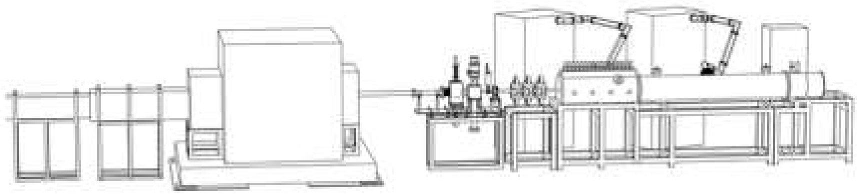
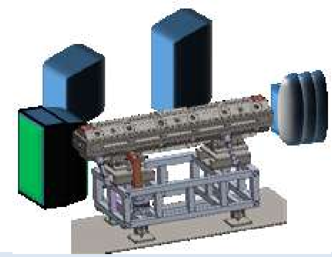
RIKEN Accelerator-driven Compact Neutron Source, RANS and Neutron Application





30 May ISINN2018 @Xi'an

RANS-RIKEN Accelerator-driven compact Neutron Source

Yoshie OTAKE大竹淑恵 Riken center for advanced Photonics(RAP), **RIKEN**
Neutron beam team technology Team RIKEN yotake@riken.jp

A.Taketani, H.Sunaga, T.Kobayashi, M.Takamura, Y.Ikeda, Y.Wakabayashi, T.Hakoyama
Y.Yoshimura, M.Mizuta, T.Hashiguchi (RAP) N.Hayashizaki (TITECH), et al

★Yoshie Otake, et al.:“ Research and Development of a Non-destructive Inspection Technique with a Compact Neutron Source“ Journal of Disaster Research Vol.12, No.3(2017) pp.585-592doi: 10.20965/jdr.2017.p0585

★Y.OTAKE, eds. Uesaka, M. and Kobayashi, H.: **Compact Neutron Sources for Energy and Security, Reviews of Accelerator-Science and Technology** ‘Accelerator Applications in Energy and Security’, Vol.08, pp.196-198, 2015, world scientific,

Accelerator-driven Compact neutron source

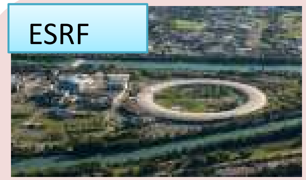
Large facilities

Neutron

?

D-D, D-T $10^{9} n s^{-1}$

Compact source
On-site



Large facilities

Complementary

X-ray

Compact, on-site

- In Europe, there have been many small size reactors, while in Japan only large-size, JAEA, or medium size, Kyoto Univ. Reactor have existed.
- Some companies use European neutron sources.

- Development of the neutron sources for practical use, for example, industrial use, it is necessary.

- First step, development of a compact source with 10^{12} n s^{-1} based on the Hokkaido University compact neutron source (HUNS, since 1974- electron linac)

Compact neutron **system** for **practical use** !

neutrons, anytime, anywhere

R&D

compact neutron source

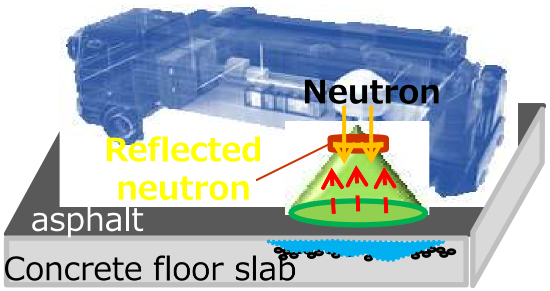
Instruments design, analytical methods especially with CANS should be based on user's strong requirements

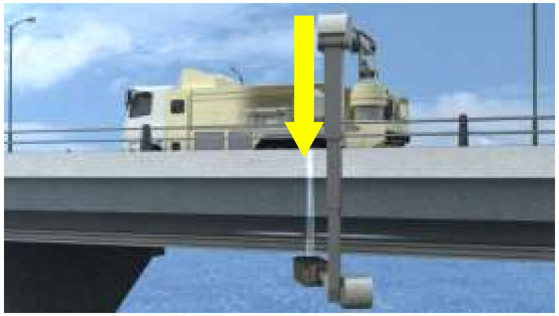
RANS project goals：CANS for practical use

Li target

- Non-destructive inspection of large scale infrastructures on-site, outdoor.

Fast neutron large area imaging system

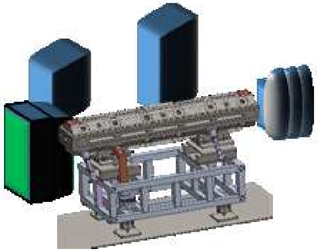




- Compact neutron source system easy to use on site

–floor-standing type

– industrial use,
  - non-destructive inspection
  - industrial material development analysis,



RAP

Proton nuclear reaction for compact N source

2011started. 2012 construction
Main members

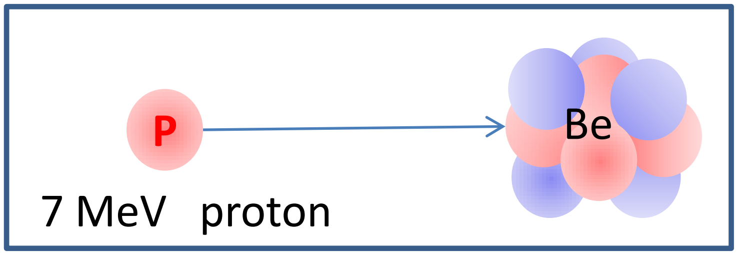
1.Compact system including shielding-> proton linac

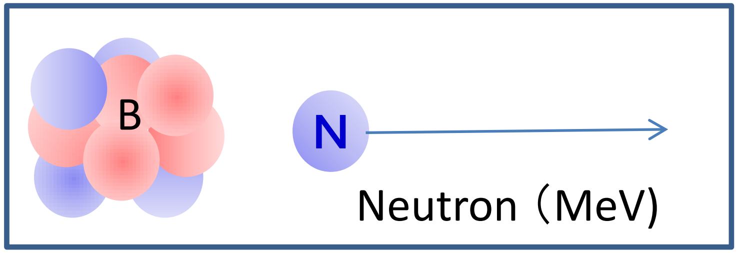
Be(p,n) nuclear reaction

7MeV proton

Be (p,n)reaction

- Neutron flux ~10^{12}/sec@7MeV,　100μA(max)





2.compact and low cost

proton linac: in our case less than <2億円=2*10^8 yen=2 million US$

shielding design

Multilayer shielding of target station

7MeV、100μA、Rf power supply.:　350kW(peak) duty 1.3%,Electric power peak　40kVA, Cooling water：75L/min ,**pulse width** (**30～200μs**)repetition frequency～**20～180Hz** RF power　425MHz, Injection energy0.030-3.5MeV

RANS: R&D schedule from 2011-

- 2011 start a compact neutron source project
- (3 years project, Y.Yamagata (TL), Otake (DTL), Sheng Wang, K Hirota)
- 2012 RANS construction (PL-7 arrived 28 March 2012)
- 2013Jan. Neutron production
- 2013April－open to collaborators (N. team starts)
- 2014 Summer, construction Neutron building
- 2015 Jan- RANS relocation from RIBF to Neutron building
- 2016 Jan. Restart of RANS
- 2017 Up-grade,

1. PE decoupled, 3 coupled moderators,
2. proton beam wire monitors. Proton tube, and detector position

- 2018 Cold source operation (2 weeks each 2 months)

RANS

1.Compact system

Be (p,n)reaction: Be long life target (Dr. Y.Yamagata)

•Neutron flux ~10^{12}/sec@7MeV, 100μA(max)

- 7MeV
- 100 μA maximum averaged current
- 10-180μs pulse width of proton
- 20-180Hz repetition rate of proton

