중성자 영상 모사 환경 구축 & 중성자 영상 특성

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Contents

- **Introduction**

  - Neutron sources & applications

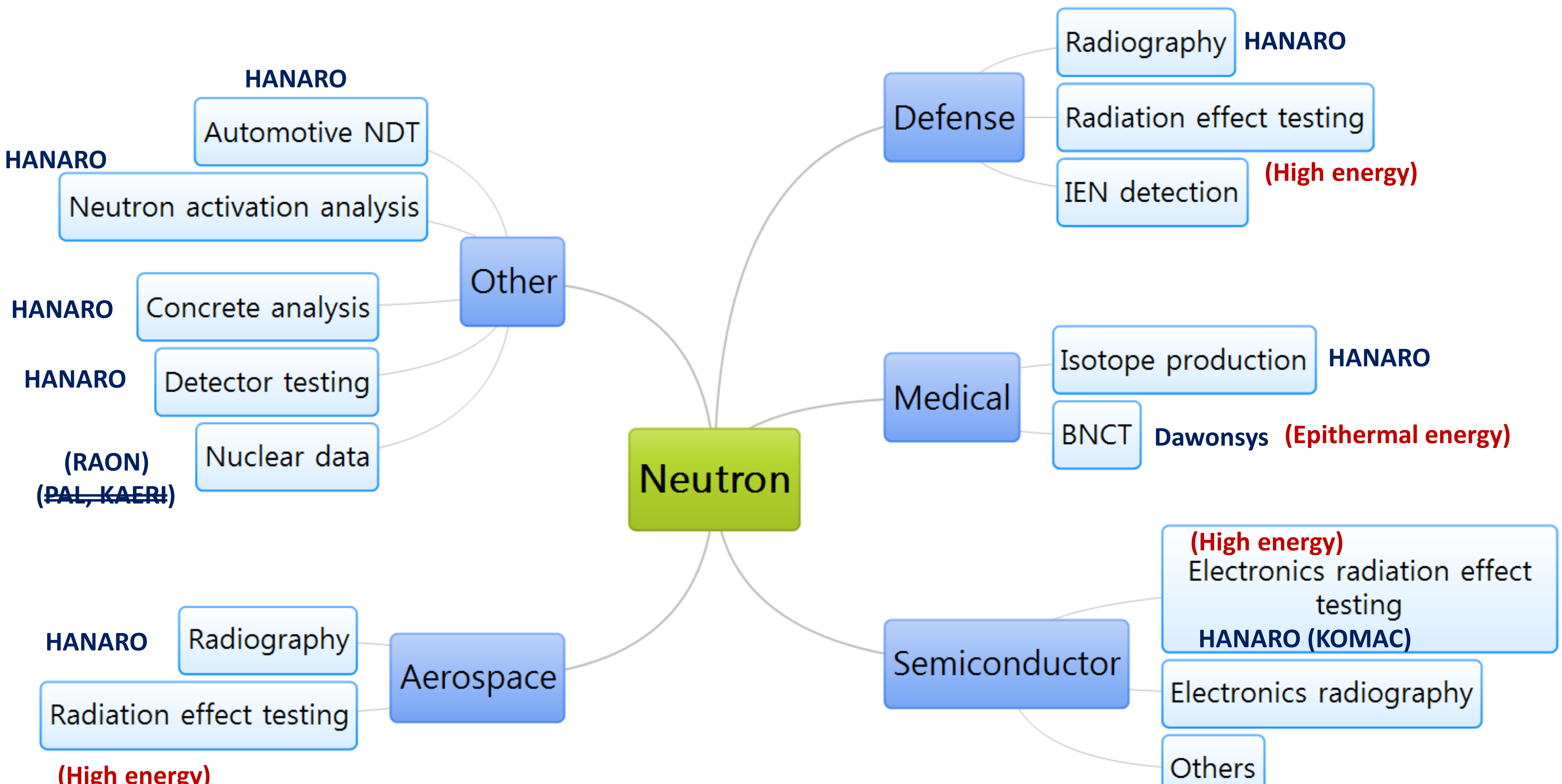
- **New accelerator-based neutron sources**

  - ARTI 30 MeV cyclotron

- **Low-flux neutron environments**

  - Research reactor → compact neutron sources
  - $10^6 \sim 10^8$ n/cm^{2}s → $10^3 \sim 10^5$ n/cm^{2}s

Neutron Applications



Exclude neutron scattering fields

Neutron Parameters

- **Neutron yield**

  - How many neutrons?

- **Flux**

  - Determine application fields

- **Energy distribution**

Accelerator-based sources

Name	Cold	Thermal	Epithermal	Cadmium	Slow & intermediate	Fast
Energy(eV)	**<0.025**	**0.025**	0.025~0.4	0.4~0.5	1 ~ 1,000,000	>1,000,000

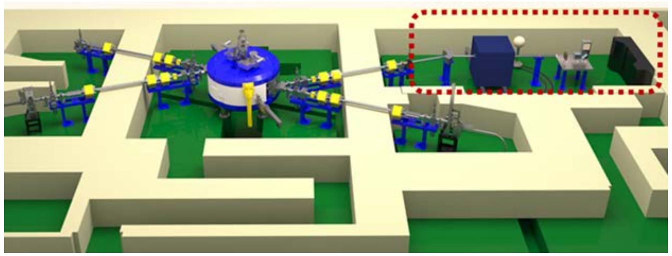
On-site possibility

Reactor sources

Neutron Yield Related Applications

Neutron generators

Accelerator-driven neutron sources



Reactors & Spallation sources

10^{6} 10^{7} 10^{8} 10^{9} 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{16} 10^{17}

