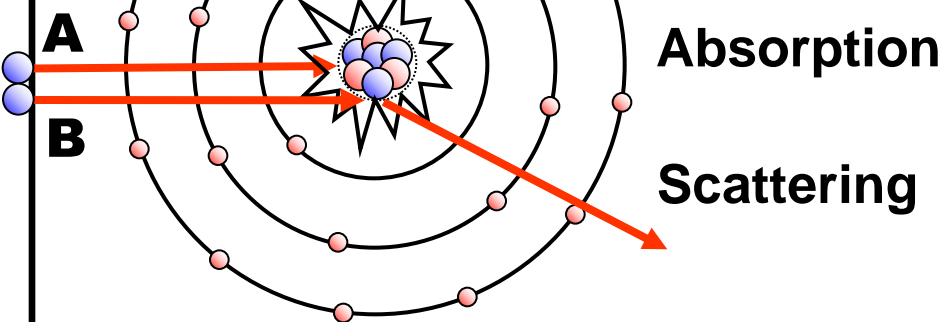
Radiography



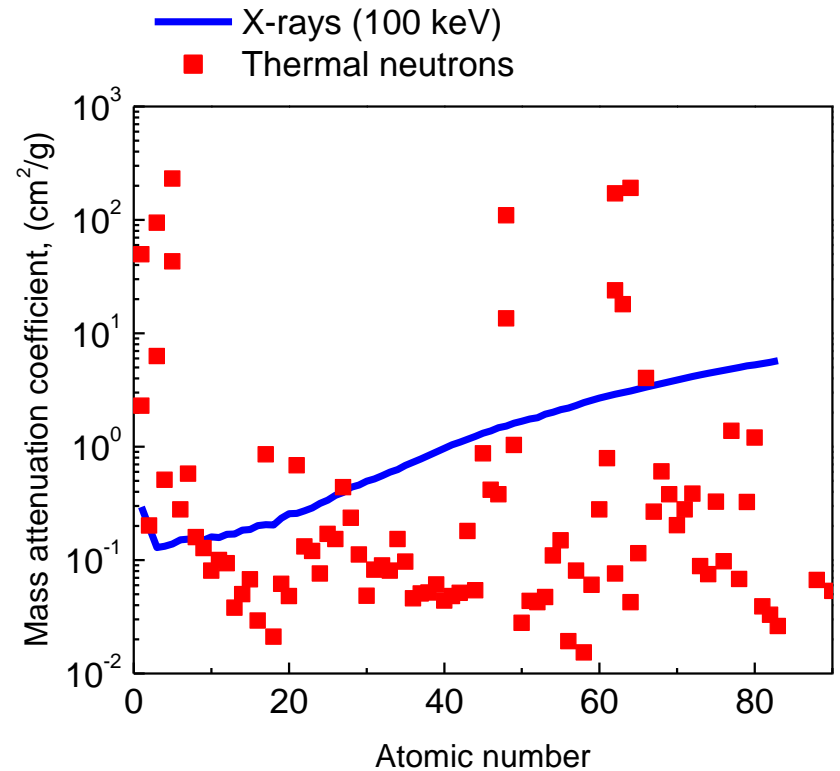
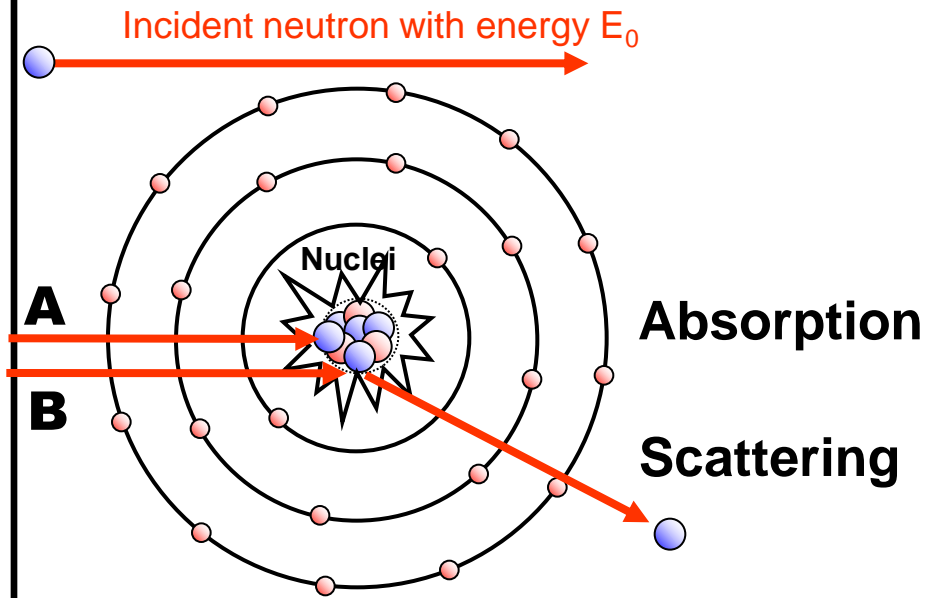
$$\Phi = \Phi_0 e^{-\mu x}$$

X-ray Interactions

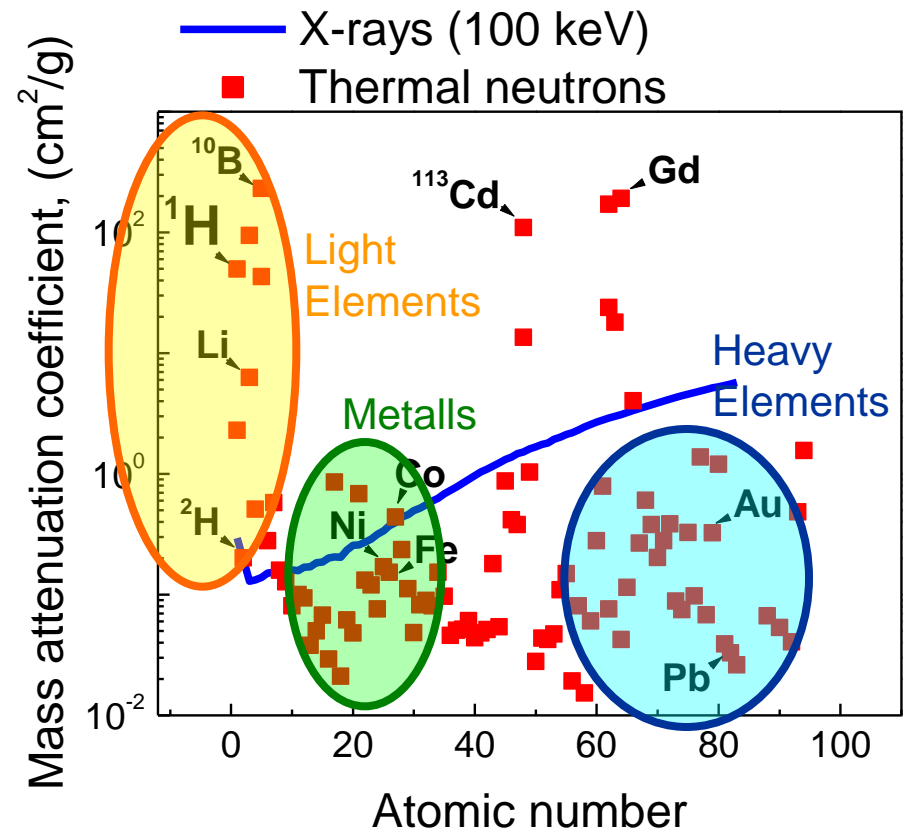
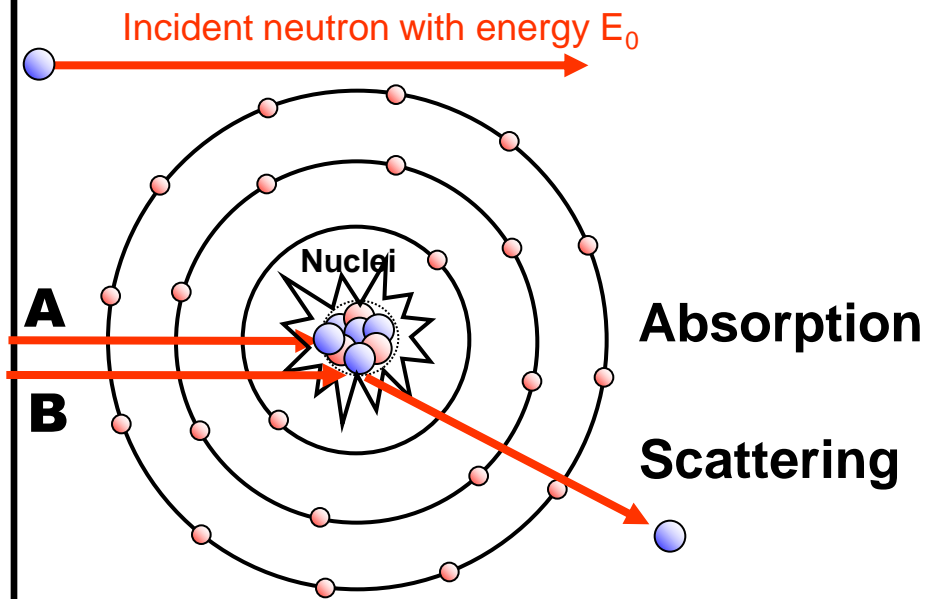