RANS development schedule
2011start
2012 construction
2013Jan Neutron production
2013April－open to collaborators
2017 Up-grade, moderators, proton beam monitors
2018 Cold source

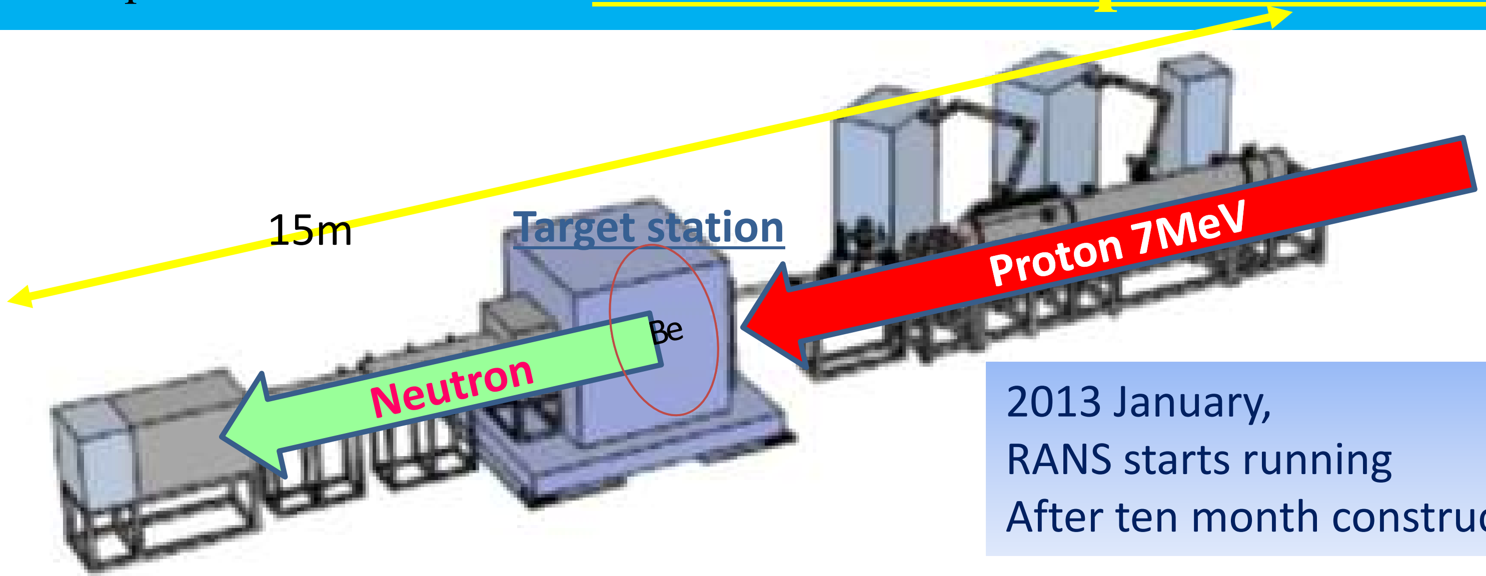
2.compact and low cost

proton linac: in our case less than <2億円=2*10^8 yen=2 million US$

shielding design Multilayer shielding of target station

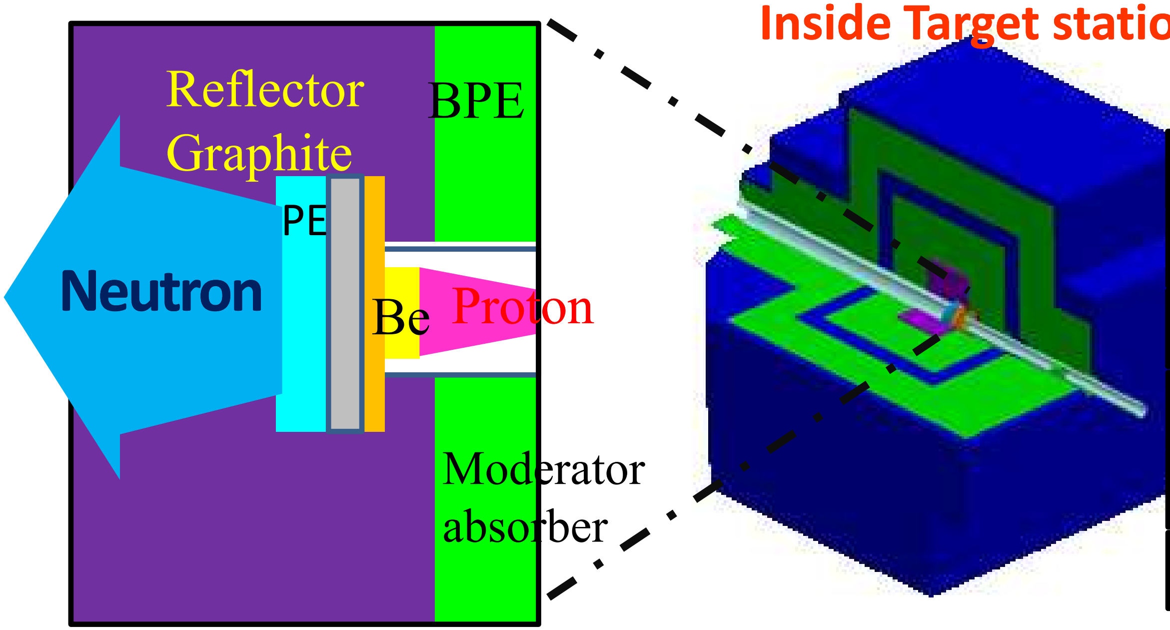
7MeV、100μA、Rf power supply.: 350kW(peak) duty 1.3%,Electric power peak 40kVA, Cooling water : 75L/min ,**pulse width** (**30～200μs**)repetition frequency～**20～180Hz** RF power 425MHz, Injection energy0.030-3.5MeV