Neutrons/second

- Oil Well Logging
- Coal/Cement Analysis
- Scientific Research

Limited Strength

- Radiography
- BNCT
- Detection
- Isotope Production
- Replace Cf-252

Low radioactive wastes

- Neutron Diffraction
- Neutron Tomography
- Electricity Production

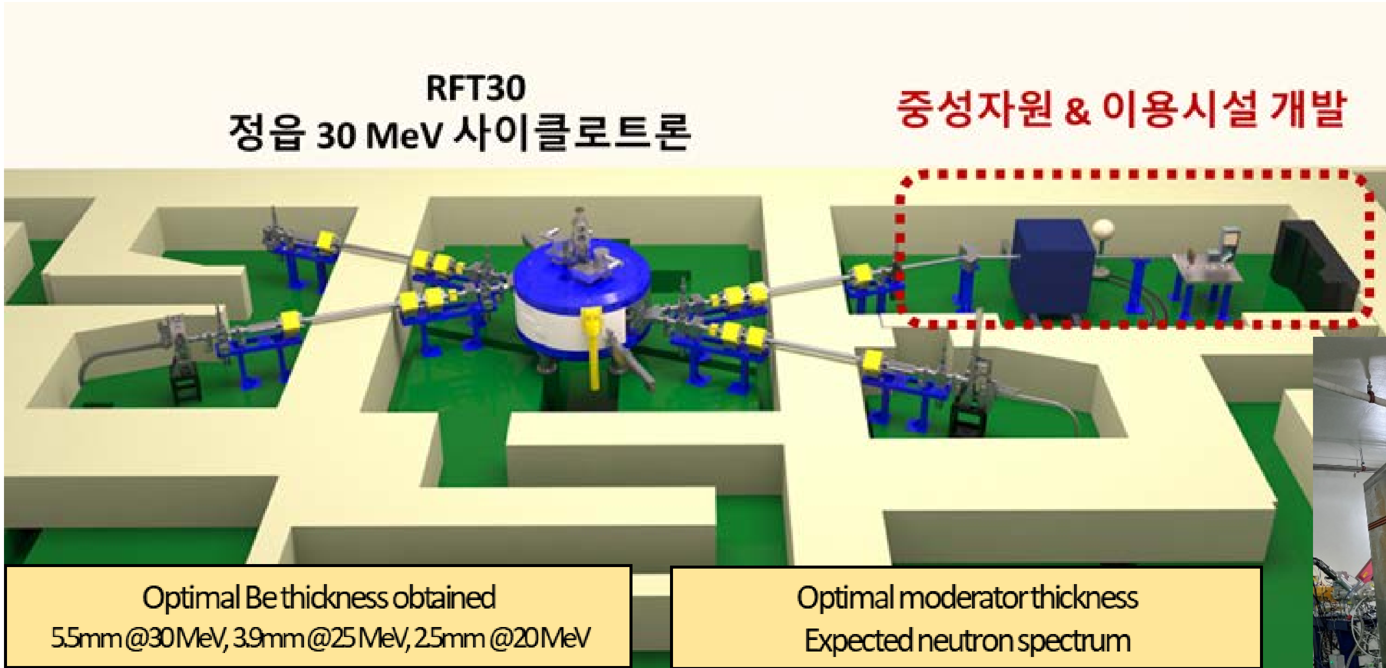
Limited Access

High radioactive wastes

Neutron Sources in Korea

- **KAERI HANARO reactor : thermal**
- **Dawon Medax 8 MeV Linear Accelerator : epithermal**
- **KOMAC 100 MeV Linear Accelerator : high energy**
- **KAERI ARTI 30 MeV cyclotron : thermal-high energy (new)**
- **IBS RAON NDPS : high energy**
- **Miscellaneous DD, DT, Cf-252, …**

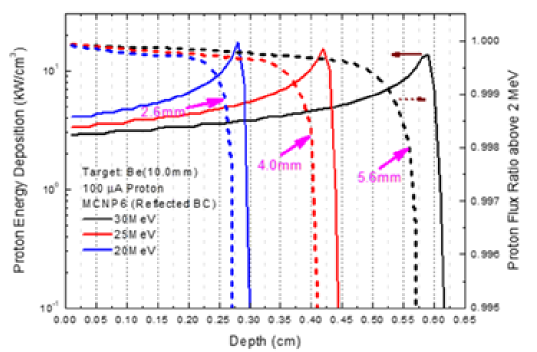
New Neutron Source Based on 30 MeV Cyclotron



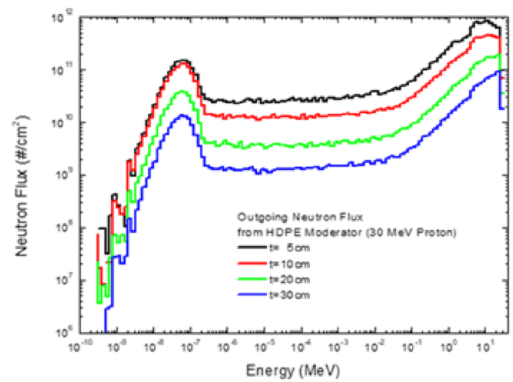
For neutron imaging

Neutron Yield : 10^{12} ~ 10^{13} n/s

Optimal Be thickness obtained
5.5mm @30MeV, 3.9mm @25MeV, 2.5mm @20MeV



Optimal moderator thickness
Expected neutron spectrum



KAERI JeongEup Outstation (ARTI)

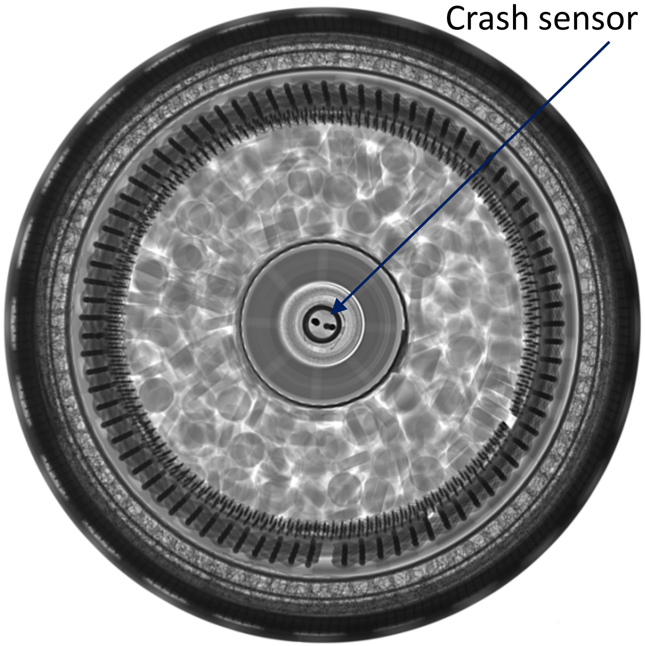
Neutron Camera System

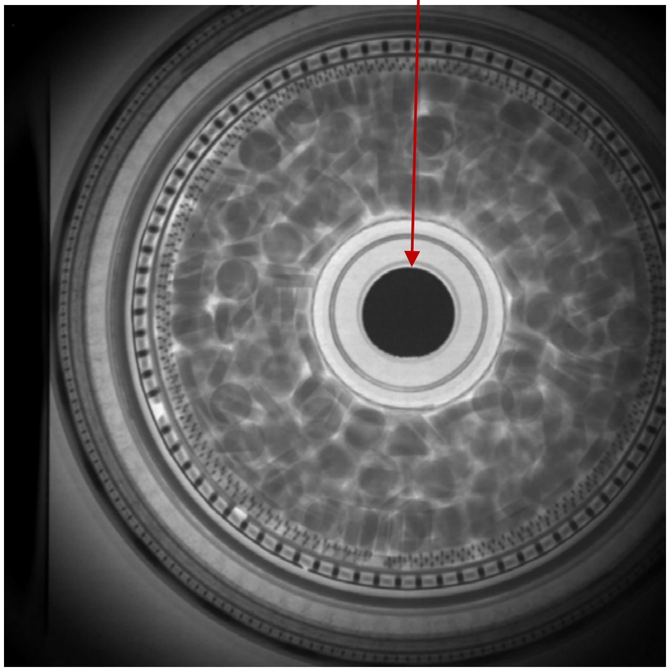
Camera Shielding

Beam Stop

- FOV 20 x 20 cm2
- ^{6}LiF/ZnS 400 um (80% efficiency)
- Spatial Resolution 0. 2 mm