X-ray vs. Neutron

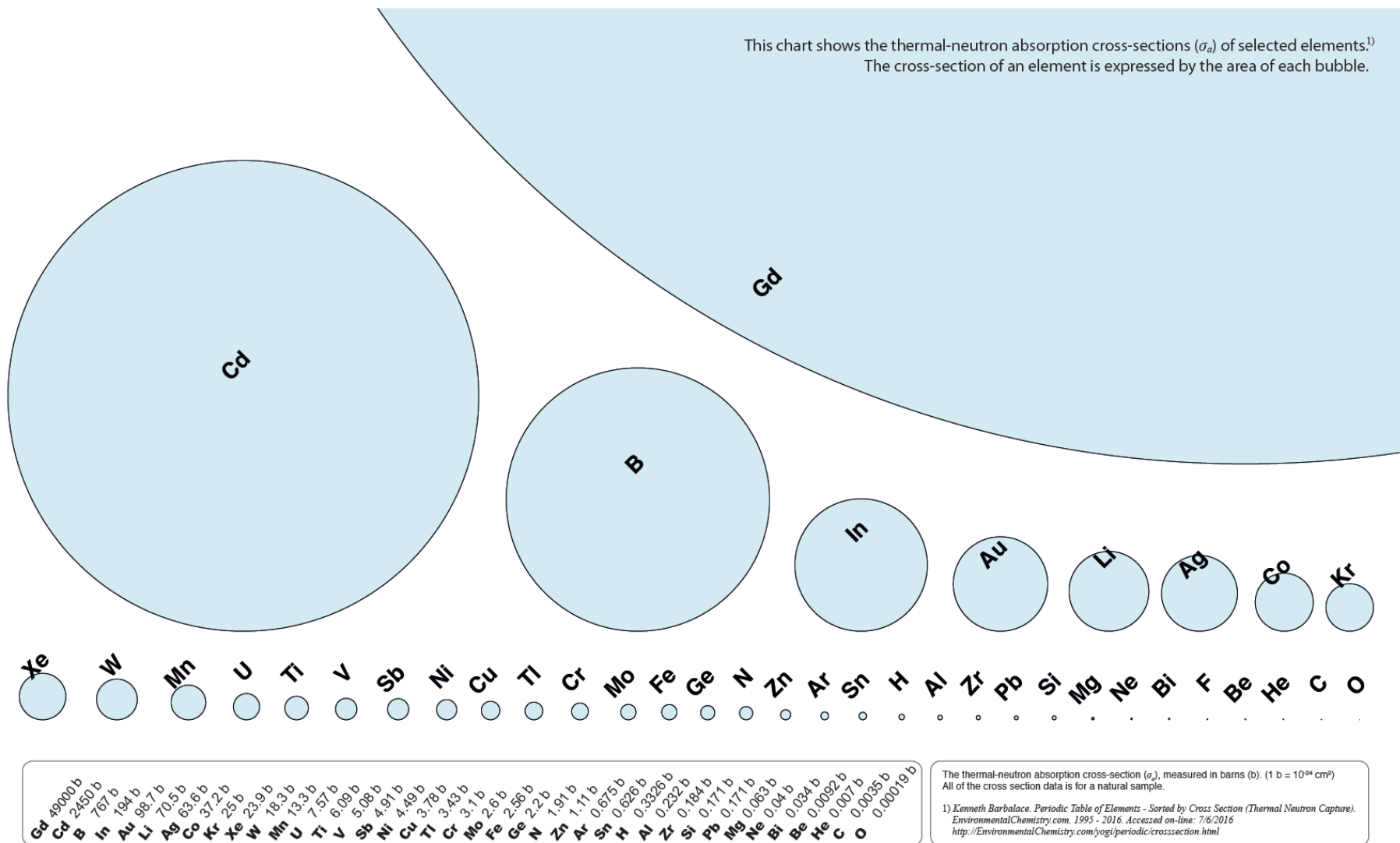


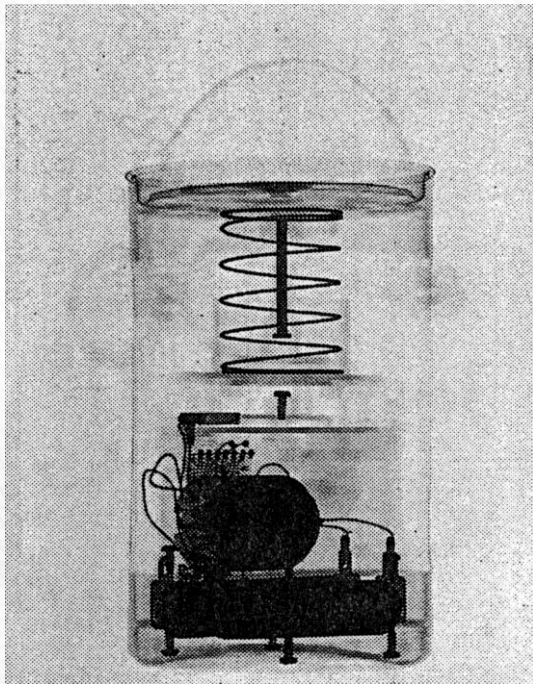
X-ray vs. Neutron



Thermal Neutron Cross Section of the Elements

This chart shows the thermal-neutron absorption cross-sections (σ_a) of selected elements.¹⁾
The cross-section of an element is expressed by the area of each bubble.

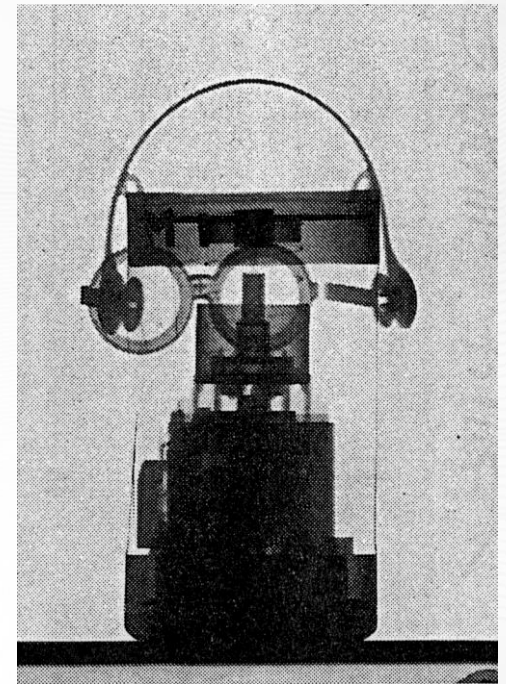




X-선

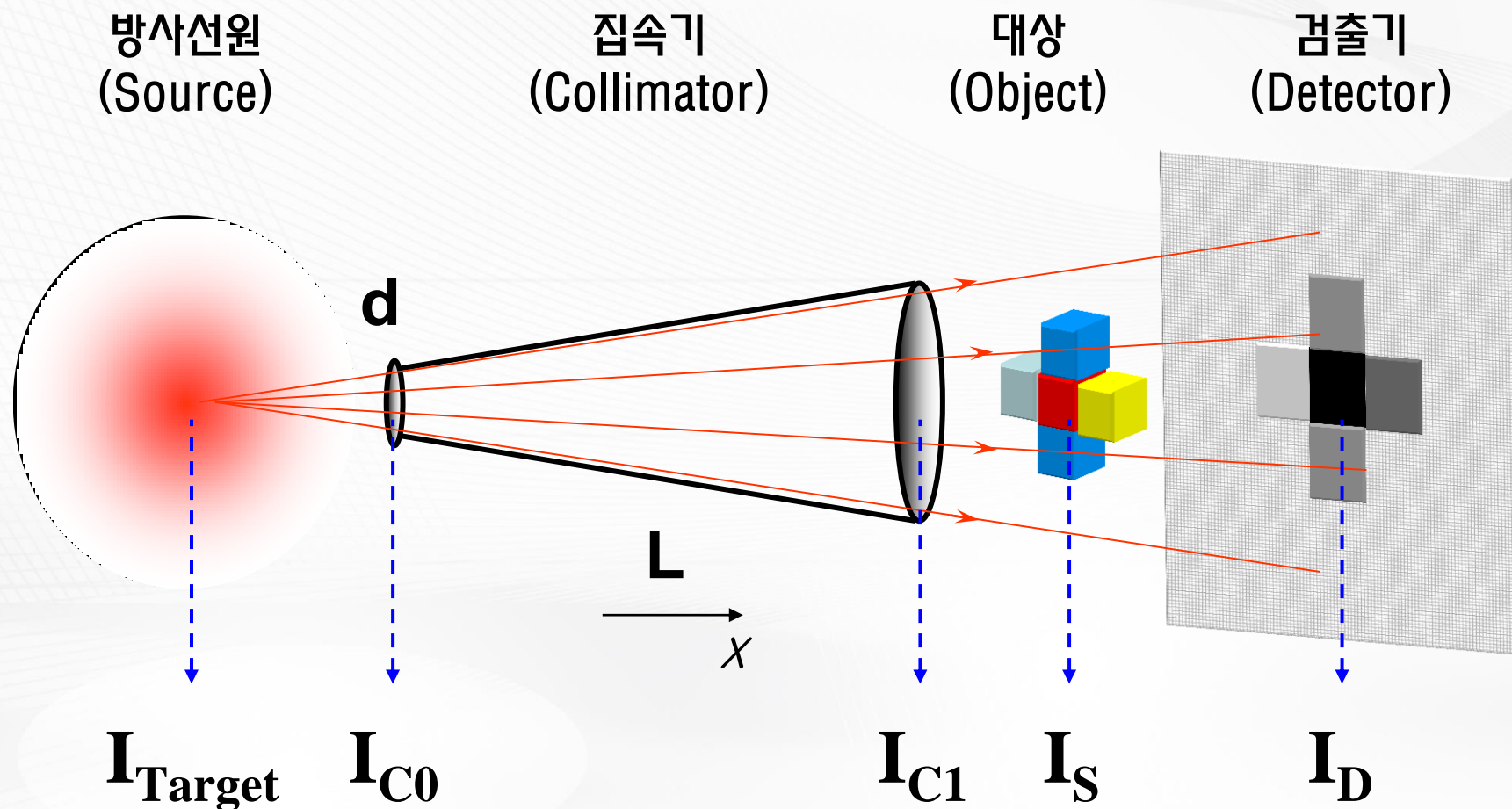


사진



중성자

SYSTEM CONFIGURATION



I — neutron flux at different position

중성자 발생원

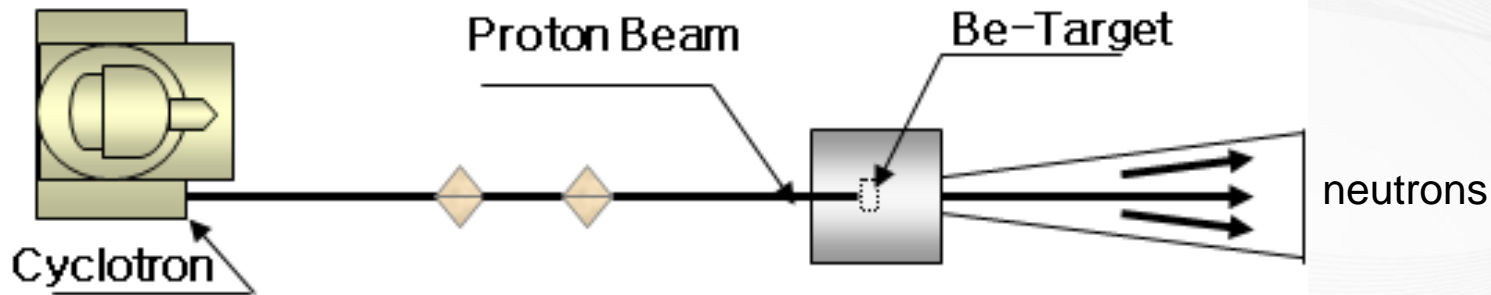
종류	선속 (n/cm ² s)	분해능	노출시간	특징
동위원소 기반	10 ¹ ~ 10 ⁴	나쁨	몇 시간	낮은 가격, 높은 이동성
가속기 기반	10 ³ ~ 10 ⁶	보통	몇 분	-
원자로 기반	10 ⁵ ~ 10 ⁸	중음	몇 초	고비용, 이동성 불가

동위원소 기반 중성자 선원

선원	반감기	반응	에너지 [MeV]
$^{124}\text{Sb-Be}$	60 day	Gamma/neutron	0.024
$^{210}\text{Po-Be}$	138 day	Alpha/neutron	4.3
$^{241}\text{Am-Be}$	458 year	Alpha /neutron	4
$^{226}\text{Ra-Be}$	1620 year	Alpha /neutron	4
$^{227}\text{Ac-Be}$	21.8 year	Alpha /neutron	4
$^{228}\text{Th-Be}$	1.91 year	Alpha /neutron	4
^{252}Cf	2.65 year	Fission	2.3

^{252}Cf 가격 = 최소 \$ 10^7 /gram (0.1 n/decay)

가속기 기반 중성자 발생원



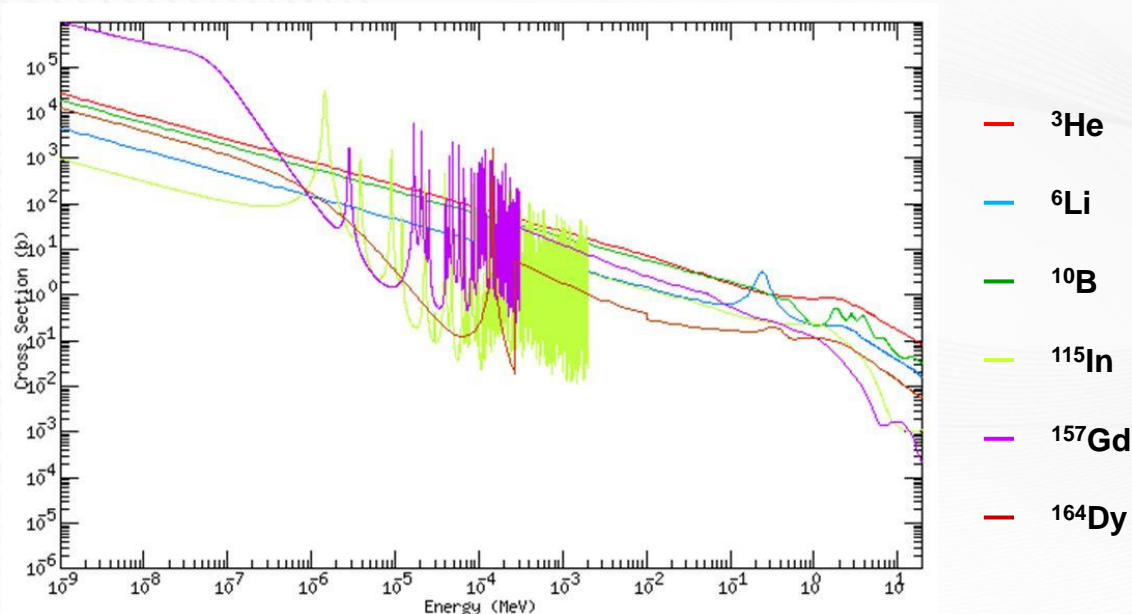
- Lineac, Van de Graaff type accelerator
- Cyclotrons
- Sealed neutron tubes

Incident Particles	Target Material	Neutron Output Energy [MeV]
Deuteron	Tritium	14
Deuteron	Beryllium	4
Deuteron	Lithium	2
X-rays	Beryllium	1.6
X-rays	Uranium	1.6
Electrons	Tantalum	1 ~ 4