RANS compact Neutron source for realization of practical use



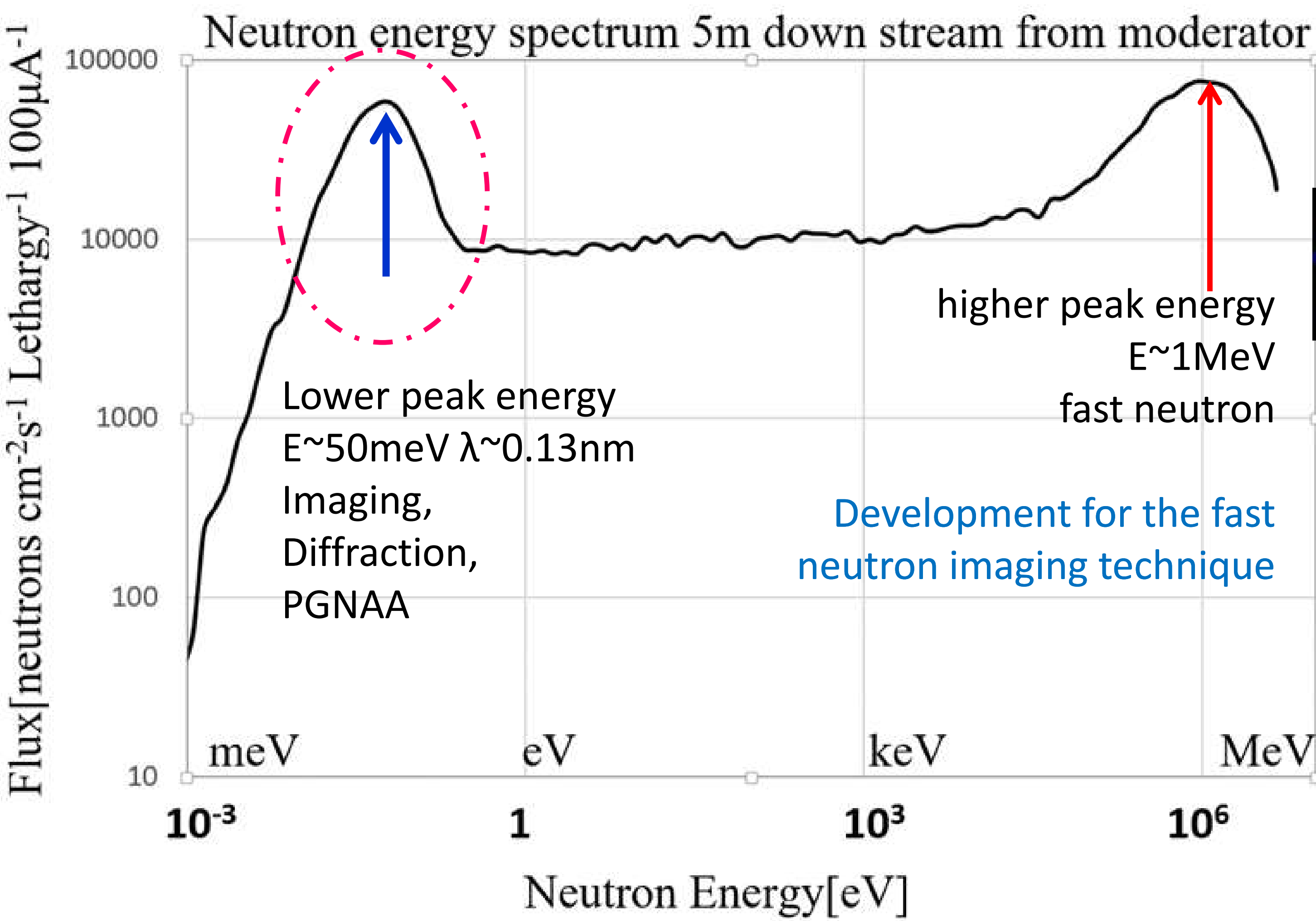
2013 January,
RANS starts running
After ten month construction.

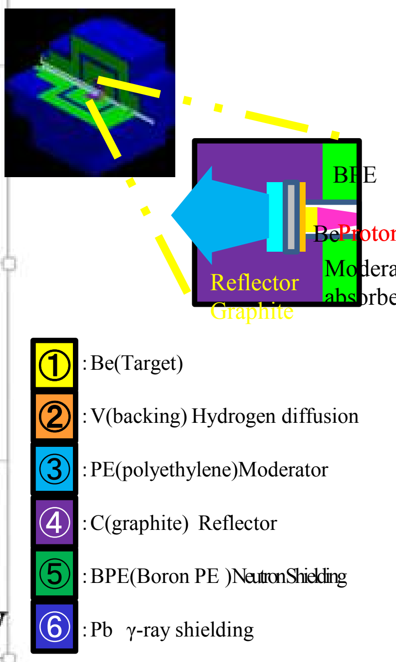
Inside Target station



① : Be(Target)
② : V(backing) Hydrogen diffusion
③ : PE(polyethylene)Moderator
④ : C(graphite) Reflector
⑤ : BPE(Boron PE)Neutron Shielding
⑥ : Pb γ-ray shielding

RANS Neutron spectrum (GEANT 4, new formalism)

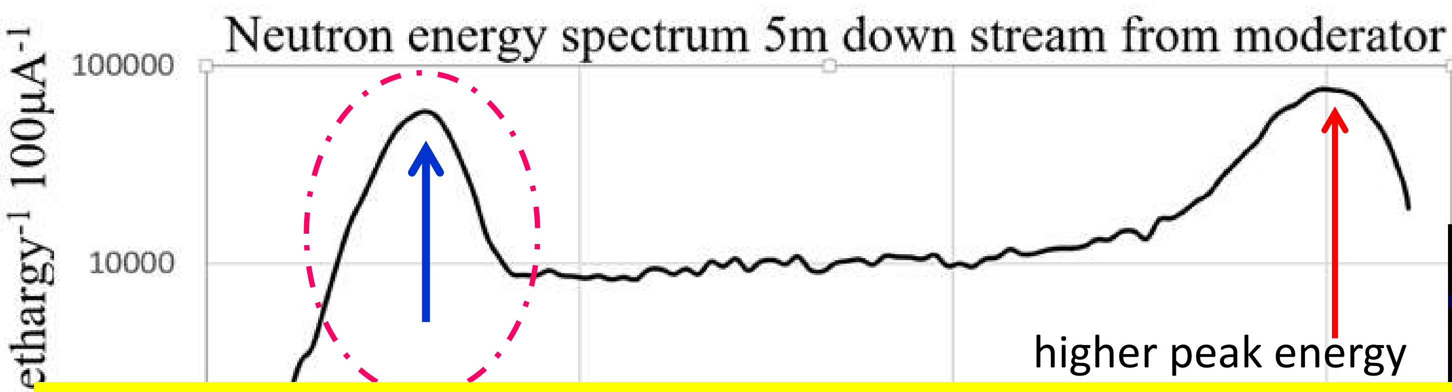


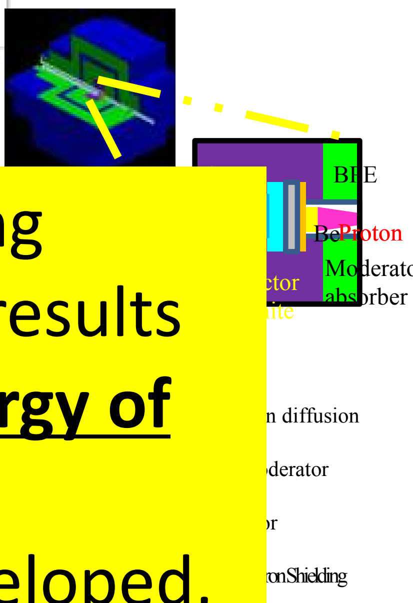



7MeV proton
Be
Neutron

RANS Neutron spectrum (GEANT 4)

Y. Wakabayashi et ail., A function to provide neutron spectrum produced from the 9Be + p reaction with protons of energy below 12 MeV **J. of Nucl. Sc. and Tech. https://doi.org.10.1080/00223131.2018.1445566**





The measured neutron spectrum, and shielding effects at RANS **do not agree with** any of MC results

->**Lack of the nuclear data for Be(p,n), Energy of proton below ＊100MeV.**

New formalism for neutron spectrum has developed, Ep<12MeV.

-> This result we have obtained.

For accurate neutron spectrum

A function to provide neutron spectrum produced from the 9Be + p reaction with protons of energy below 12 MeV

Y.Wakabayashi et al. J. of Nucl. Sc. and Tech. https://doi.org.10.1080/00223131.2018.1445566

JOURNAL OF NUCLEAR SCIENCE AND TECHNOLOGY, 2018
https://doi.org/10.1080/00223131.2018.1445566
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ARTICLE

Check for updates

A function to provide neutron spectrum produced from the ^{9}Be + p reaction with protons of energy below 12 MeV

Yasuo Wakabayashi[a], Atsushi Taketani[a], Takao Hashiguchi[a], Yoshimasa Ikeda[a], Tomohiro Kobayashi[a], Sheng Wang[b], Mingfei Yan[b], Masahide Harada[c], Yujiro Ikeda[a,c] and Yoshie Otake[a]

[a]RIKEN Center for Advanced Photonics, RIKEN, Wako, Saitama, Japan; [b]School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi, China; [c]J-PARC Center, Japan Atomic Energy Agency, Naka-gun, Ibaraki, Japan

ABSTRACT
A function to give the total neutron production cross section, angular distribution, and energy spectrum via the ^{9}Be + p reaction has been created by fitting experimental data to characterize compact neutron sources with thick Be targets bombarded by protons with energy below 12 MeV. To examine the suitability of the function, calculations of the angle-dependent neutron energy spectra produced in thick Be targets with 4- and 12-MeV protons using the function were compared with corresponding experiments and calculations using the nuclear data libraries of ENDF/B-VII.0 and JENDL4.0/HE. The function was in better agreement with the experiments than the calculations using the libraries except for at backward angles. The ^{115}In(n,n')^{115m}In reaction rates calculated using GEANT4 with source neutrons given by both the function and ENDF/B-VII.0 were compared with that measured at the RIKEN Accelerator-Driven Compact Neutron Source to evaluate the neutron spectrum above 1 MeV. The function slightly overestimated the measurement by 14% and the calculation with ENDF/B-VII.0 underestimated by 35%. It was concluded that the function can be applied in compact neutron source designs.