Neutron vs. X-ray Imaging



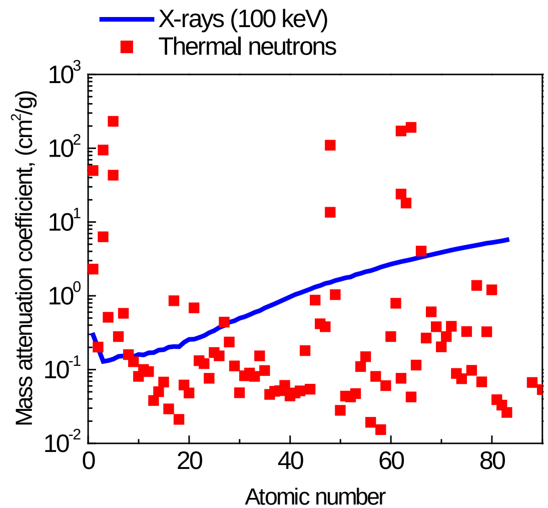


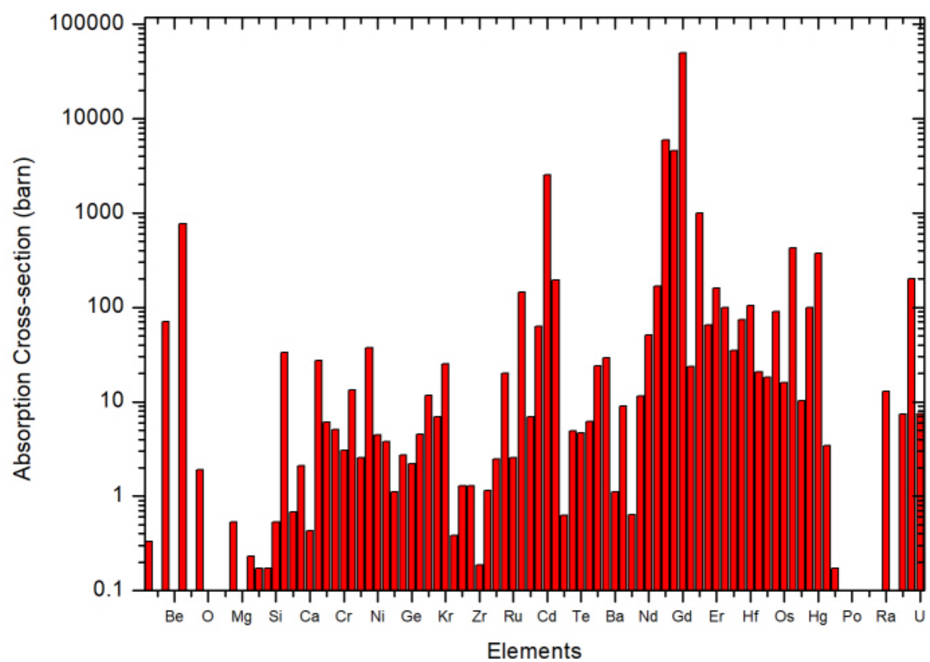
X-선 영상 @ 150Wp
(2k x 2k)

중성자 영상 @ 30 MWp
(2k x 2k)

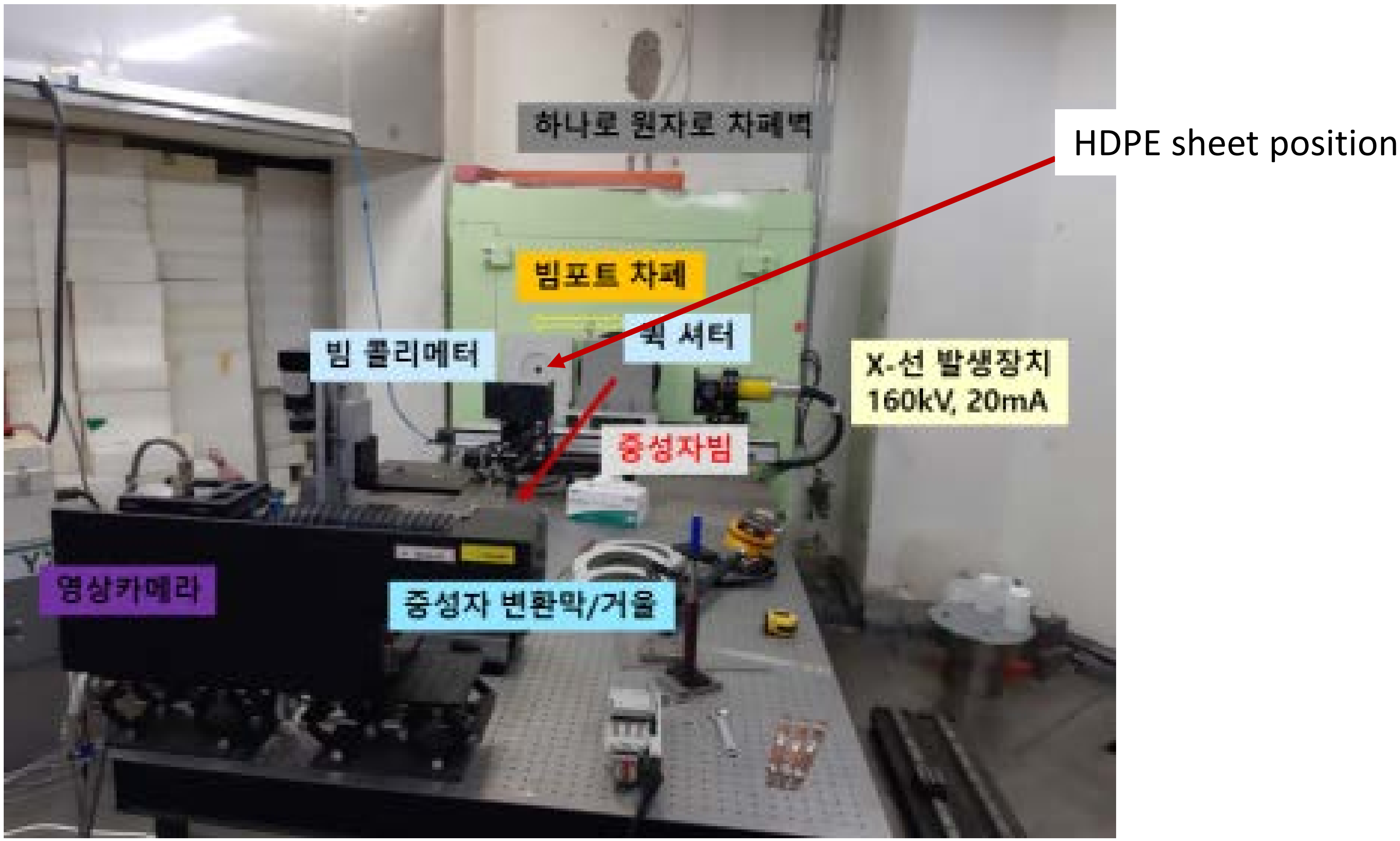
Thermal Neutron Absorption Cross-section

1	H	0.3326	32	Ge	2.2	63	Eu	4530
2	He	0.00747	33	As	4.5	64	Gd	49700
3	Li	70.5	34	Se	11.7	65	Tb	23.4
4	Be	0.0076	35	Br	6.9	66	Dy	994
5	B	767	36	Kr	25	67	Ho	64.7
6	C	0.0035	37	Rb	0.38	68	Er	159
7	N	1.9	38	Sr	1.28	69	Tm	100
8	O	0.00019	39	Y	1.28	70	Yb	34.8
9	F	0.0096	40	Zr	0.185	71	Lu	74
10	Ne	0.039	41	Nb	1.15	72	Hf	104.1
11	Na	0.53	42	Mo	2.48	73	Ta	20.6
12	Mg	0.063	43	Tc	20	74	W	18.3
13	Al	0.231	44	Ru	2.56	75	Re	89.7
14	Si	0.171	45	Rh	144.8	76	Os	16
15	P	0.172	46	Pd	6.9	77	Ir	425
16	S	0.53	47	Ag	63.3	78	Pt	10.3
17	Cl	33.5	48	Cd	2520	79	Au	98.65
18	Ar	0.675	49	In	193.8	80	Hg	372.3
19	K	2.1	50	Sn	0.626	81	Tl	3.43
20	Ca	0.43	51	Sb	4.91	82	Pb	0.171
21	Sc	27.5	52	Te	4.7	83	Bi	0.0338
22	Ti	6.09	53	I	6.15	84	Po	-
23	V	5.08	54	Xe	23.9	85	At	-
24	Cr	3.05	55	Cs	29	86	Rn	-
25	Mn	13.3	56	Ba	1.1	87	Fr	-
26	Fe	2.56	57	La	8.97	88	Ra	12.8
27	Co	37.18	58	Ce	0.63	89	Ac	-
28	Ni	4.49	59	Pr	11.5	90	Th	7.37
29	Cu	3.78	60	Nd	50.5	91	Pa	200.6
30	Zn	1.11	61	Pm	168.4	92	U	7.57
31	Ga	2.75	62	Sm	5922			