원자로 기반 중성자 발생원

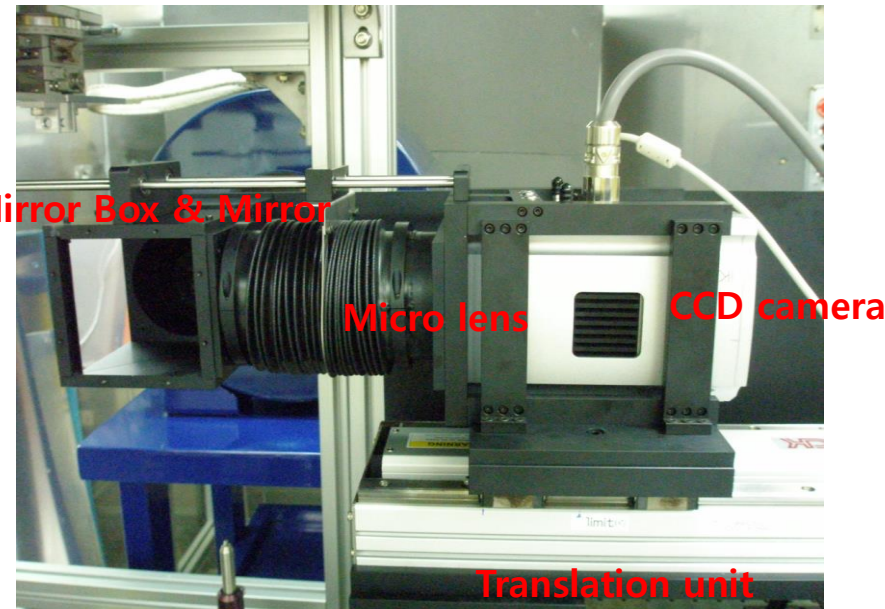
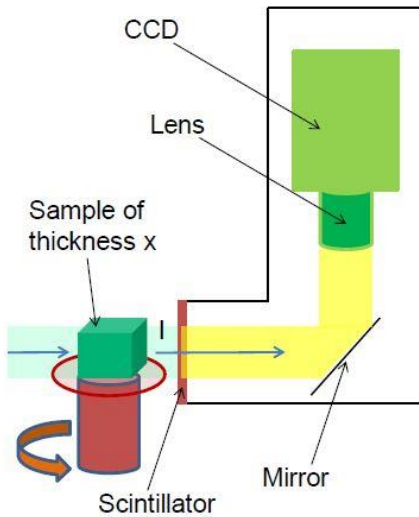


Neutron Detection

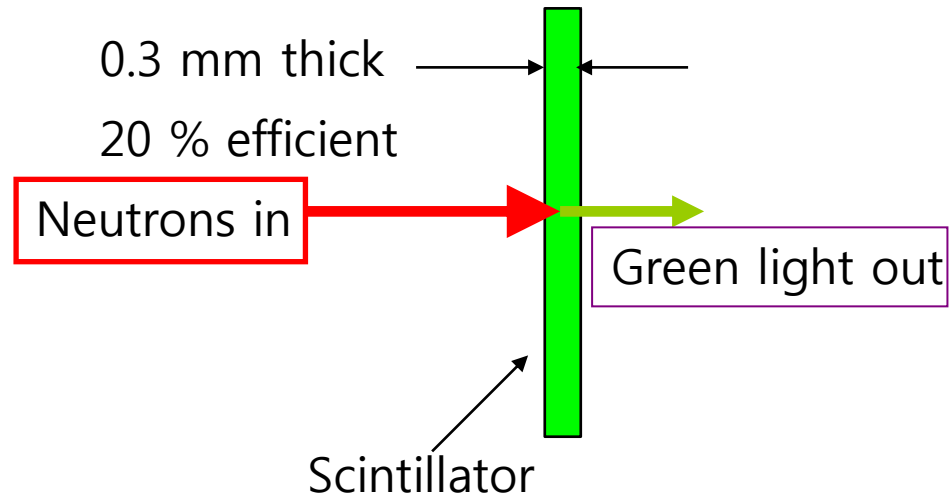
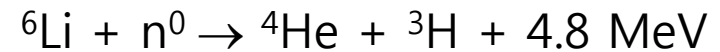
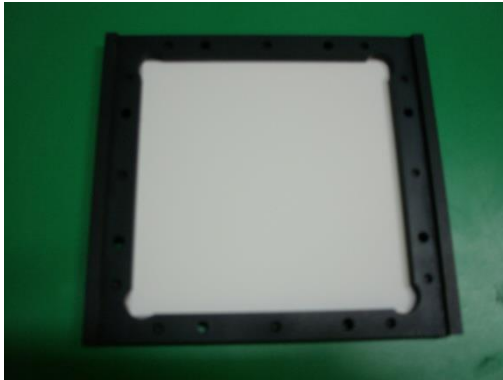


Isotope	Reaction	Cross section at 25meV	Cross section at 14MeV	Half-life	Gamma-ray production
^3He (0.000137%)	$^3\text{He}(n,p)^3\text{H}$	5,328b	139.7mb	Prompt	No
^6Li (7.5%)	$^6\text{Li}(n,\alpha)^3\text{H}$	940b	28.04mb	Prompt	No
^{10}B (20%)	$^{10}\text{B}(n,\alpha)^7\text{Li}$	3,837b	48.95mb	Prompt	Yes
^{115}In (95.71%)	$^{115}\text{In}(n,\gamma)^{116}\text{In}$	201b	1.021mb	54min	Yes
^{157}Gd (15.65%)	$^{157}\text{Gd}(n,\gamma)^{158}\text{Gd}$	25,400b	1.002mb	Prompt	Yes
^{164}Dy (28.2%)	$^{164}\text{Dy}(n,\gamma)^{165}\text{Dy}$	3,000b	10.05mb	140min	Yes

Neutron Imaging System



Neutron Scintillator



GadOx ($\text{Gd}_2\text{O}_3\text{:Tb}$)

$\text{Gd} + n \rightarrow e^-$, energy ≤ 71 keV per neutron capture on average

Resolution ~ 10 - 20 μm , thermal stopping power up to 80%

Low light yield (10^3 photons / neutron)

Main use: Tomography with 20 μm resolution

$\text{ZnS:}^6\text{LiF}$

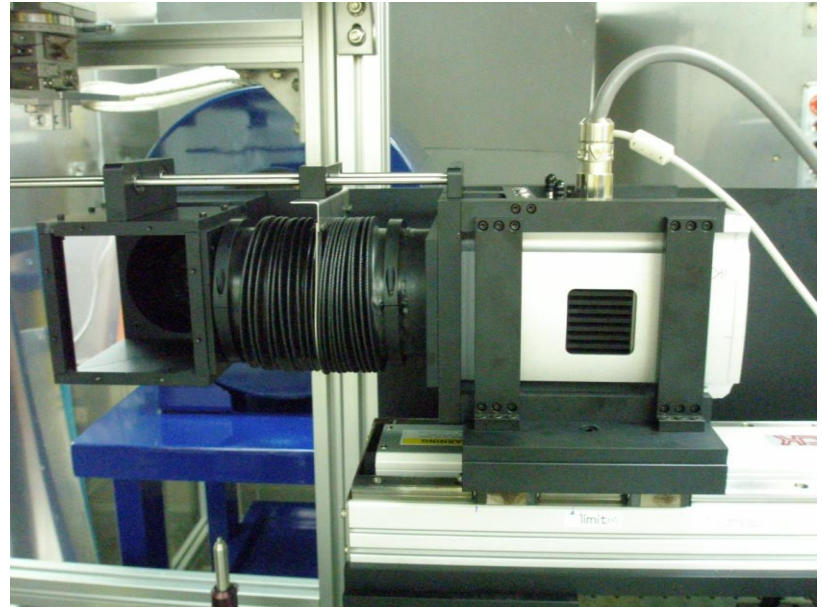
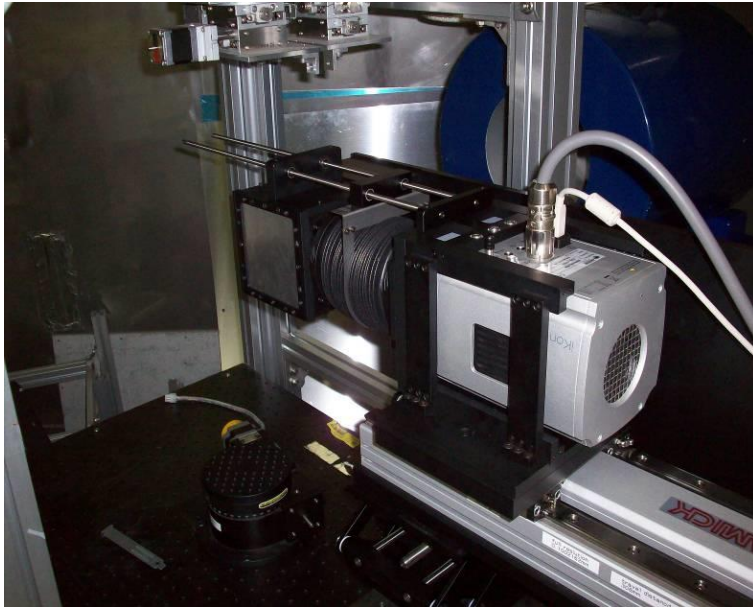
$n + {}^6\text{Li} \rightarrow {}^4\text{He} + \text{T} + \sim 5 \text{ MeV}$

Resolution from 150 μm to 300 μm ,

thermal stopping power of 20%

High light yield (10^5 photons / neutron)

Detectors: CCD (Charge Coupled Device) camera



CCD, EMCCD & sCMOS

13.5, 8.5, 6.5 μm pixels, respectively

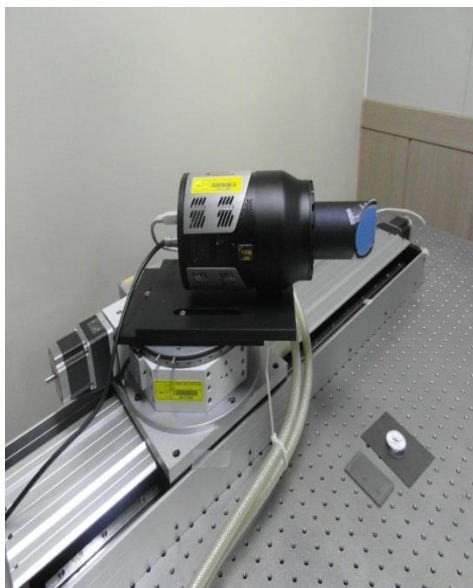
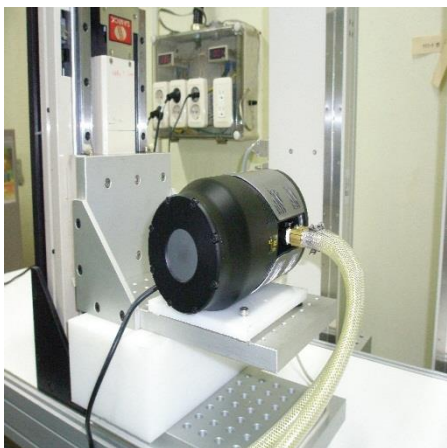
Lens coupled enables flexibility

CCD has slow readout that limits time resolution

EMCCD and sCMOS have low read noise (1 e-) at high frame rates

sCMOS up to 50 Hz, 5 MP camera and has become our primary camera

CCD with Fiber Optic Plate & Scintillator



CCD image sensor	e2v CCD42-40; front-illuminated, grade 1, AIMO
CCD format	2048 x 2048 imaging pixels 13.5 x 13.5 um pixels 100% fill factor 27.6 x 27.6 mm imaging area
Deepest cooling temperature	-35°C guaranteed with room temperature water
Cooling method	Water cooling standard
Dark Current @ -35°C	0.05e-/p/sec (typical), 0.15e-/p/sec (max)
Non-linearity	<2% @ 100kHz