ARTICLE HISTORY
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Accepted 20 February 2018

KEYWORDS
Compact neutron source; neutron spectrum; cross section; angular distribution; nuclear data; calculation; simulation

RAP

New Formulation of neutron, Be(p,n)B to give more accurate neutron spectrum

RIKEN
RIKEN Center for Advanced Photonics (RAP)
Neutron Beam Technology Team

Yasuo Wakabayashi

Collaborators
A. Taketani[1)], Y. Ikeda[1)], T. Hashiguchi[1)], T. Kobayashi[1)], S. Wang[2)], Y. Mingfei[2)], M. Harada[1)], Y. Ikeda[1,3)], Y. Otake[1)]

[1]RIKEN Center for Advanced Photonics
[2]Xi'an Jiaotong University
[3]J-PARC Center, Japan Atomic Energy Agency

This work was condensed in
Y. Wakabayashi, et al.,
"A function to provide neutron spectrum produced from the 9Be + p reaction with protons of energy below 12 MeV"
Journal of Nuclear Science and Technology, (2018), online
doi: 10.1080/00223131.2018.1445566

Background

Neutron production by the p-Be reaction：present problems

It is one of fundamental issues to have reliable data
to simulate neutron source characteristics for compact neutron sources.
There is little experiments of angular distribution and energy spectrum for the p-Be with low energy proton.
How should we solve this problem for RANS and compact neutron sources with $^{9}Be+p$?

①Nuclear models in simulation codes (GEANT4, MCNP, PHITS) → Not proper in low energy particles.

②Interpolate (or extrapolate) the available experimental data → Large uncertainty remain.

③Simulation with nuclear data library (JENDL, ENDF etc.) → Different results between nuclear data library

Purpose

Need more reliable estimation results for neutron spectrum in the p-Be reaction

It is needed to have more accurate and reliable simulated neutron spectrum for the $^{9}Be+p$ reaction,
for designing the target station and shield, and improvement of RANS and next compact neutron sources.

✓<u>We select to prepare a reliable source by ourselves</u>
How do we prepare the source?
→ Make a function dedicating to calculate the neutron spectrum of the p-Be reaction
for compact neutron sources with low energy proton.

→ The function incorporate neutron yield, angular distribution, and energy spectrum,
according to incident proton energies and target thickness as input parameters.

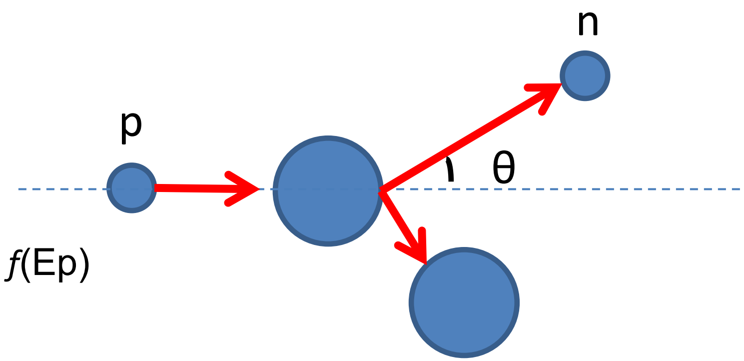
Method

Model to make original function in p-Be reaction

・Thick target is sum of thin target.

・Make the function to reproduce the experimental values of neutron spectrum
(total cross section, angular distribution, and energy spectrum) using thin Be target.

・Use EXFOR [4] and ENSDF [5] to search available experiments.



Steps to make the function

①Total cross section (σ(Ep))

Make a function following incident proton energy "Ep" --- σ(Ep) = *f*(Ep)

↓ Get total cross section σ(Ep) with certain "Ep"

②Angular distribution (dσ(θ, Ep) θ: scattering angle)

Make a function following "Ep" using σ(Ep) --- dσ(θ, Ep) = σ(Ep) x *f*(θ,Ep)

↓ Get dσ(θ) with certain "Ep"

③Energy spectrum (dσ(En, θ, Ep))

Maximum outgoing neutron energy (En_max) is determined from kinematics at certain "Ep" and "θ".

Make a function following "En_max" using dσ(θ, Ep) --- dσ(En, θ, Ep) = dσ(θ, Ep) x *f*(En, En_max(θ, Ep))

↓ Get En with certain "Ep" and "θ"

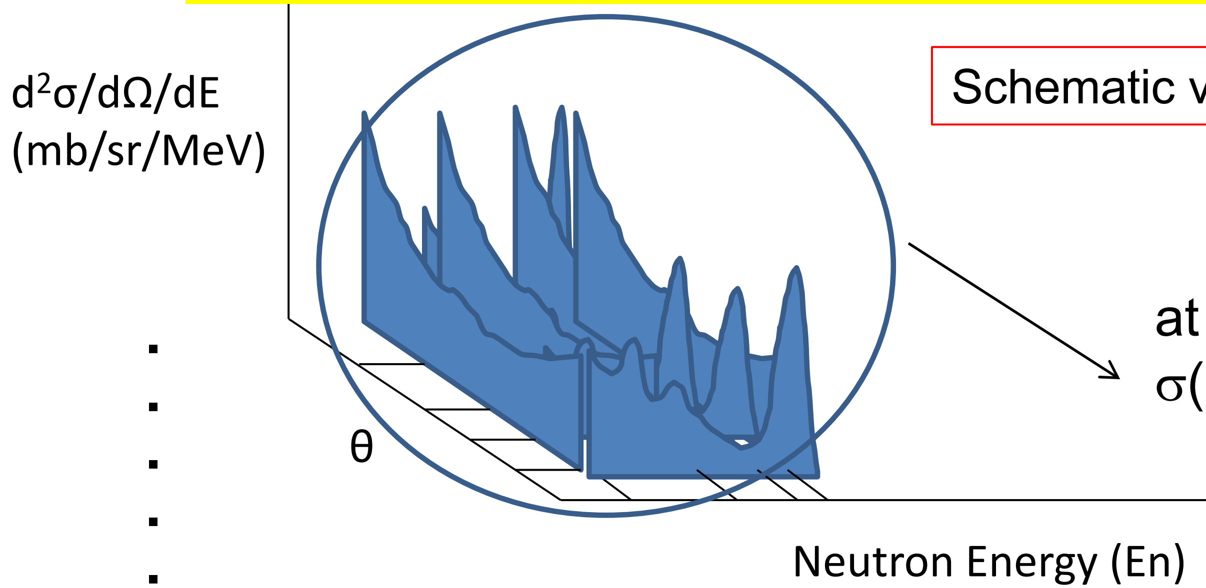
"Ep" proton energy ⇒ neutron spectrum (①～③) is obtained.