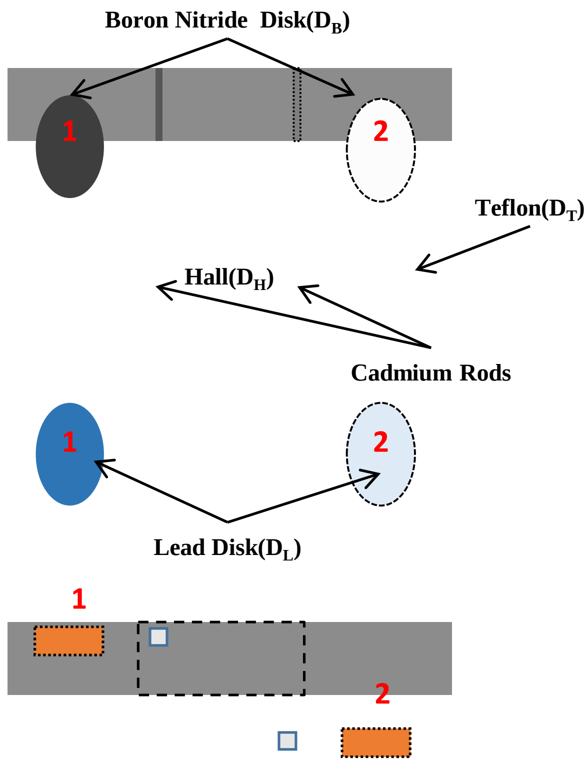


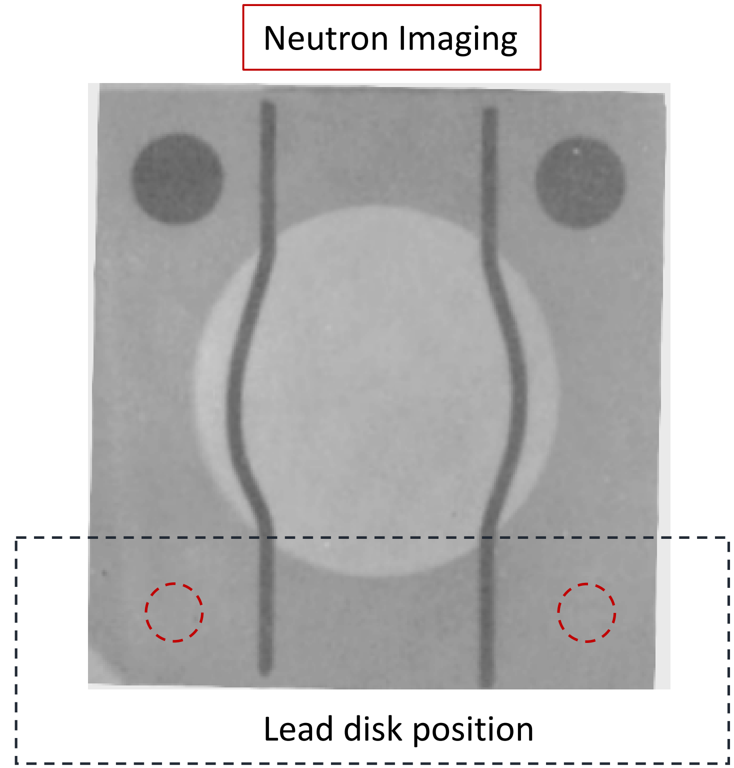
Low Neutron Flux Environments



HANARO ENF (Ex-core Neutron irradiation Facility)

Neutron Beam Purity Indicator





중성자 흡수 계수: 납(0.256), 테플론(0.260)

저 에너지 감마선 흡수율: 납(75%), 테플론(3%)

➔ $D_T = D_L$: 중성자 빔에 저 에너지 감마선 없음.

➔ $D_T \neq D_L$: 중성자 빔에 저 에너지 감마선 존재함.

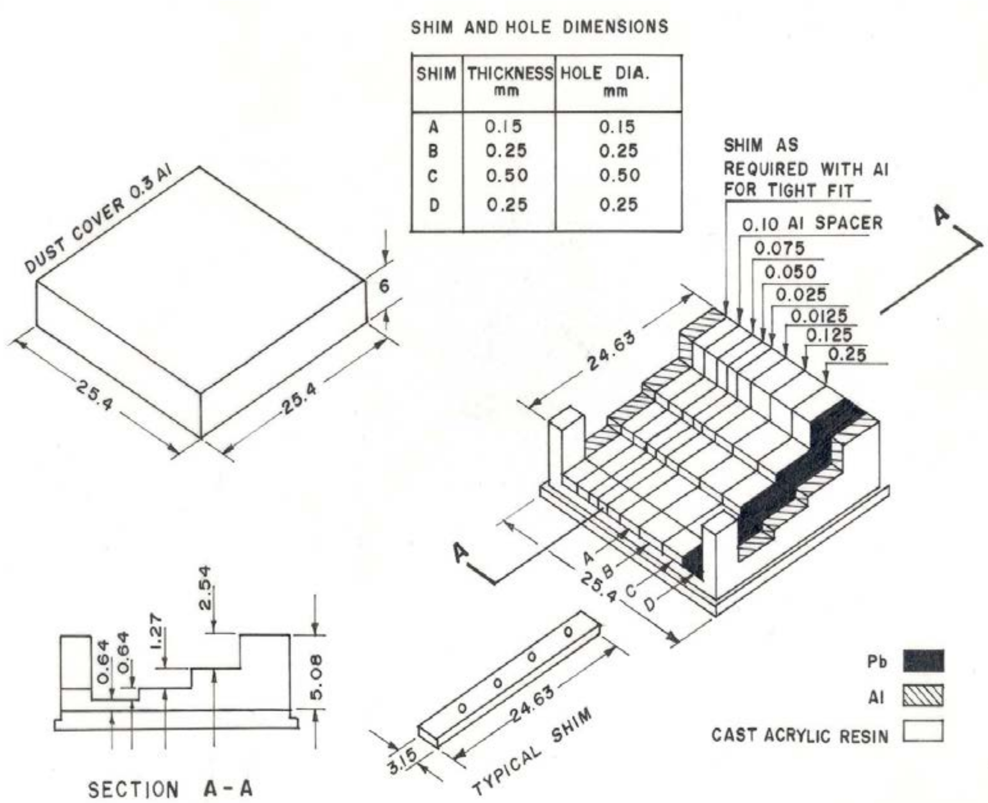
납 디스크의 음영 차이

➔ $D_{L1} = D_{L2}$: 중성자 빔에 고 에너지 감마선 없음.

➔ $D_{L1} \neq D_{L2}$: 중성자 빔에 고 에너지 감마선 존재함.