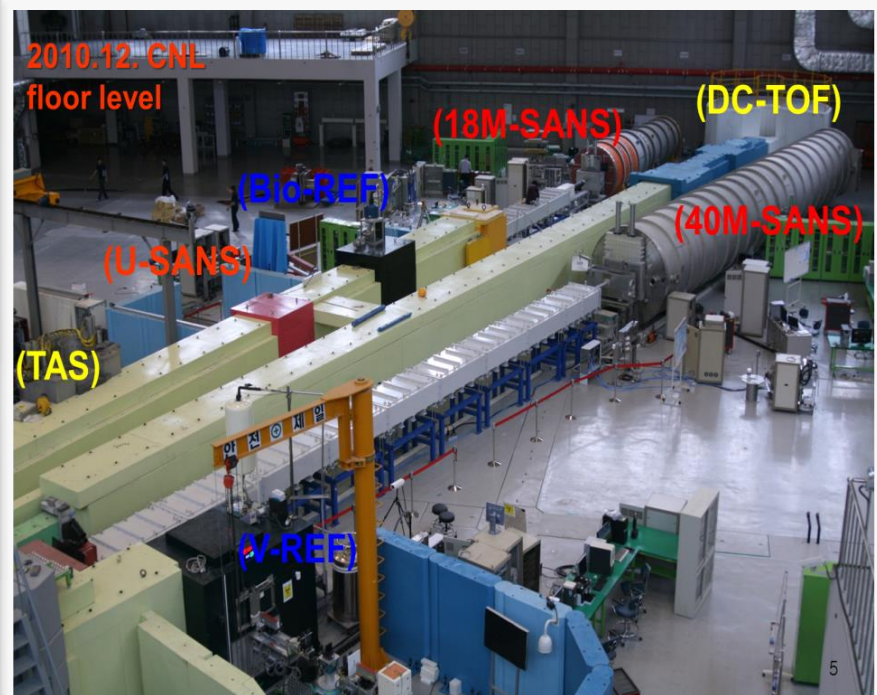
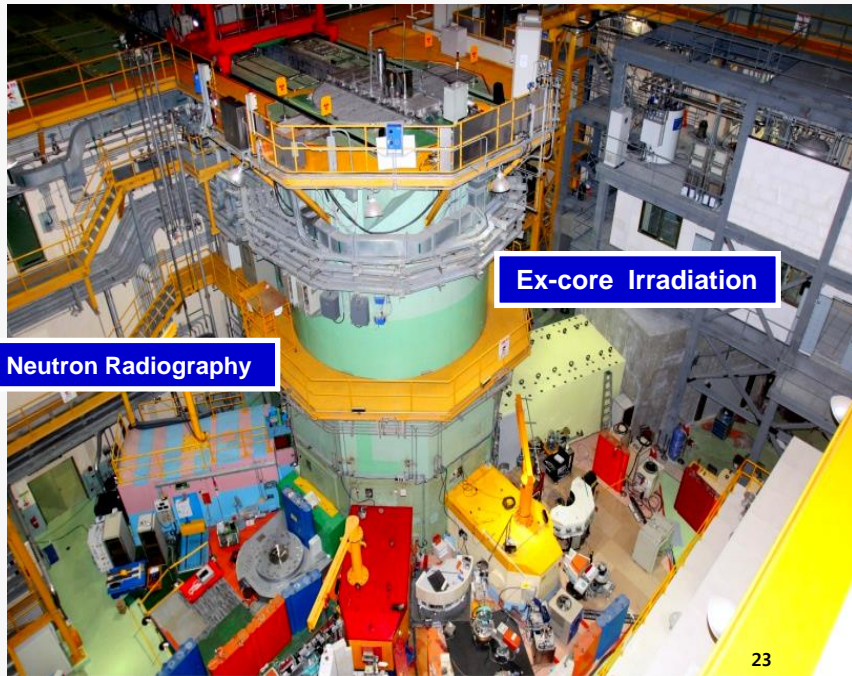
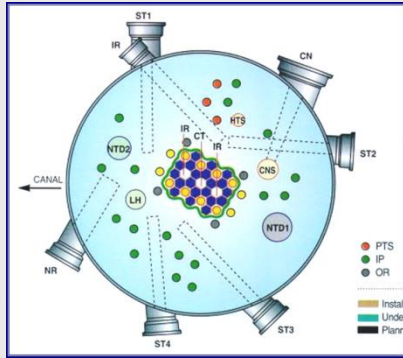
Detector Selection

- High density but thin converter
- For high resolution
 - Fiber optic plate, MCP
- For high frame rate
 - EMCCD, sCMOS, ICCD
- For bigger sample

HANARO NEUTRON RADIOGRAPHY

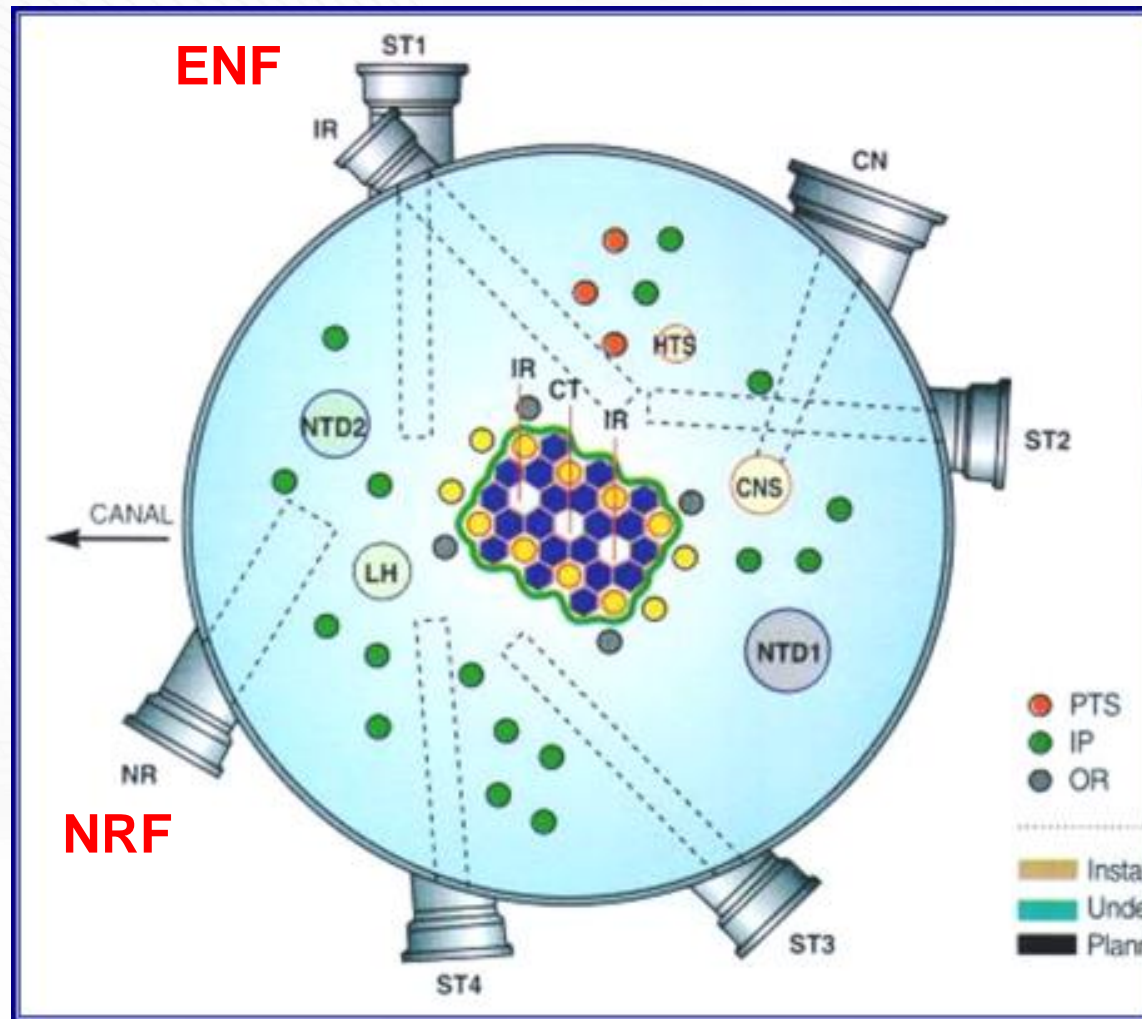
HANARO reactor : A multi-Purpose Research Reactor (30 MW)

HANARO & cold neutron research facility



Neutron Beam Research
Neutron Activation Analysis
RI Production
Neutron Transmutation Doping
Material & Fuel Irradiation Test

30 MW Reactor



Neutron production : $> 10^{18}$ neutrons /sec @30 MW thermal power

Neutron Radiography Facility

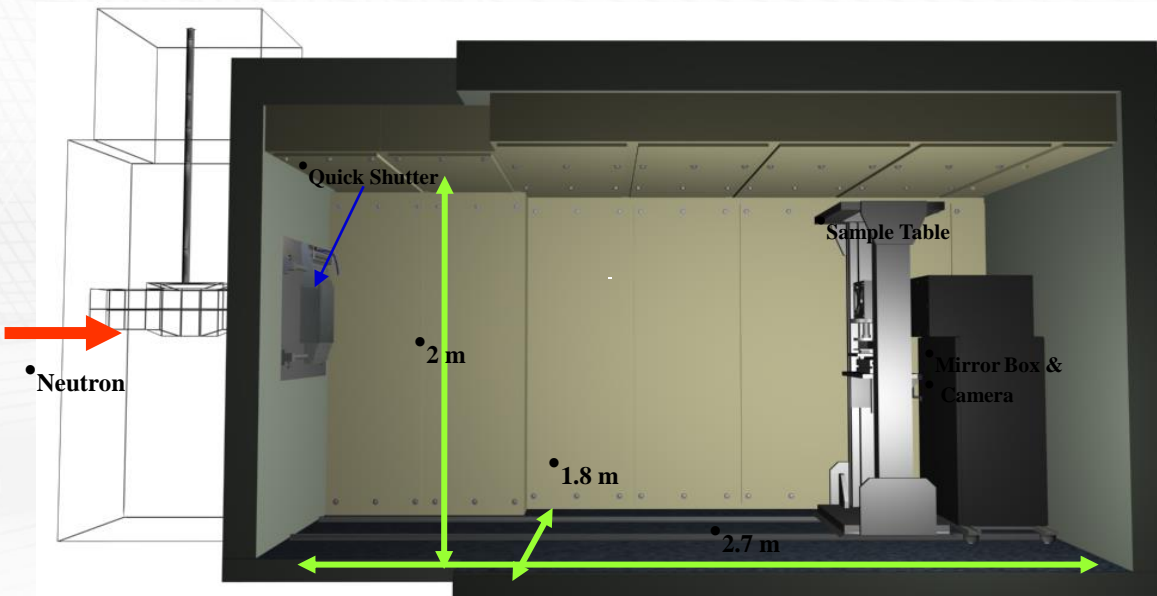
Neutron Flux [n/cm ² s]	$6 \times 10^6 \sim 2 \times 10^7$
L/D ratio	190 ~ 290
Beam Size [cm ²]	34(w) * 45(h)



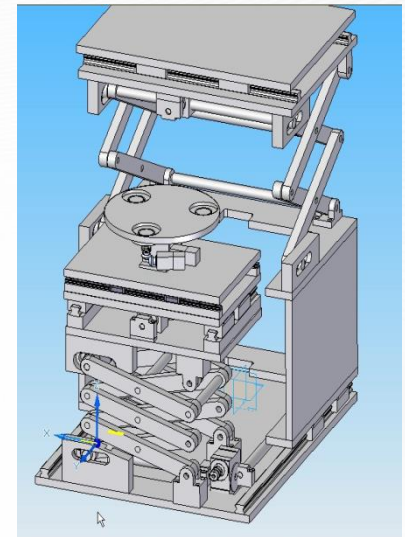
3 CCD Cameras (2 high resolution, 1 high speed) and Image Intensifier system.

→ Various researches are possible.