[4] http://www.nndc.bnl.gov/exfor/exfor.htm
[5] http://www.nndc.bnl.gov/ensdf/

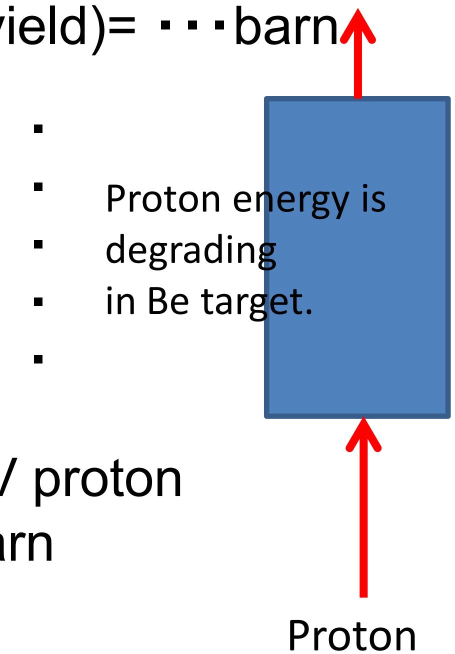
Method

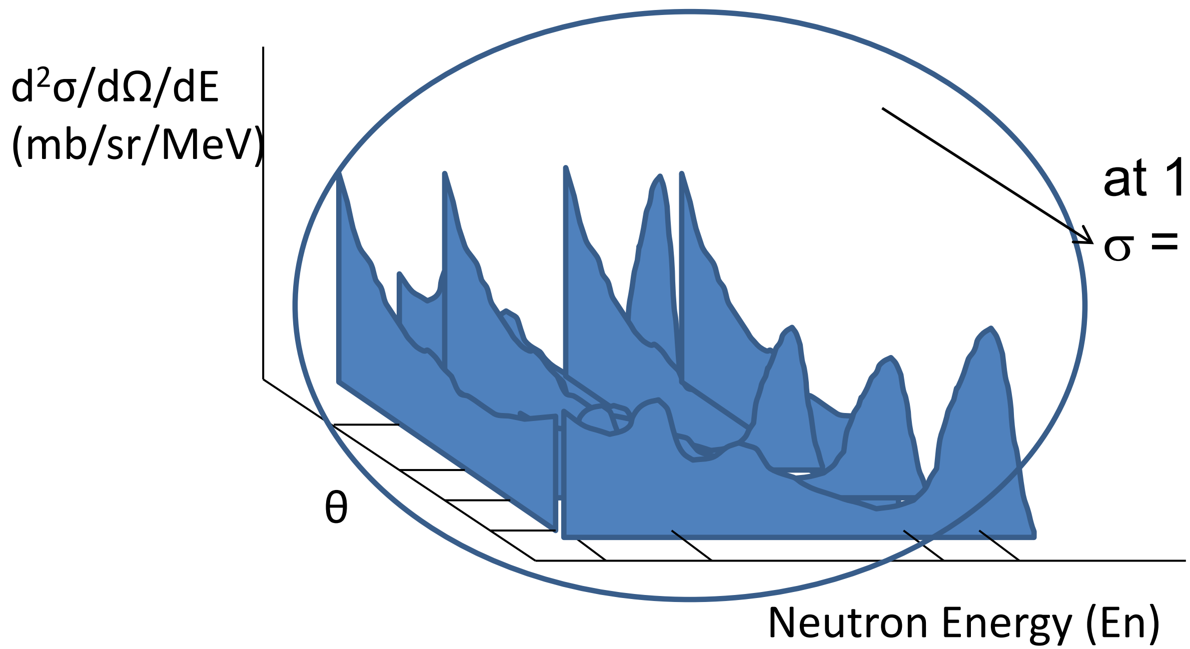
Model to make original function in p-Be reaction

Schematic view of σ, θ, En



at 4 MeV proton
σ(Total yield)= ･･･barn



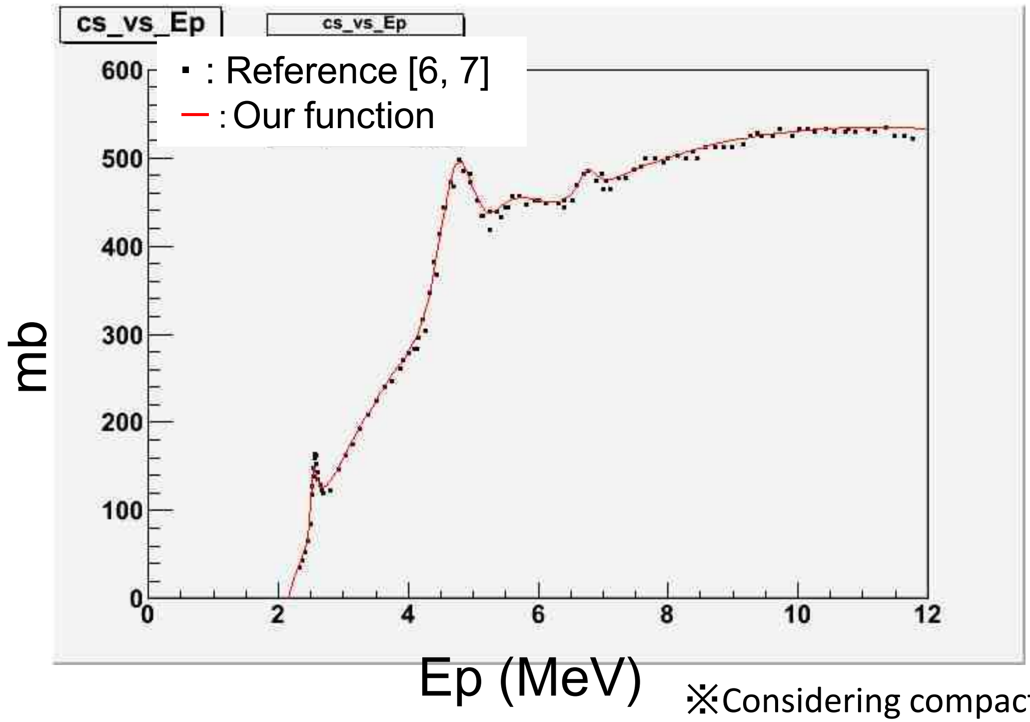


at 12 MeV proton
σ = ･･･barn

By adding them,
neutron spectrum in the target
is obtained.

1st step **Total cross section**

New formalism p-Be: comparison with existing data



[6] J.H.Gibbons and R.L.Macklin, PR114, 571 (1959)
Ep = 2.33 ～ 5.42MeV

[7] J.K.Bair et al., NP53, 209 (1964)
Ep = 3.92 ～ 12MeV

※Since values in Ref.[6] are given by "arb. unit"
they are plotted to be a peak around 4.56 MeV in Ref.[5].

※Considering compact neutron source and available data,
original function is made to reproduce the data less than Ep=12MeV.