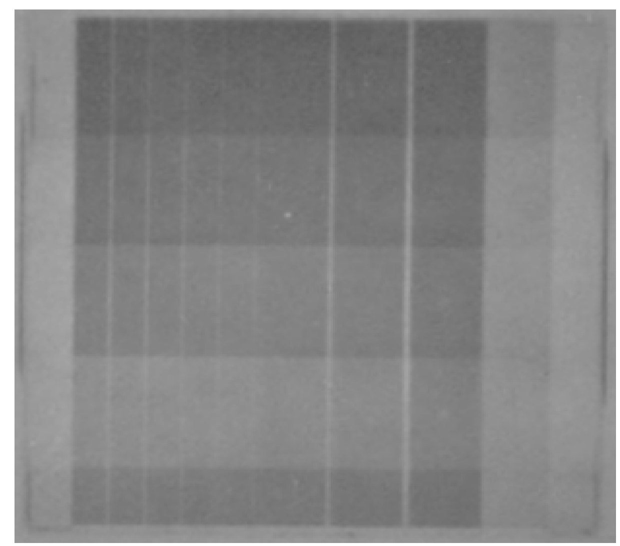
➔ 전자쌍생성(Pair Production)

Neutron Sensitivity Indicator



Sensitivity Indicator

- 관찰 가능한 가장 작은 구멍 크기(H)
- 관찰 가능한 가장 작은 간격 (G)



Neutron Imaging

Evaluation of Neutron Beam Quality

Optical Density

$$OD = log_{10}\left(\frac{I_o}{I}\right)$$

$$I_o = incident\ optical\ intensity$$
$$I = transmitted\ optical\ intensity$$

2 = 1 %, 3 = 0.1%

Neutron content (NC)

$$NC = \frac{D_H - (higher\ D_B + \Delta D_L)}{D_H} \times 100$$

Scattered neutron content (S)

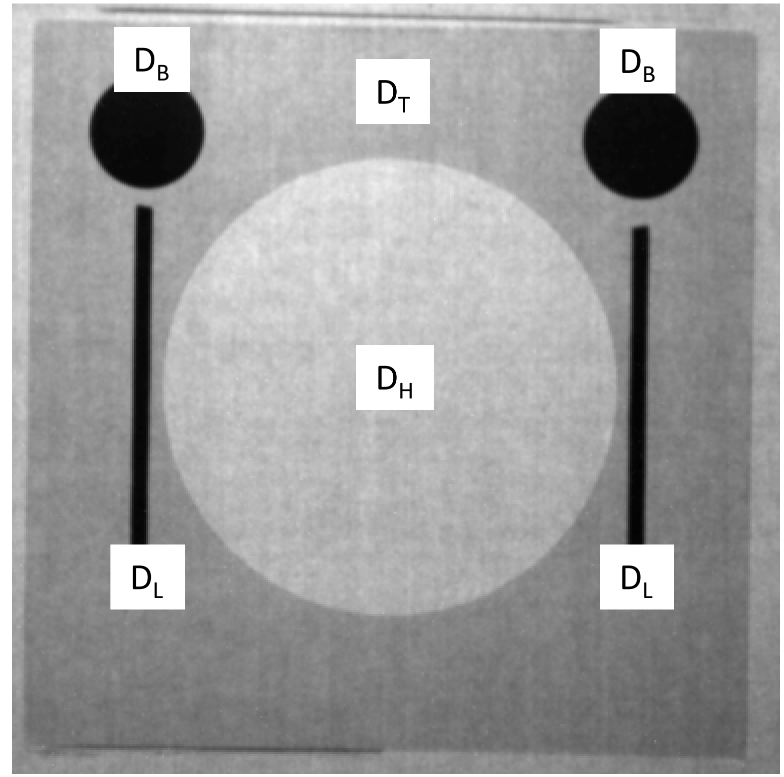
$$S = \left(\frac{\Delta D_B}{D_H}\right) \times 100$$

Gamma content (γ)

$$\gamma = (D_T - lower\ D_L)/D_H \times 100$$

Pair production content (P)

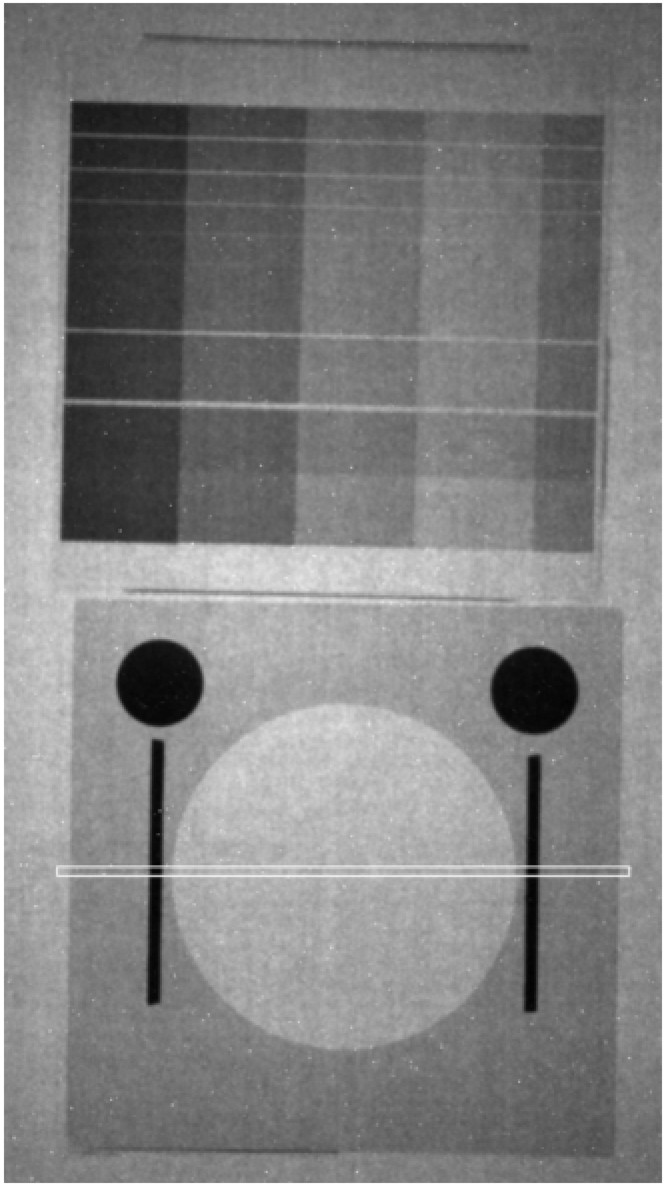
$$P = \left(\frac{\Delta D_L}{D_H}\right) \times 100$$

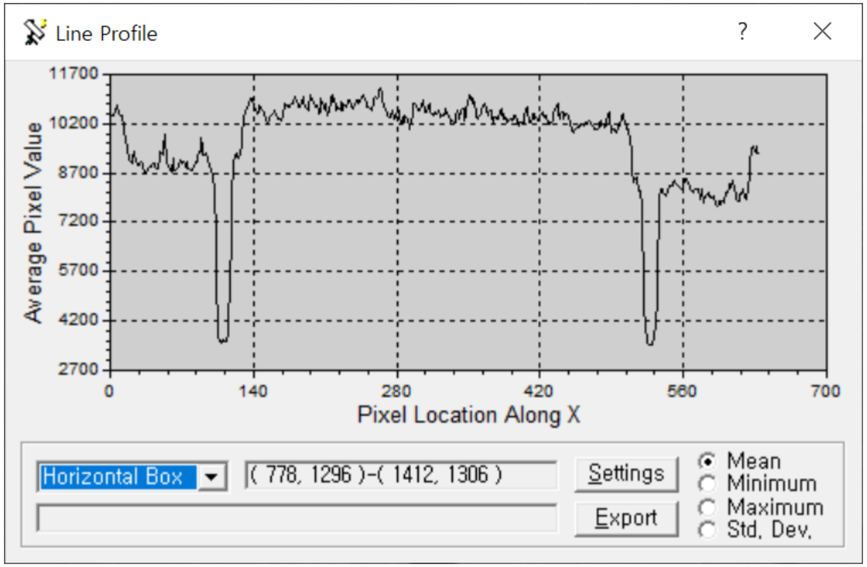


Category	NC	H	G	S	γ	P
I	65	6	6	5	3	3
II	60	6	6	6	4	4
III	55	5	5	7	5	5
IV	50	4	5	8	6	6
V	45	3	5	9	7	7