→ Limited sample size (<1m long)



Schematic Diagram of NRF

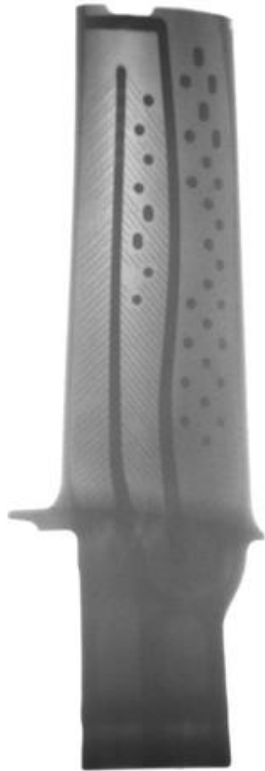


Sample Table for 3D Tomography: 3 samples

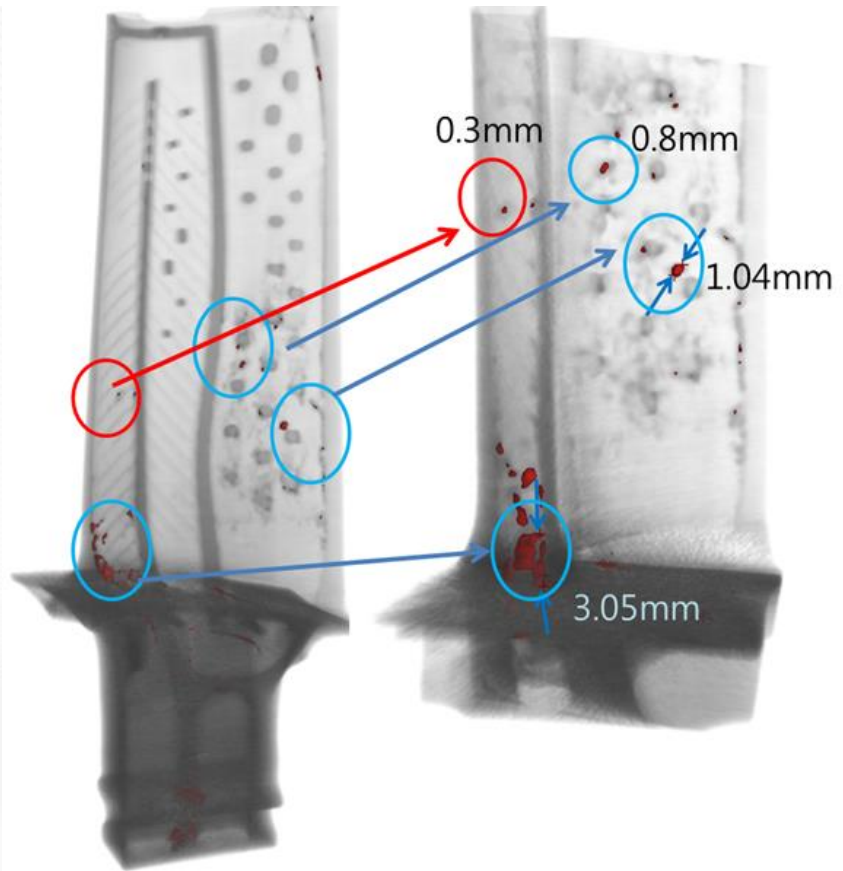
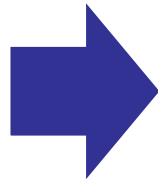
Neutron Radiography

X-ray cannot find but neutron does it

Gd-tagging method



**X-ray tomography
(passed)**

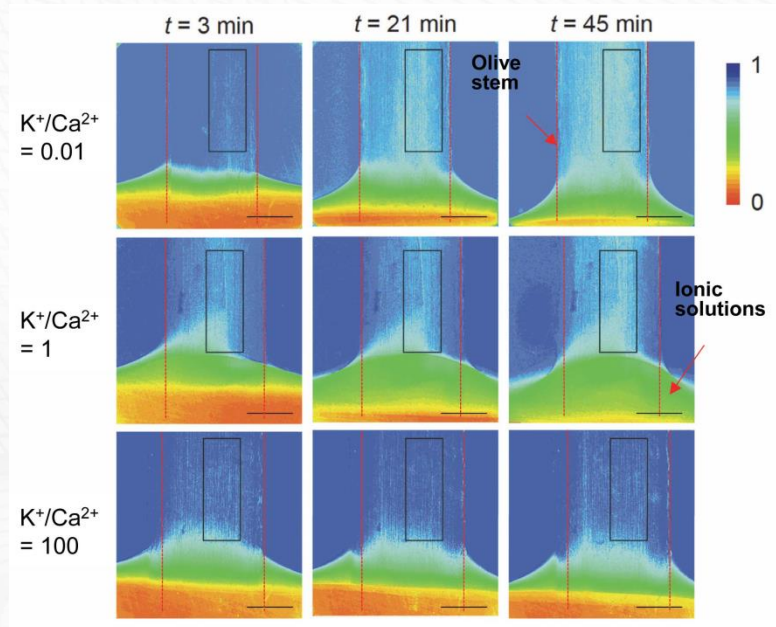


Neutron tomography

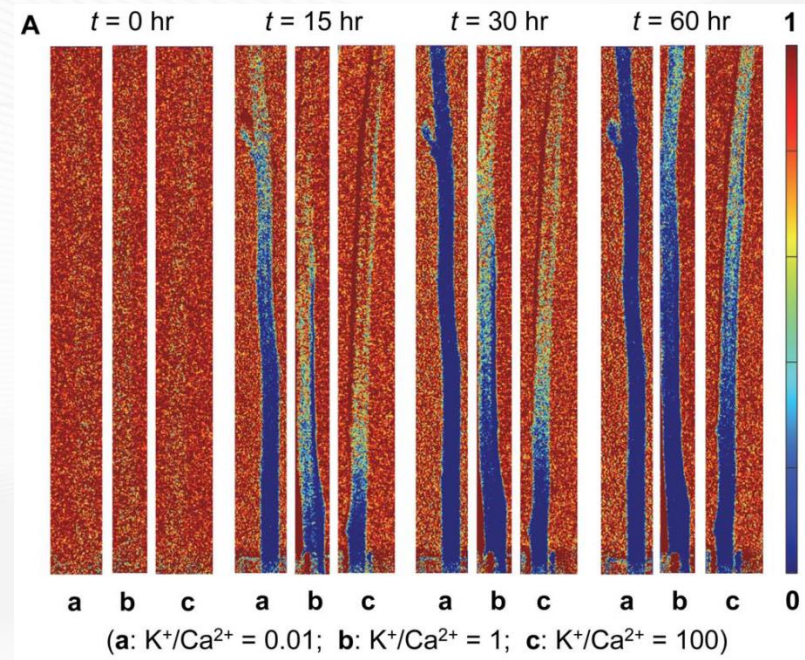
Neutron Radiography

Ion effect on water transport in plant

Investigate the effect of ionic ratio for water up-take by X-ray and Neutron : Olive and Laurel



X-ray Image(10um, 3min)



Neutron Image(100um, 40sec)

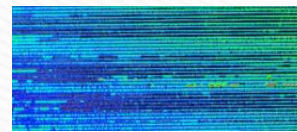
Neutron Radiography

PEM Fuel Cell with Hyundai Motors

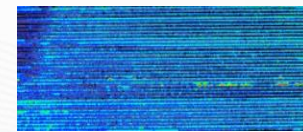


Celebration of First Fuel Cell Vehicle
for Mass Production

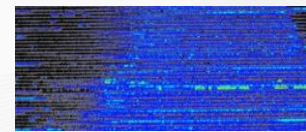
<Neutron image with temperature and current>



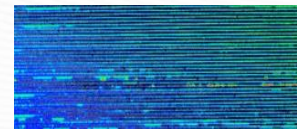
30°C, 115A



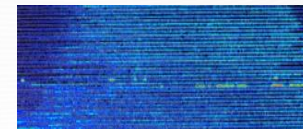
50°C, 115A



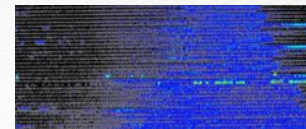
65°C, 115A



30°C, 216A

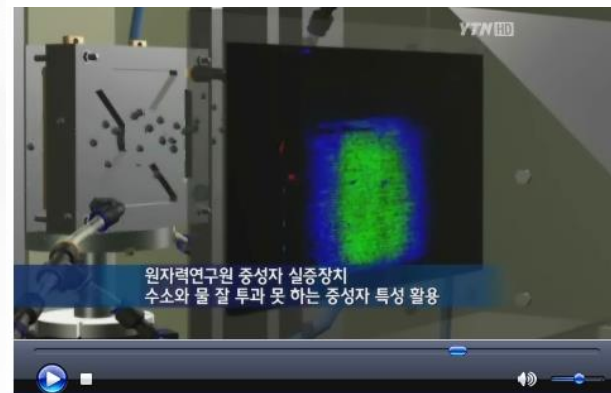


50°C, 216A



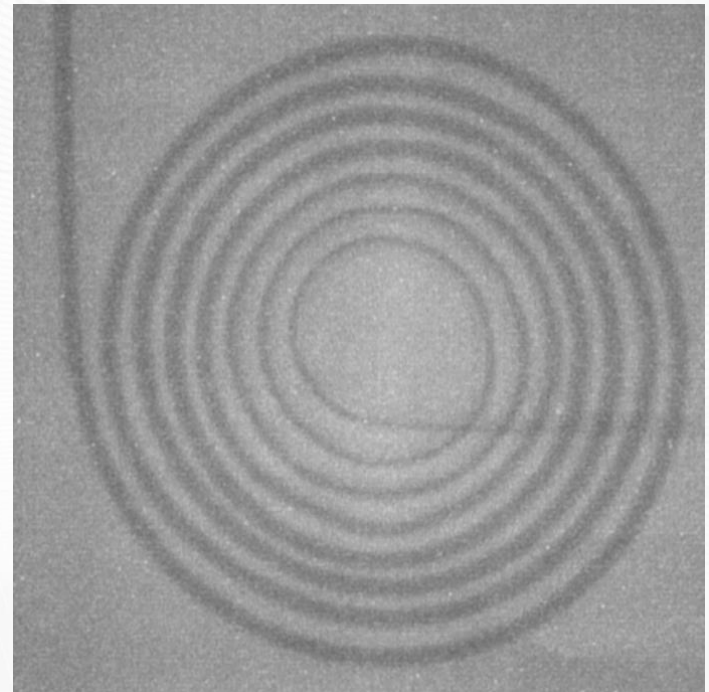
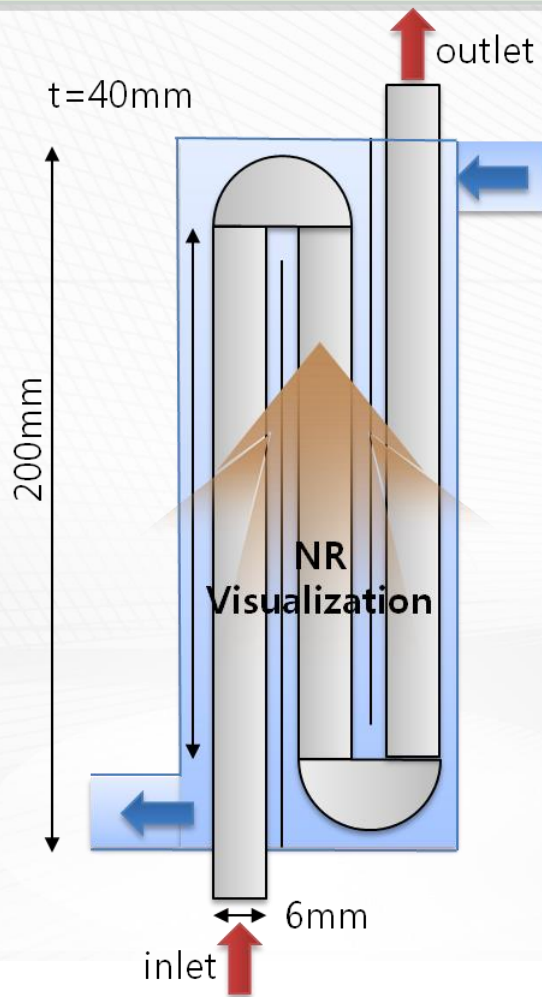
65°C, 216A

대덕] '하나로' 수소연료자동차 기술 주도!