Total Cross section (TCS [mb])
Fit by incident proton energy "Ep [MeV]"

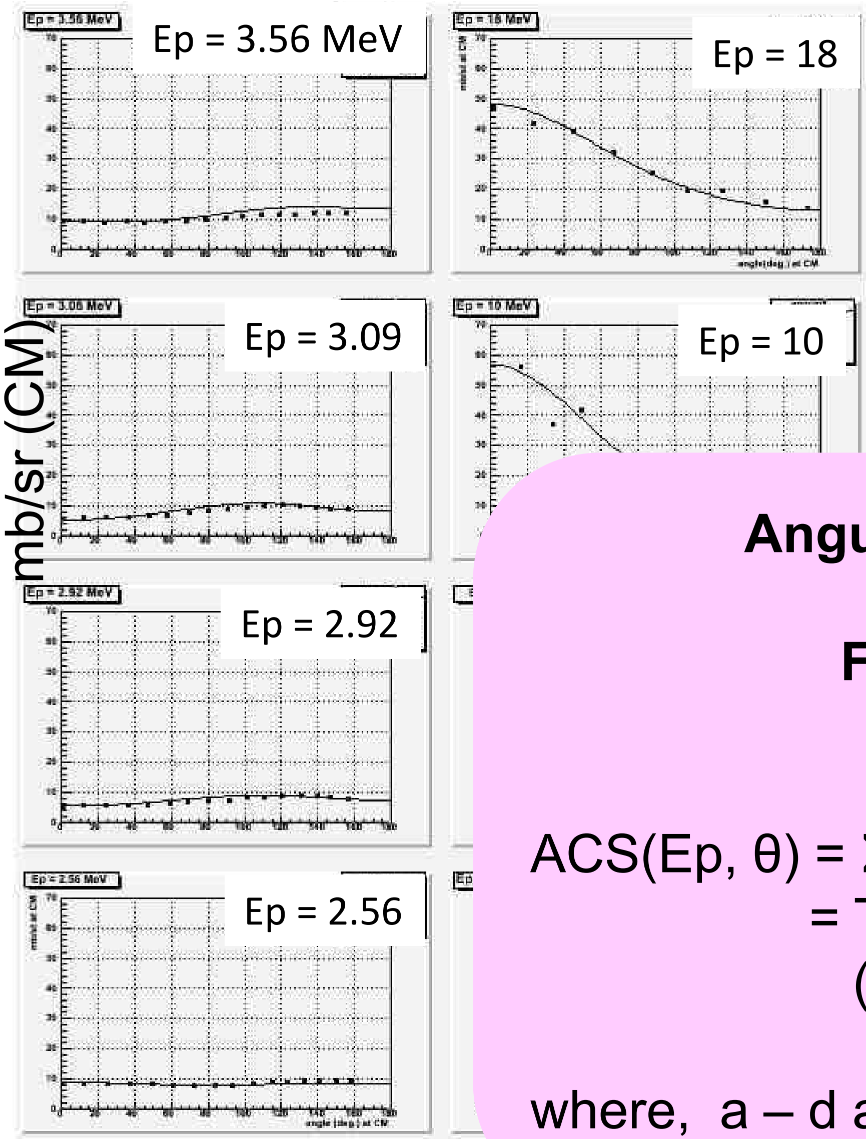
$$TCS(Ep) = [a]*Ep^{[b]} \times \exp(-[c]*Ep) \times \ln(Ep - [d]) + \text{Breit-Wigner(1peak)} + \text{Gaussian(3peaks)}$$

where, [a] – [d] are Constant.

2nd step

Angular distribution

New formalism via p-Be : Comparison with existing data



・: References [8～11]

ー : Our function

[8] J.B.Marion et al, PR103, 713 (1956) Ep : 2.56～4.56 MeV

[9] R.W.Bauer et al., NP56, 117 (1964) Ep : 6.3 & 7.4 MeV

[10] Y. Iwamoto et al., NIMA598, 687 (2009) Ep : 10 MeV

[11] V.V.Verbinski et al., PR177, 1671 (1969) Ep : 18 MeV

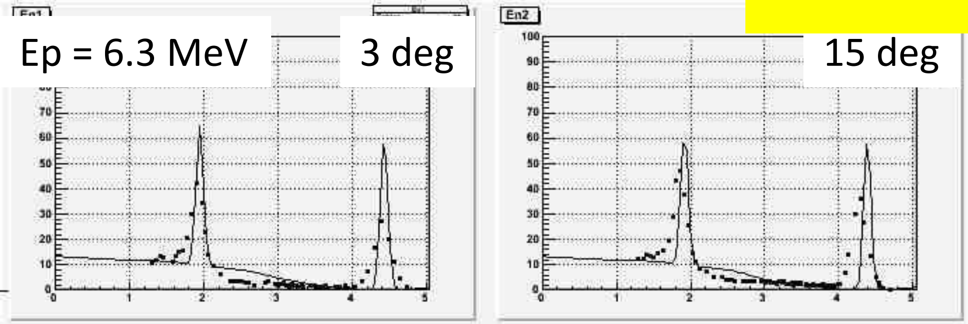
Angular distribution (ACS [mb/sr])
At certain ”Ep”,
Fit by scattering angle “θ ”

$$ACS(Ep, \theta) = \Sigma A_j P_j(\cos\theta)$$
$$= TCS(Ep) \times C \times (a + b(\cos\theta) + c(\cos\theta)^2 + d(\cos\theta)^3)$$

where, a – d are the function of “Ep”
and C is normalization factor to be TCS.

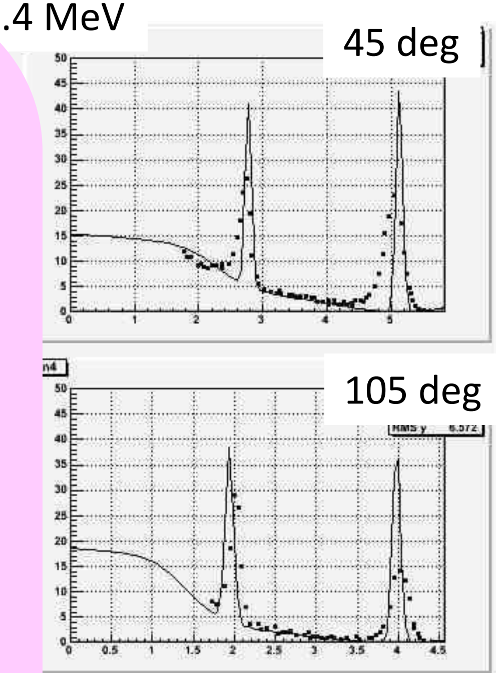
3rd step | Energy spectrum

New formalism, p-Be: Comparison with existing data



▪ : References [9, 10]

— : Our function ver.1



) is obtained from kinematics.

Energy spectrum (ECS [mb/MeV/sr])
At certain "Ep" and "θ"
Fit by "En"

ECS(Ep, θ)
= Continuum part
+ transition to ground state, 1st Ex, and 2nd Ex in ^{9}B

$$= ACS(E_p,\theta) \times \{ ([1] / (1+\exp[(E_n-[2])/[3]]) + [4]*\log(([5] - E_n)^{2}+1)) / (1 + \exp[(E_n - E_{n\_max})/0.001]) + [6]*\exp[-(E_n - [7])^{2}/([8]^{2})] + [9]*\exp[-(E_n - [10])^{2}/([11]^{2})] + [12]*\exp[-(E_n - [13])^{2}/([14]^{2})] \}$$

where, [1] – [14] are the function of "Ep"