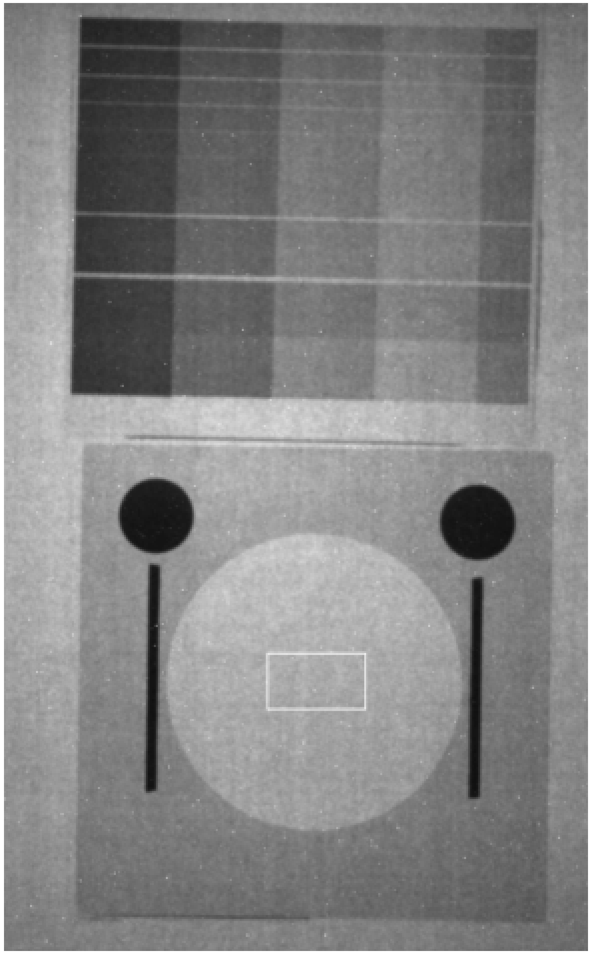
Need to converting as a film

Evaluation of Neutron Beam Quality





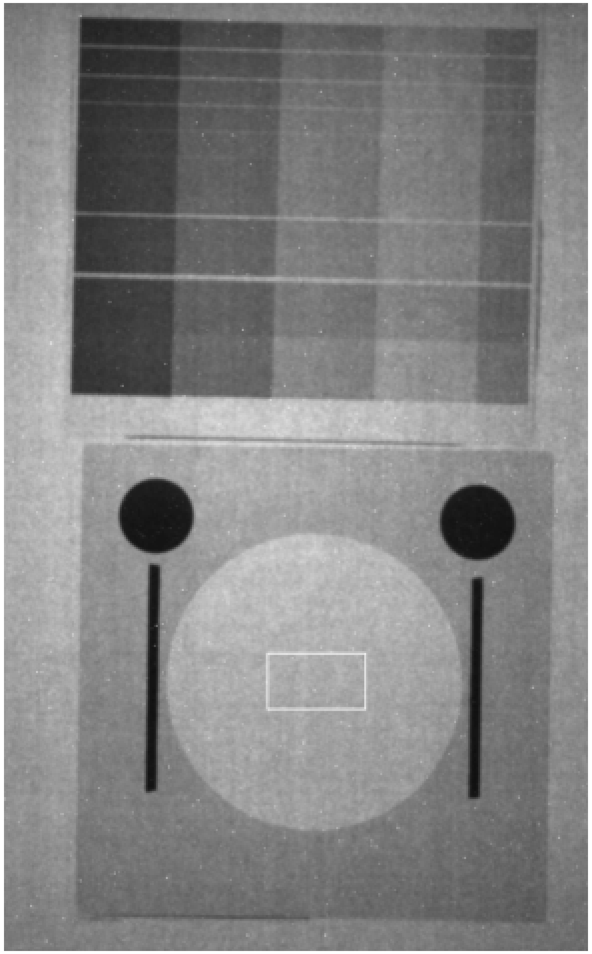
Evaluation of Neutron Beam Quality



d : 5 cm, L = 313 cm			
HDPE (mm)	Time (s)	Average Intensity	Neutron Flux ($n/cm^2 \cdot s$)
0	**1**	10,570	**~10^7**
0	**2**	18,500	
0	**3**	26,700	
0	**4**	35,000	
0	**5**	43,100	
0	**6**	51,200	

$$I = 8150*t + 2320$$

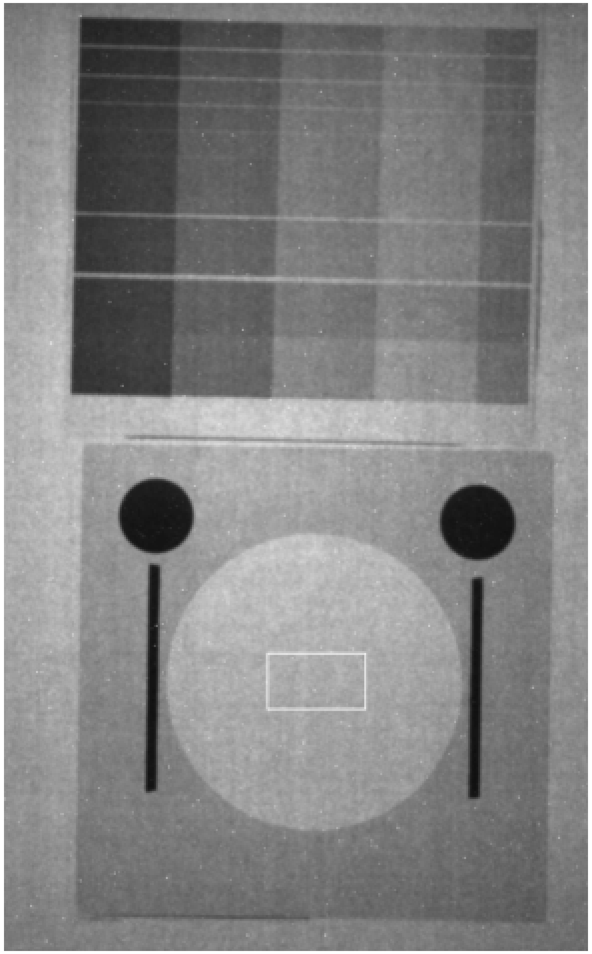
Evaluation of Neutron Beam Quality



d : 5 cm, L = 313 cm			
HDPE (mm)	Time (s)	Average Intensity	Neutron Flux ($n/cm^2 \cdot s$)
5	**60**	31,600	**6×10^5**
5	**90**	47,800	
5	**100**	52,400	

$I = 524 * t + 215$

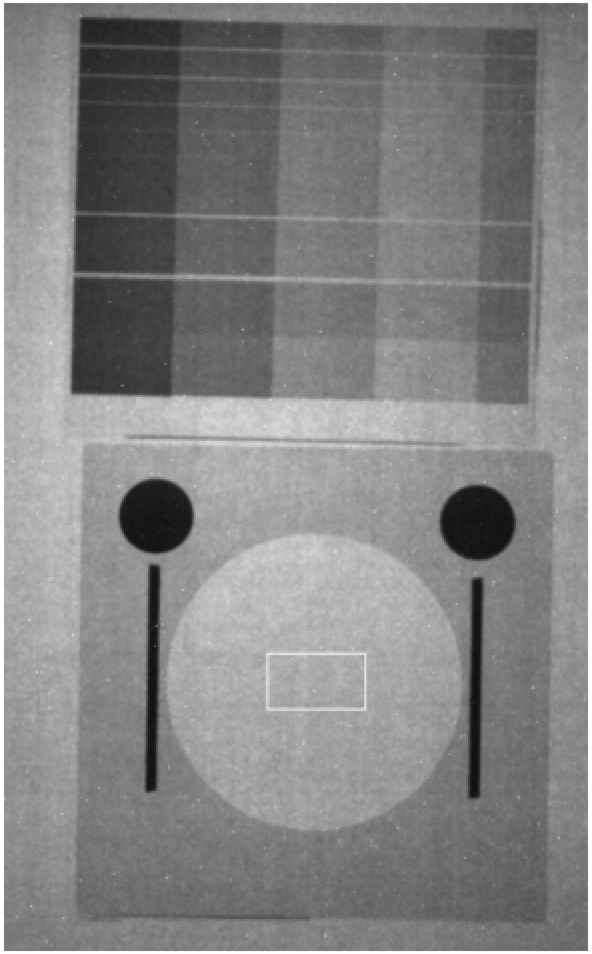
Evaluation of Neutron Beam Quality



d : 5 cm, L = 313 cm			
HDPE (mm)	Time (s)	Average Intensity	Neutron Flux ($n/cm^2 \cdot s$)
10	**60**	5,740	**$6x10^4$**
10	**600**	38,500	