Neutron Radiography

Two phase flow research in heat exchange pipe



Neutron Radiography

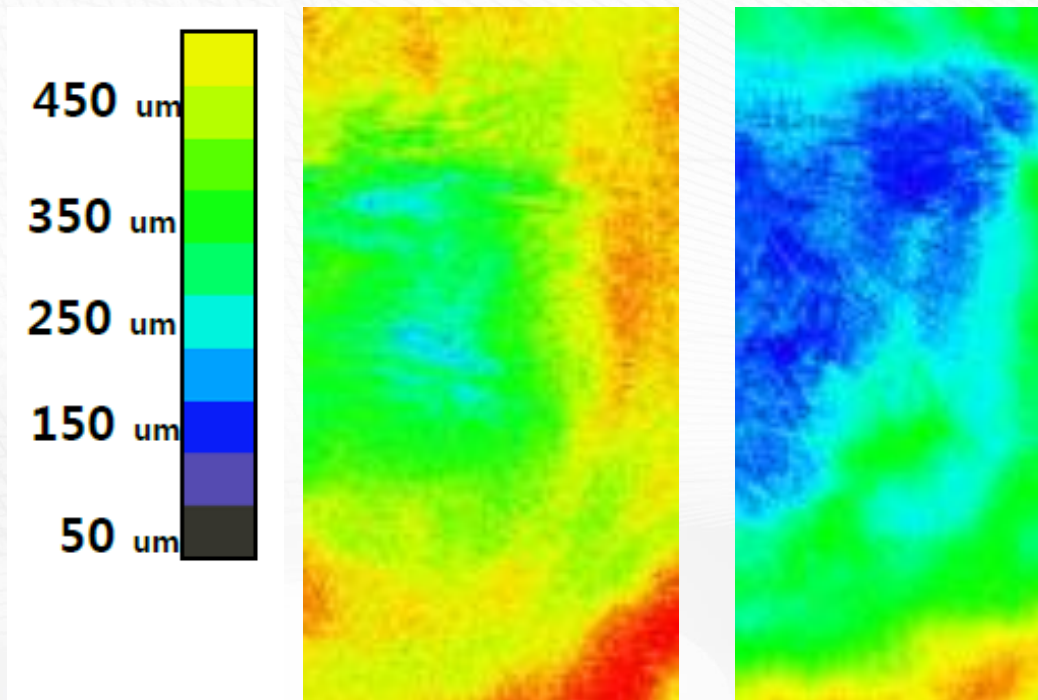
Lithium in Li-ion battery



Li-6 : 7.5%

Li-7 : 72.5%

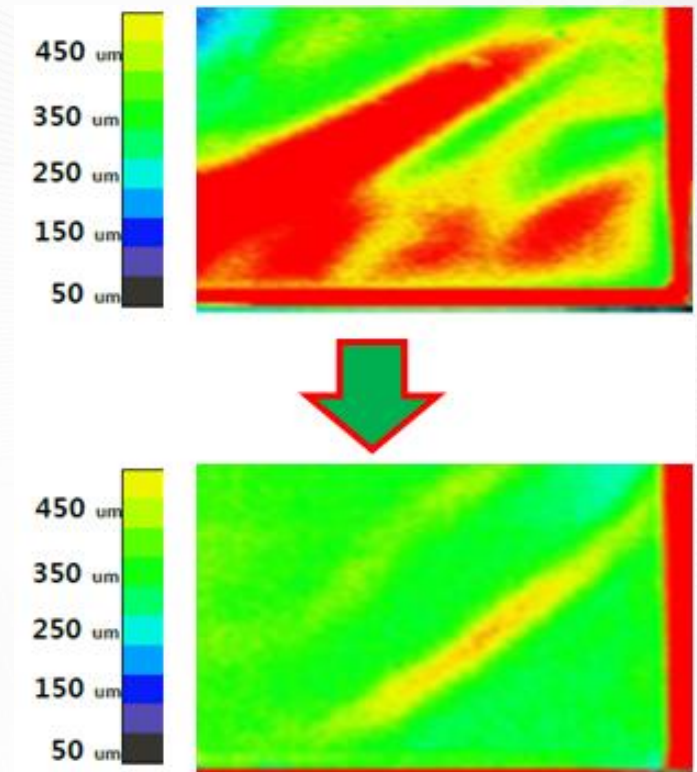
Direction Effect



Lie down

Stand

Aging Effect

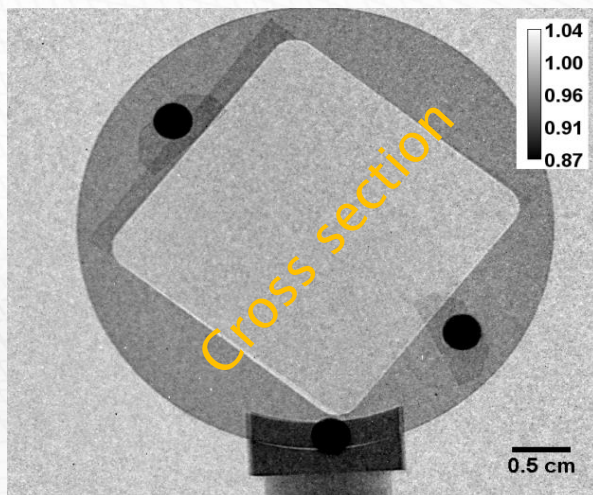


Neutron Imaging is powerful tool for the Li-ion Battery research.

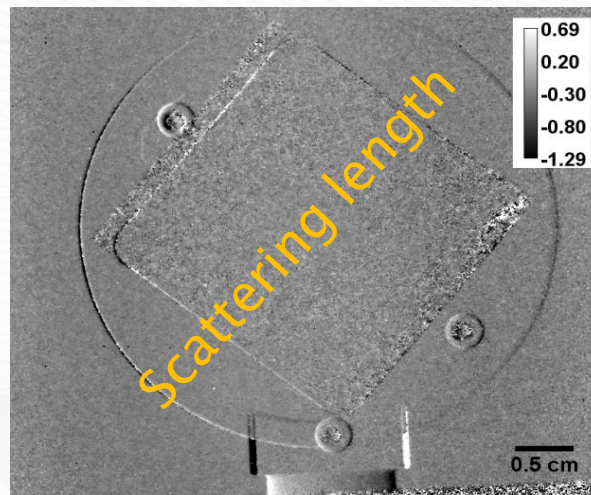
Neutron Radiography

Example Image from the Grating Imaging System

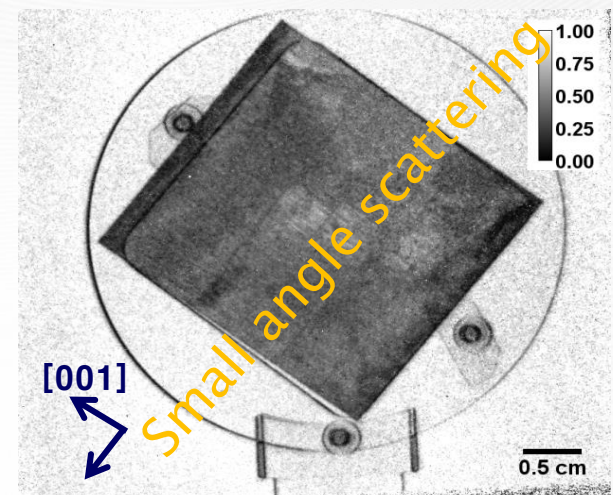
~16% of visibility



Absorption



Differential Phase

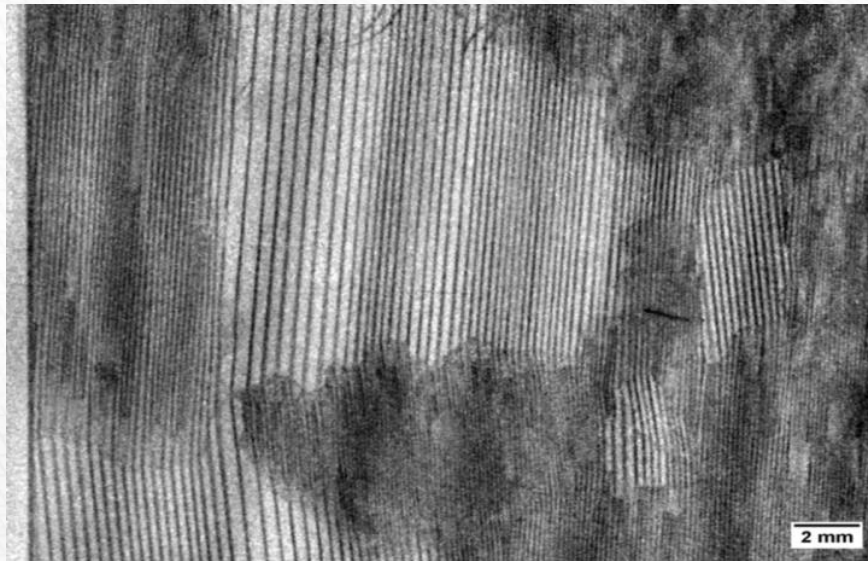


Dark-field

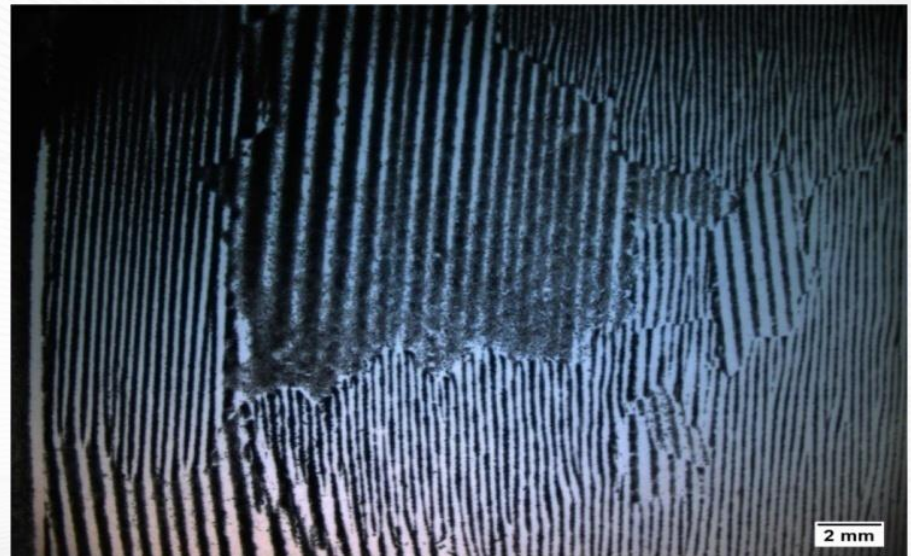
Beryllium filtered thermal neutron was used for this example measurement.

Neutron Radiography

Neutron Dark-field Imaging



Magnetic Powder Method



High Resol. Example: Magnetic Domains in Electrical Steel

Seung Wook Lee, Ki Yeon Kim, Oh Yeoul Kwon, Nikolay Kardjilov, Martin Dawson, Andre Hilger, Ingo Manke, "Observation of Magnetic Domains in Insulation-Coated Electrical Steels by Neutron Dark-Field Imaging", Applied Physics Express, 2010

NEW NEUTRON RADIOGRAPHY FACILITY

하나로 NRF에서의 실험 예

- 중성자속 (neutron flux): 2×10^6 n/sec-cm²,
- L/D ratio: 200
- FOV에 따른 Camera 노출 시간
 - ✓ 400 × 400 mm² : 5 초
 - ✓ 200 × 200 mm² : 10 초
 - ✓ 100 × 100 mm² : 60 초
- 시편 두께에 따른 노출 시간
 - ✓ 1~2 cm : 5 ~ 10 초
 - ✓ ~5 cm : 20 ~ 30 초
 - ✓ ~20 cm : 30 초 이상
- 통상적인 NDT 실험에서는 5분 조사 후, 15분 후에 조사실 출입함.

중성자속 @ 시편 or 검출기(I_s or I_D)

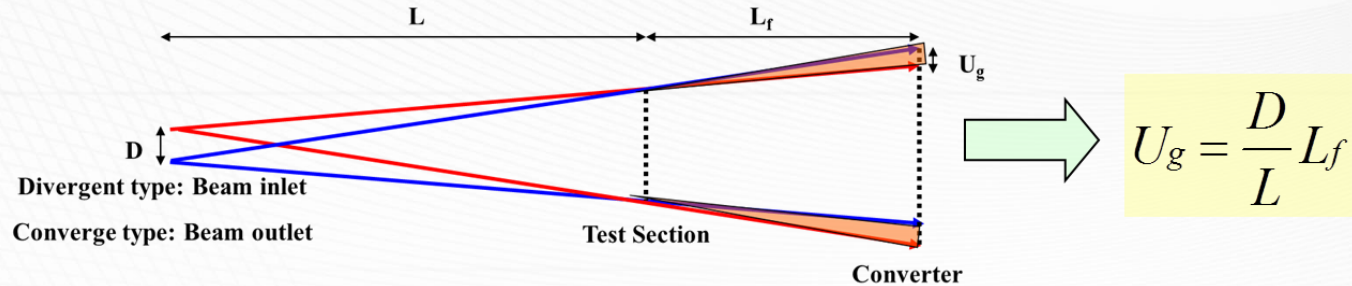
- 산업체의 희망사항 또는 요구: 가능한 짧은 시간에 많은 시편 측정
 - ✓ 중성자속 변화에 따른 노출 시간 변화(at HZB)

중성자속	노출시간[초]
2.0×10^8	0.5
1.6×10^7	5
5.8×10^6	10

- ✓ 중성자속이 $5 \times 10^5 \text{ n/sec-cm}^2$ 으로 감소할 경우, 노출시간은 100초
 $5 \times 10^4 \text{ n/sec-cm}^2$ 으로 감소할 경우, 노출시간은 1,000초(16분)
- ✓ 산업적 적용 가능성
 - ✓ 철도, 대형 구조물: $5 \times 10^4 \text{ n/sec-cm}^2$ 사용 가능
 - ✓ 자동차, 항공기 부품: $5 \times 10^4 \text{ n/sec-cm}^2$ 사용 불가능.