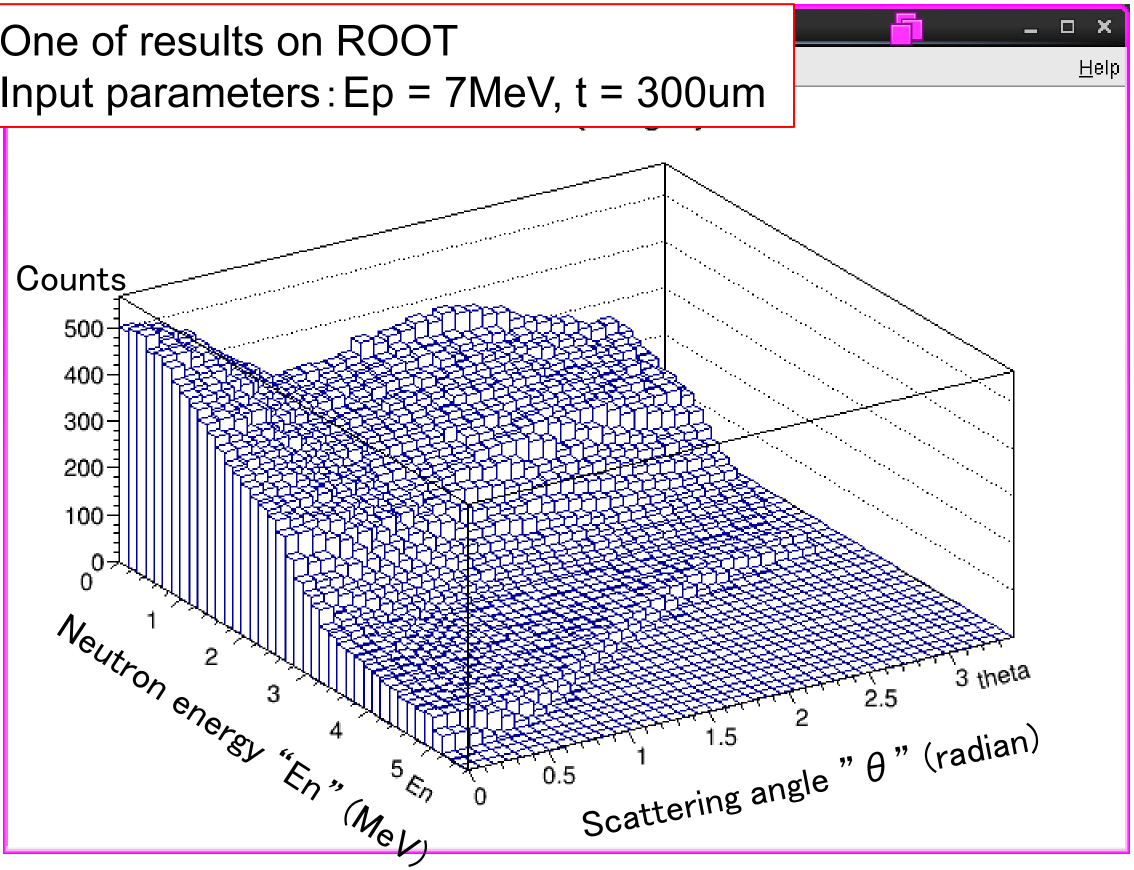
Calculation code with our formalism

neutron spectrum with thin and/ or thick target p-Be:

Make the code with C++ which work on ROOT software

①Input parameters are "Incident proton energy (Ep)" and "Be target thickness (t)"
②Energy loss (dE/dx) in Be target is calculated by SRIM code
③Monte-Carlo simulation using our function

One of results on ROOT
Input parameters : Ep = 7MeV, t = 300um



Proton energy
+
Be target thickness

↓

dE/dx by SRIM code (In Be)

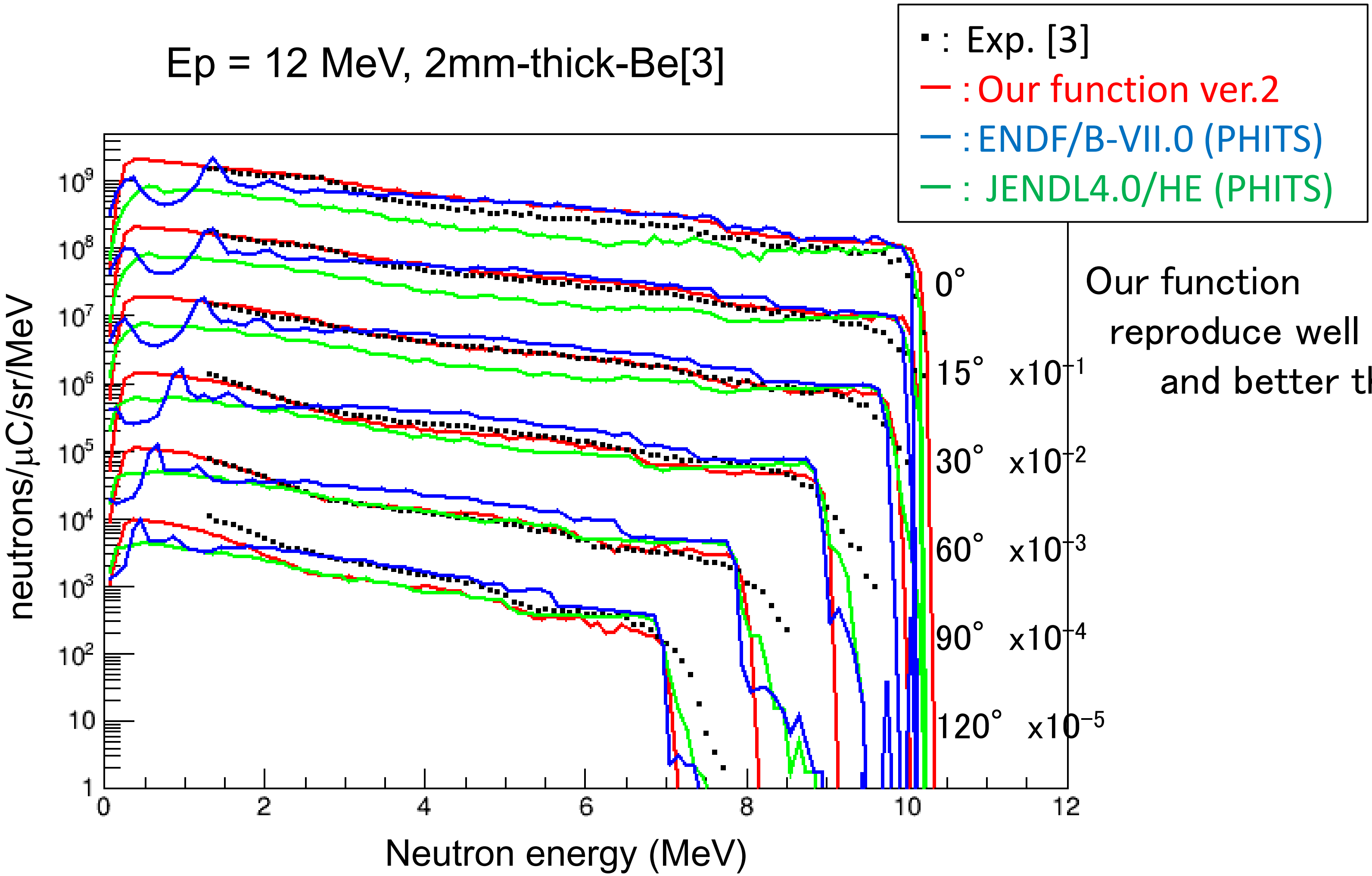
Monte-Carlo of Waka Func.

↓

N Intensity(En, θ)

Comparison with existing data, nuclear data library, and our function --- 1

p-Be: neutron spectrum Proton energy 12MeV



Our function reproduce well the data and better than others.