$$I = 56*t + 2400$$

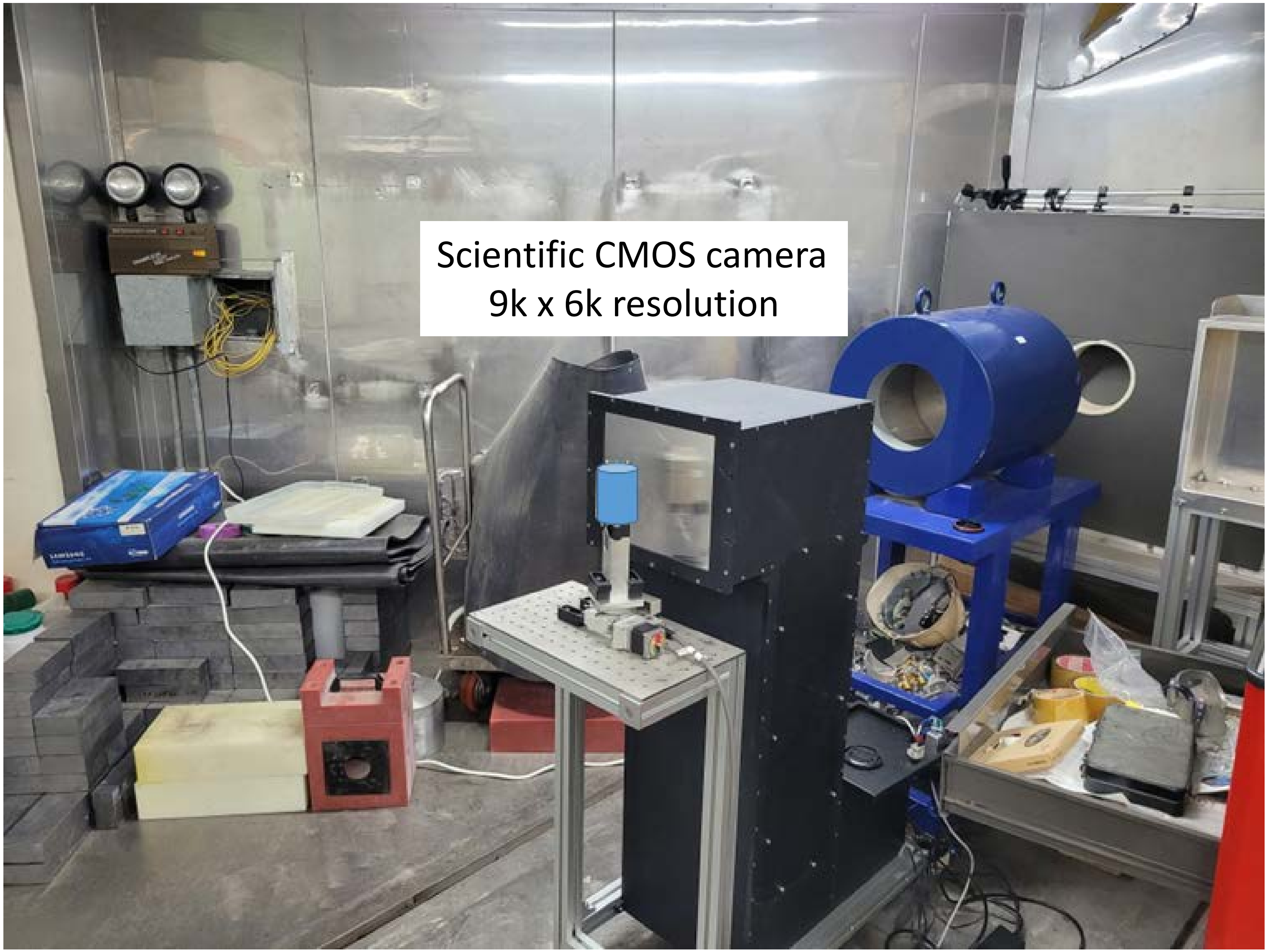
Evaluation of Neutron Beam Quality



d : 5 cm, L = 313 cm			
HDPE (mm)	Time (s)	Average Intensity	Neutron Flux ($n/cm^2 \cdot s$)
15	**3600**	47500	~10^4
15	**3600**	48000	