중성자속 @ 집속기 상단(I_{c0} or I_{c1})

- 집속기 상단에서 요구되는 중성자속(I_{c0} or I_{c1})의 범위는?
 - ✓ L/D Ratio에 의한 기하학적 오차



$$\begin{aligned} L_f &= 10\text{mm}, \\ \text{If } L/D &= 50 \\ U_g &= 0.211 \text{ mm} \end{aligned}$$

$$U_g = \frac{D}{L} L_f = \frac{10}{50} = 0.2\text{mm}$$

$$\begin{aligned} \text{If } L/D &= 500 \\ U_g &= 0.02 \text{ mm} \end{aligned}$$

$$U_g = \frac{D}{L} L_f = \frac{10}{500} = 0.02\text{mm}$$

중성자속 @ 집속기 상단(I_{c0} or I_{c1})

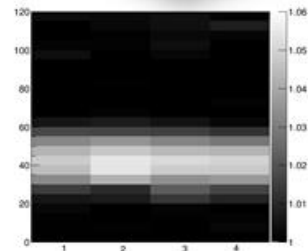
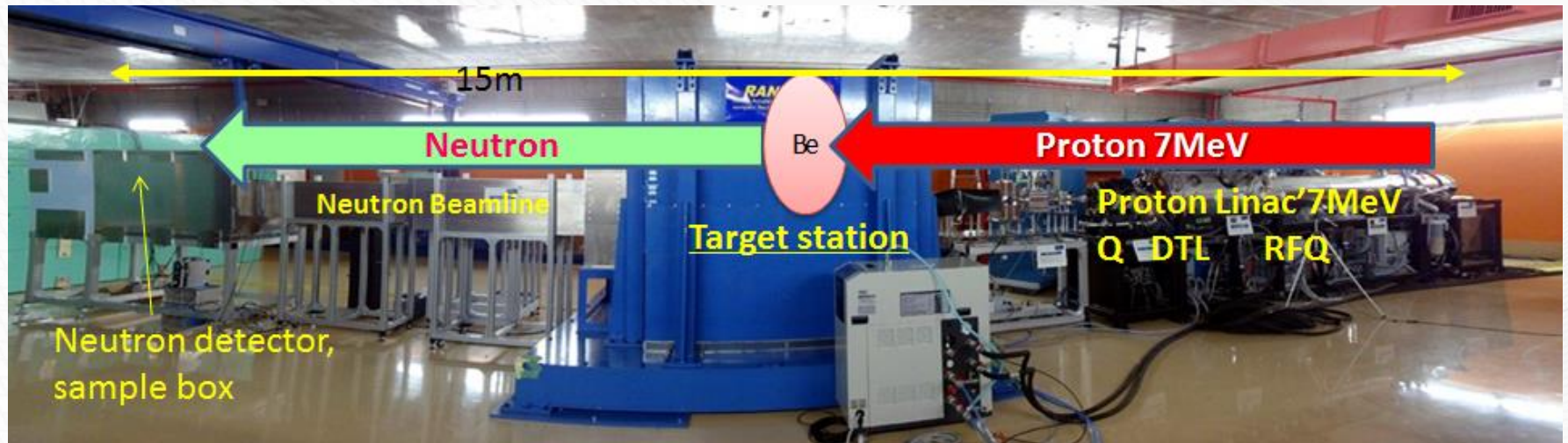
- 집속기 상단에서 요구되는 중성자속(I_{c0} or I_{c1})의 범위는?
 - ✓ L/D에 따른 요구되는 중성자속(I_{c0})

중성자속 (I_s)	L/D	중성자속(I_{c0})	기하학적 분해능 (U_g)
5.0×10^5	10	1.3×10^7	1.0 mm
	50	1.3×10^9	0.2 mm
	100	5.0×10^9	0.1 mm
5.0×10^4	10	5.0×10^6	1.0 mm
	50	1.3×10^8	0.2 mm
	100	5.0×10^8	0.1 mm

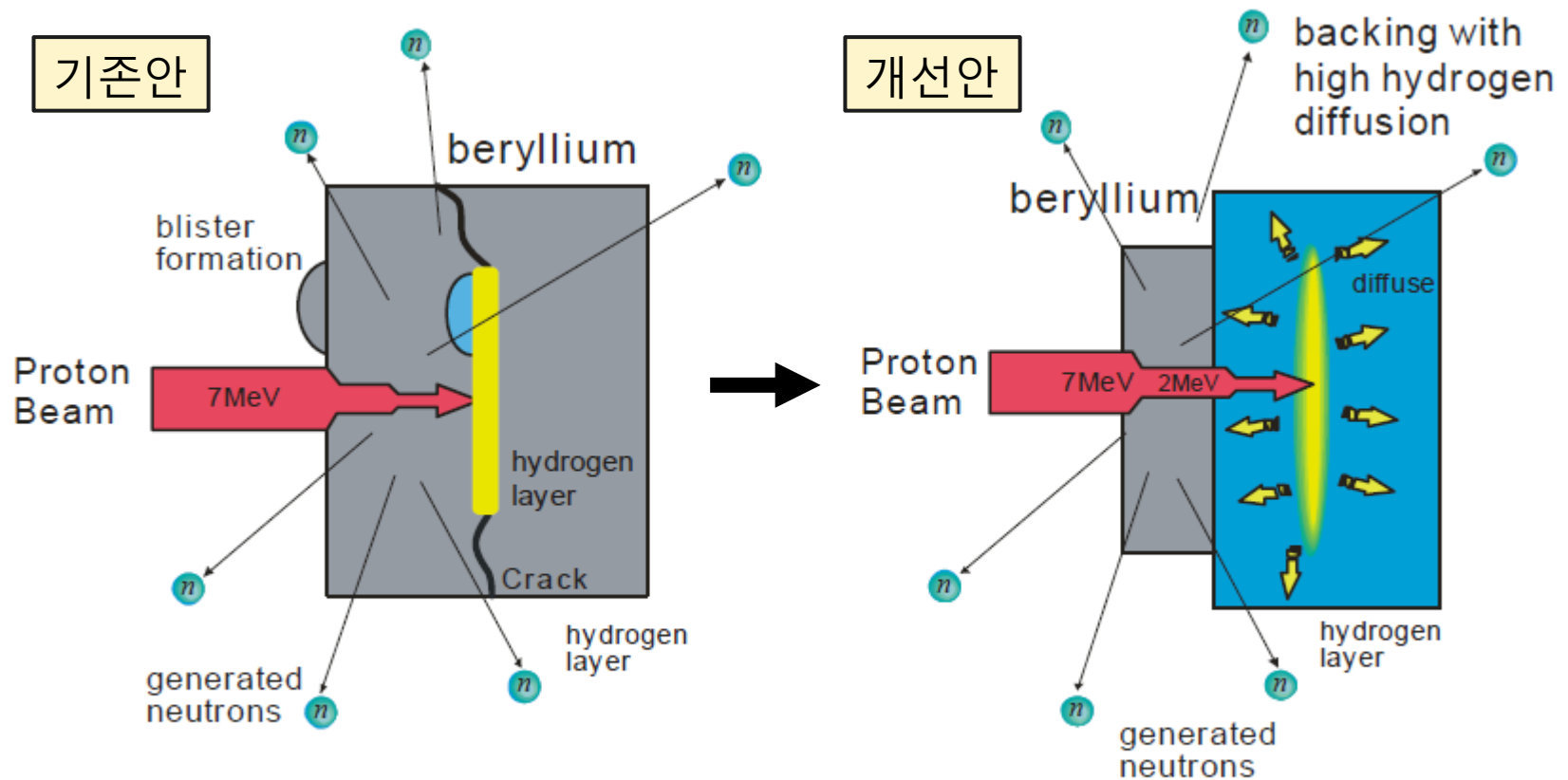
- 기하학적 분해능 이하로는 측정 불가능.
 - ✓ 일반적으로 항공기 부품은 0.1 mm 이하의 분해능이 요구됨.

소형 가속기 기반 중성자 영상 시스템

RANS (RIKEN Accelerator-driven Neutron Source)



Neutron Production



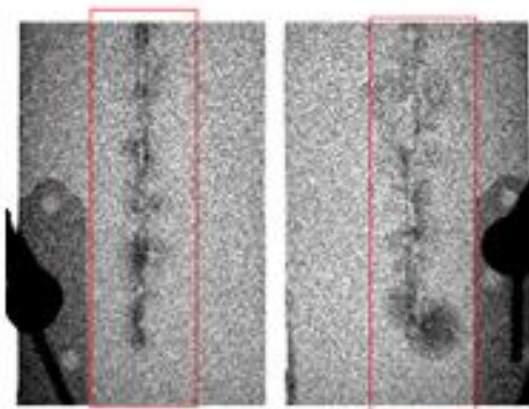
Hydrogen embrittlement -> Blistering, Cracking -> Destruction of target

➔ 1년을 사용해도 문제없음 (기존: 수일)

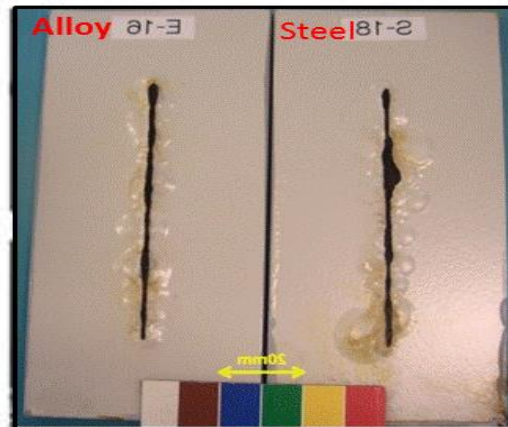
중성자 영상

○ Thermal Neutron Research

- 부족한 중성자속을 고성능 검출기로 보충함. (중성자속: $3 \times 10^3 \text{n/sec-cm}^2$)
- 노출시간은 시편에 따라 다르지만, 5 ~ 10분 정도 소요 됨.