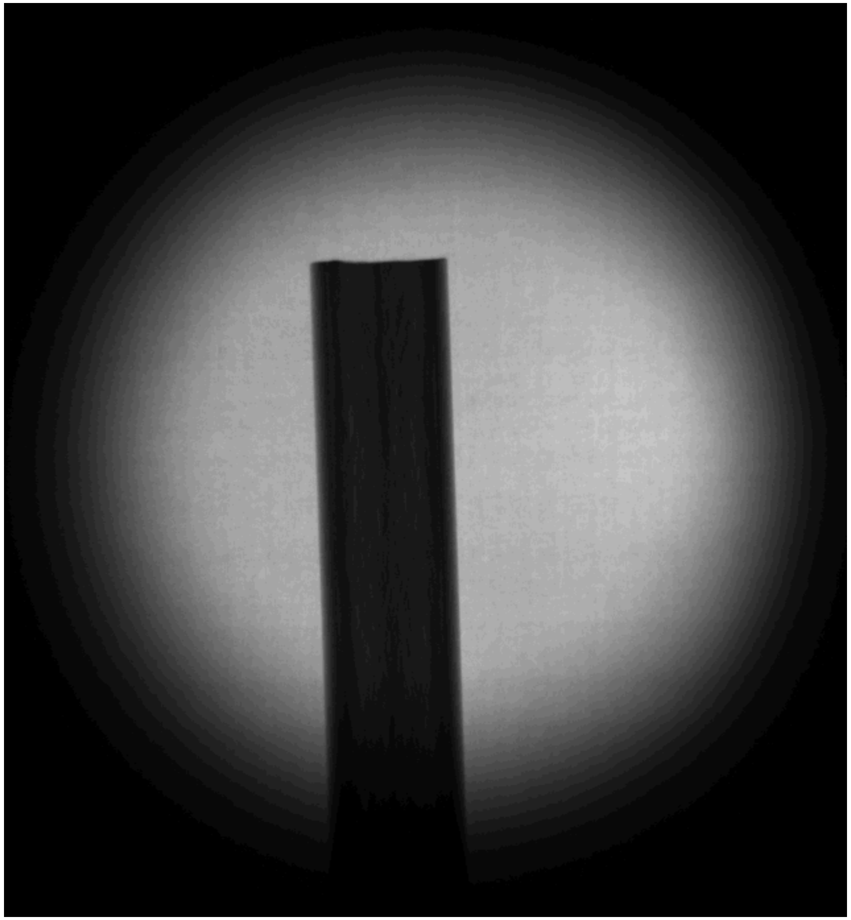
I = *t + 7946

New Neutron Camera



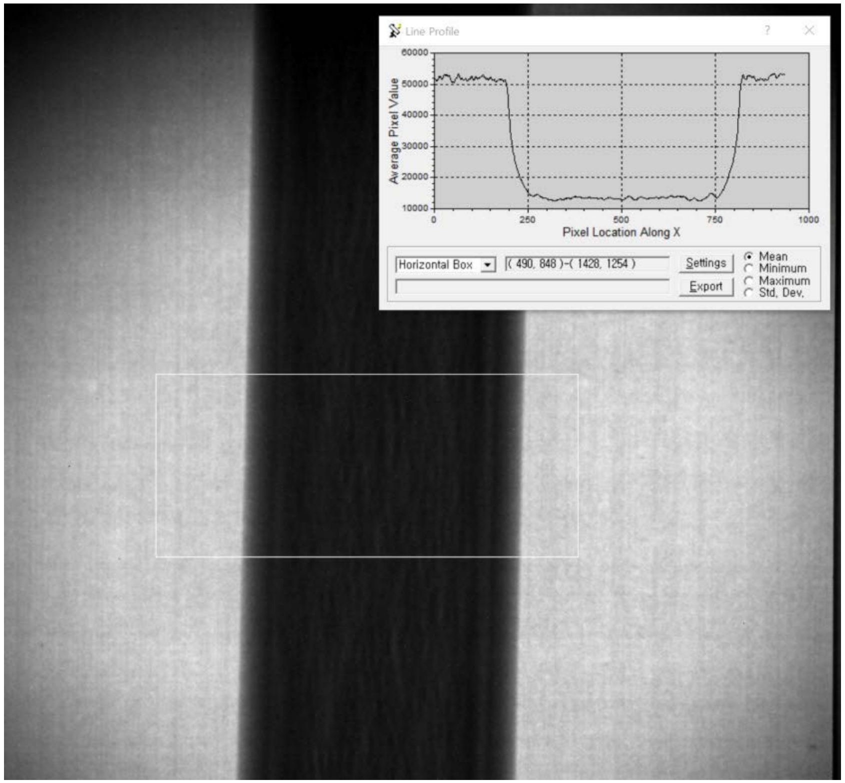
Neutron Imaging Characteristics

KSTAR CICC
CICC : Cable-In-Conduit Conductor

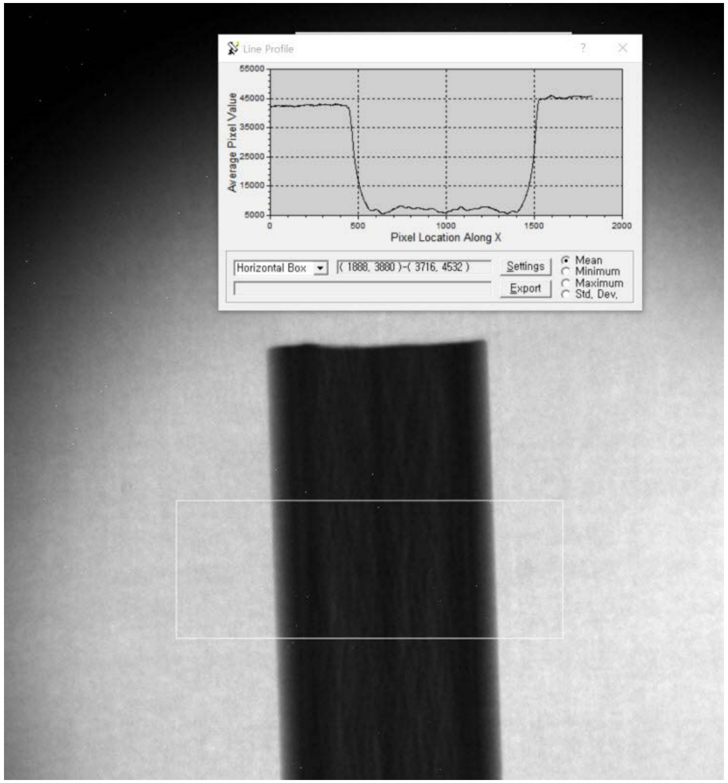


Neutron Imaging

Neutron Imaging Characteristics

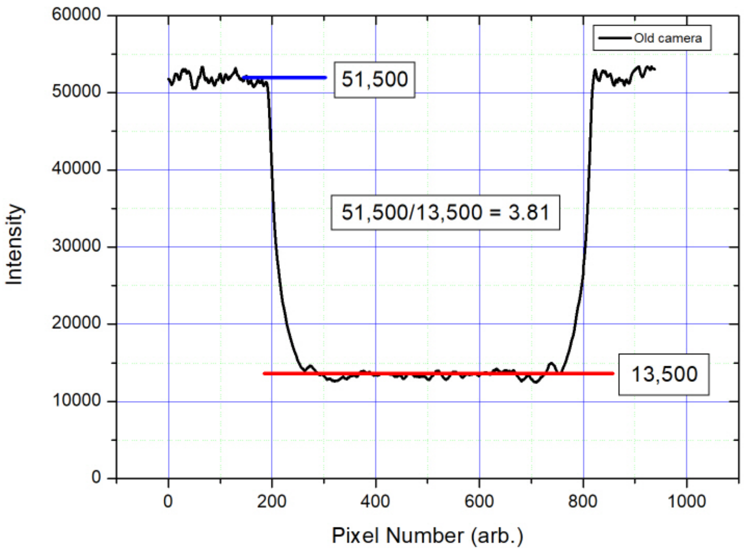


Old Camera

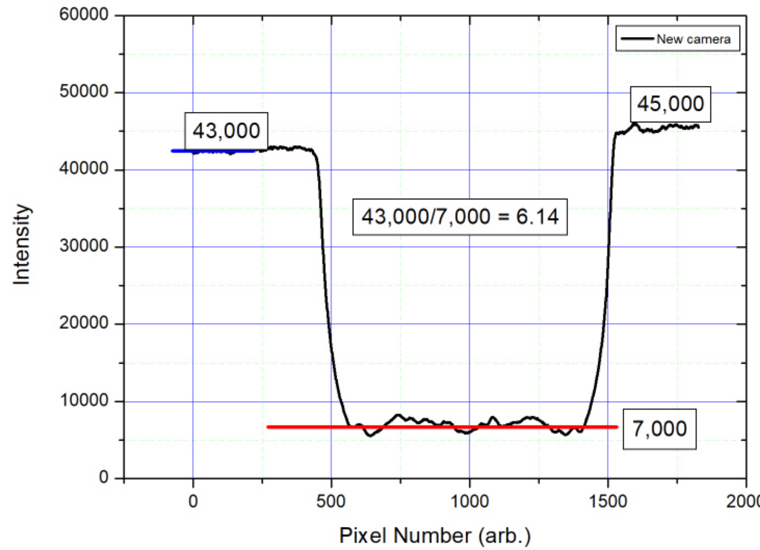


New Camera

Neutron Imaging Characteristics



Old Camera



New Camera

Conclusion & Future Works

- **Low-flux neutron environments at HANARO**
  - **Implementation with HDPE thickness and aperture adjustment**
  - **Flux range 10^3 ~ 10^6 n/cm^2s**
- **Low-flux neutron beam (< 10^5 n/cm^2s)**
  - **Long measurement time → Number of Images in a day (how many?)**
  - **Poor image quality → Real application (submillimeter resolution needed)**
- **Neutron camera upgrade**
  - **Image contrast enhancement**
- **Alternative neutron sources are needed**
  - **Wide neutron energy applications**