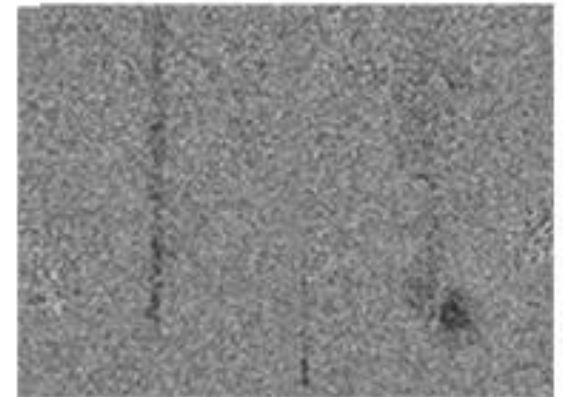


Wetting



합금강

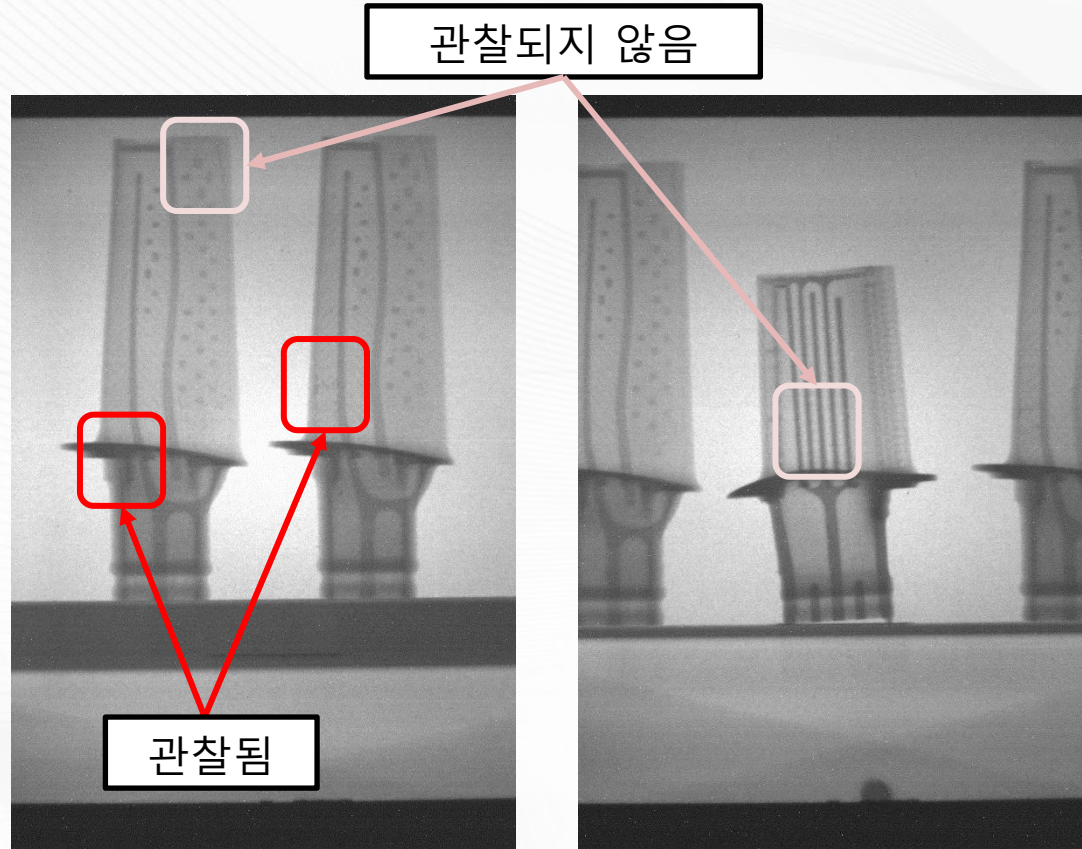
보통강



Drying

중성자 영상

Turbine Blade



HANARO NRF에서 측정 결과와 비교

소형 가속기 기반 중성자 발생

- Optimization of TMR structure for Neutron Radiography

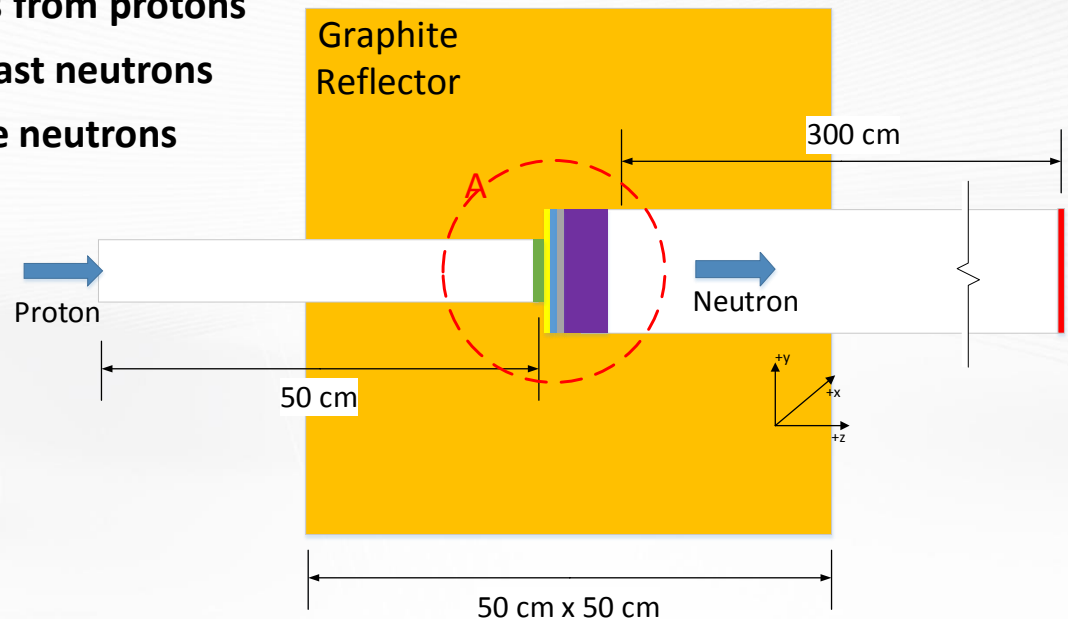
- > Target thickness + Moderator thickness

- > Maximum thermal yield

- Using Monte Carlo simulation (Geant4)

- TMR (Target, Moderator, Reflector)

- Target : Generating neutrons from protons
- Moderator : Slowing down fast neutrons
- Reflector : Gathering leakage neutrons



The target assembly as consisted of Beryllium target, cooling system. is slab type of compact neutron source

소형 가속기 기반 중성자 발생

- 양성자 충돌에 의한 Be 타겟에서의 중성자 발생
 - Be에 입사된 양성자 가운데 0.1~0.5% 정도만 중성자 발생 (양성자 에너지에 따라 변함)
 - 나머지 99.5% 이상은 열로 변환

- 중성자 발생률

$$Y_N(E_p) = 3.42 \times 10^8 (E_p - 1.87)^{2.05} \text{ (n/uC)}$$

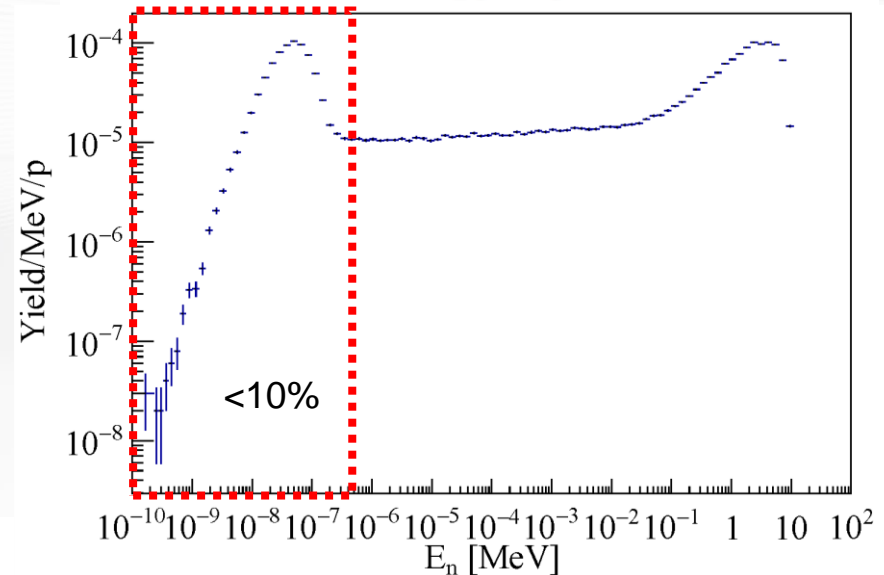
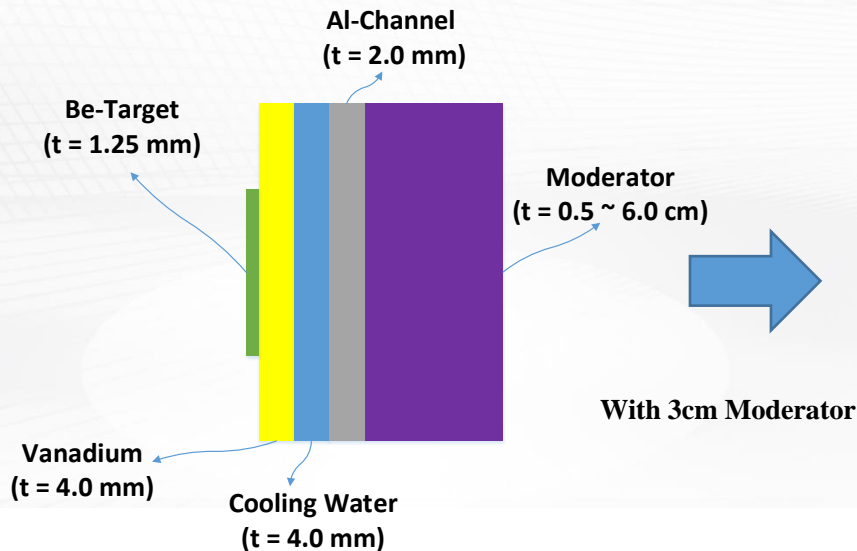
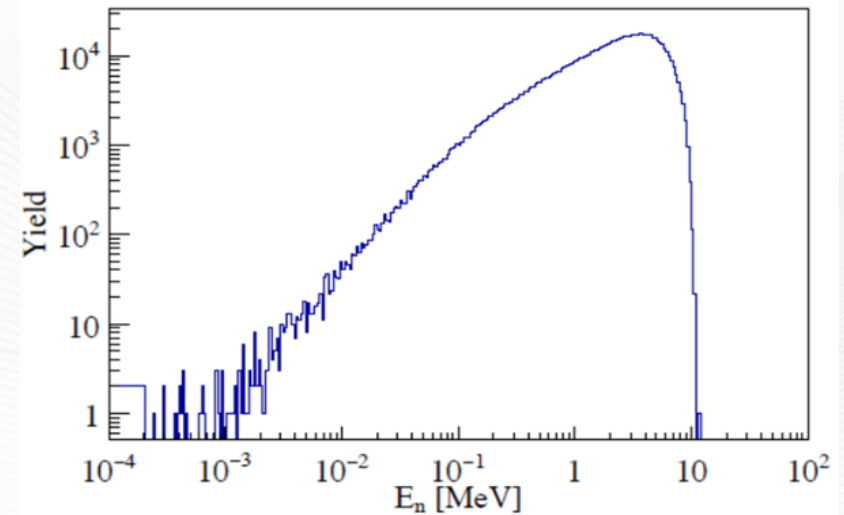
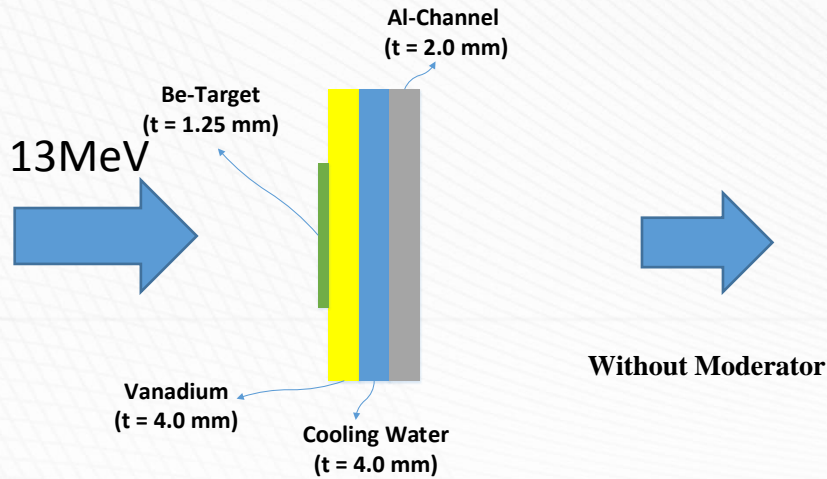
- $\sim 10^{13}/\text{mA}$ for 7MeV
- $\sim 2.5 \times 10^{13}/\text{mA}$ for 10MeV
- $\sim 5 \times 10^{13}/\text{mA}$ for 13MeV

❖ 전체 중성자 수 (영상에 기여할 수 없는 고에너지 중성자 포함)

Optimization of TMR structure for Neutron Radiography

-> Target thickness + Moderator thickness

-> Maximum thermal yield



표적에서 ...

1. 가속기에서 공급하는 입자빔과 표적열량
 - 1) 10 Mev / 1 mA proton \rightarrow 10 kW
 - 2) 7 Mev / 0.5 mA(500 μ A) \rightarrow 3.5 kW
2. 표적이 냉각해야 하는 열밀도(heat density)
 - 1) 10 kW / 25 cm² (5 cm x 5 cm) \rightarrow 400 watt/cm²
 - 2) 3.5 kW / 19.6 cm² (5 cm ϕ) \rightarrow ~180 watt/cm²
3. 기술적인 열밀도 한계
 - 1) 현재 실용적 수준 \rightarrow 500 watt/cm²
 - 2) 현재 가능한 최대 수준 \rightarrow 1000 watt/cm²
 - 3) X3 안전 마진을 감안할 경우 \rightarrow 350 watt/cm² (?)
4. 가속기 규격은?
 - 1) 7 MeV~10 MeV / 1 mA 면 단순구조의 표적 냉각한계 도달
 - 2) 가속기는 용량보다 견고함, 단순함, 안정성, 편리성이 더 중요

간단한 잠정 목표 예시

1. L/D~100 수준의 기하학적 구조에서
 - 1) Port nose에서 시료까지 5m (500 cm)라면 표적길이는 ~5cm
2. 시료 위치 실효 **열중성자**속 5.0×10^5 (실제 시료를 지나 검출기로 가는 방향성 flux, 즉 brightness임)를 얻어
3. ~100 sec 정도의 노출시간으로
4. 영상 분해능 ~0.1mm 수준 질적 영상을 얻으려면
5. 수평공 선단(port nose)에서 5.0×10^9 flux(즉, brightness)를 생산해야 하고,
6. 이러한 **열중성자** 속을 얻기 위한 표적에서의 입자 수송은 7 ~10 MeV / 1 mA가 열적 냉각 한계
7. 이에 따른 Target-Moderator-Reflector-Shielding&port 설계가 필요

결론과 전망

- 원자로 기반 중성자 영상기술은 기확보
 - 첨단 기술 개발 진행 (에너지 선택 중성자 영상기술 등)
- 현장가동형 중성자 영상장치 개발 필요
 - 소형 가속기 기반
 - Target-Moderator-Reflector-Shielding 기술개발 필요
- 인허가 문제