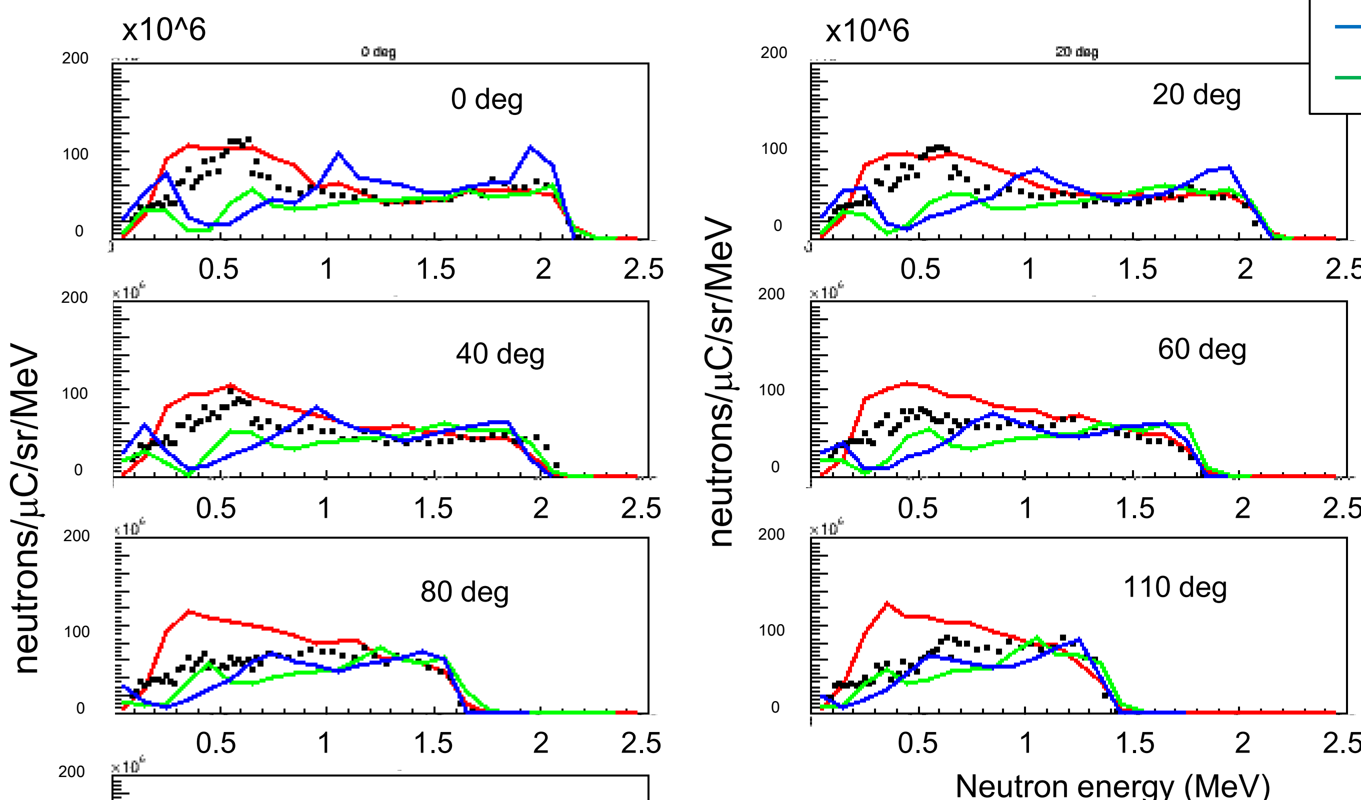
[3] M.Hagiwara et al., Proceedings of the 2011 Symposium on Nuclear Data, p.111 (2012)

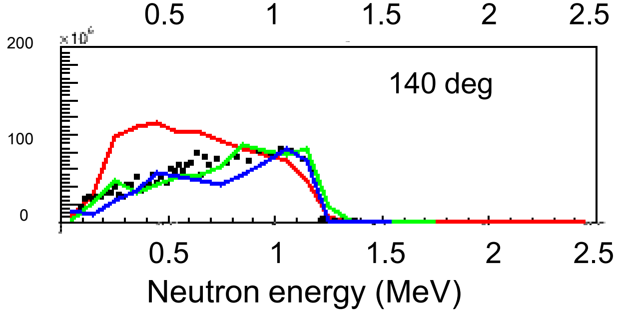
Comparison with existing data, nuclear data library, and our function --- 2

p-Be: proton energy 4MeV case comparison with other methods

▪ : Exp. [12]
— : Our function ver.2
— : ENDF/B-VII.0 (PHITS)
— : JENDL4.0/HE (PHITS)

Ep = 4 MeV, 0.5mm-thick Be[12]





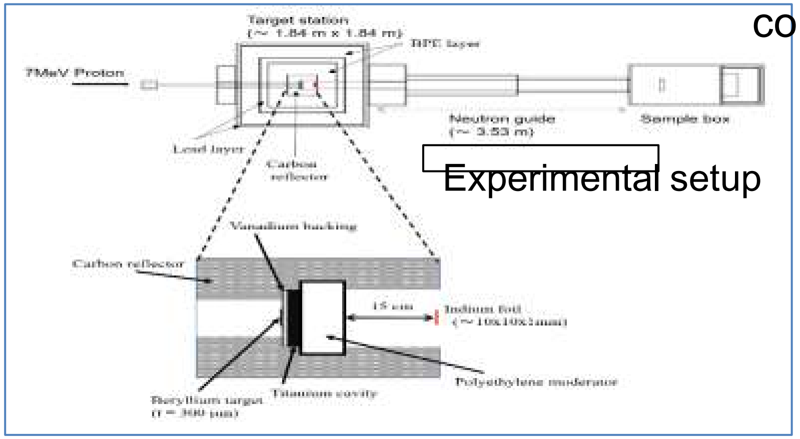
Our function reproduce well the data.

From comparisons 1 and 2,
they indicate the adequacy of our function.

[12] W.B.Howard et al., Nuclear Science and Engineering, Vol.138, p.145 (2001)

Verification with $^{115}In(n,n')^{115m}In$ reaction rate

RANS, Be target = p-Be : 7MeV



To evaluate total neutron flux > about 1MeV, the experimental $^{115}In(n,n')^{115m}In$ reaction rate was compared with calculated ones.

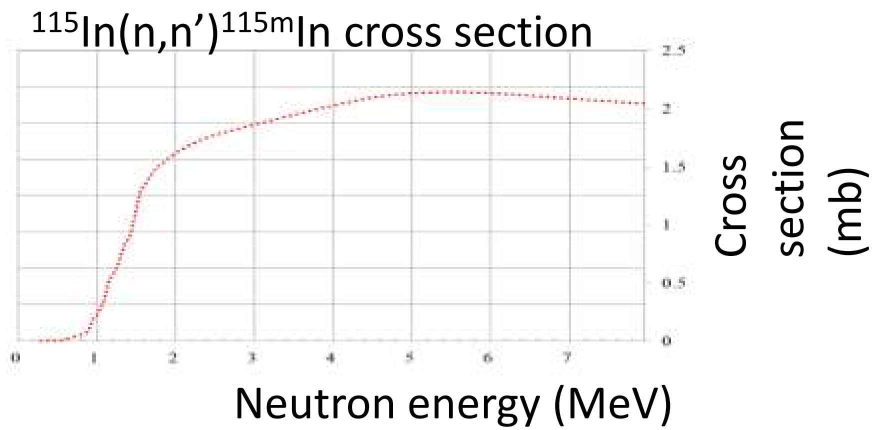


Table 1. Comparison of the reaction rate of In5n. The C/E ratio is the calculated result divided by the experimental value.

	Reaction rate [1/s/100 μA]	C/E ratio
Experimental value	$2.55 \pm 20 \times 10^{-17}$	-----------
Calculation with the CF	2.91×10^{-17}	1.14 ± 0.07
Calculation with ENDF/B VII.0	1.66×10^{-17}	0.65 ± 0.04

The gamma ray from ^{115m}In were measured by a Ge detector.

Using GEANT4, neutron production implemented by our formulation and ENDF/B-VII and neutron transport were calculated. Then, C/E ratio of the reaction rates were compared with our function and ENDF(C/E ratio, C=Calculation, E=Experiment)

Calculation/ Experiment=1 is perfect!

Our formulation agrees with the experimental results of Be(p,n) 7MeV RANS.

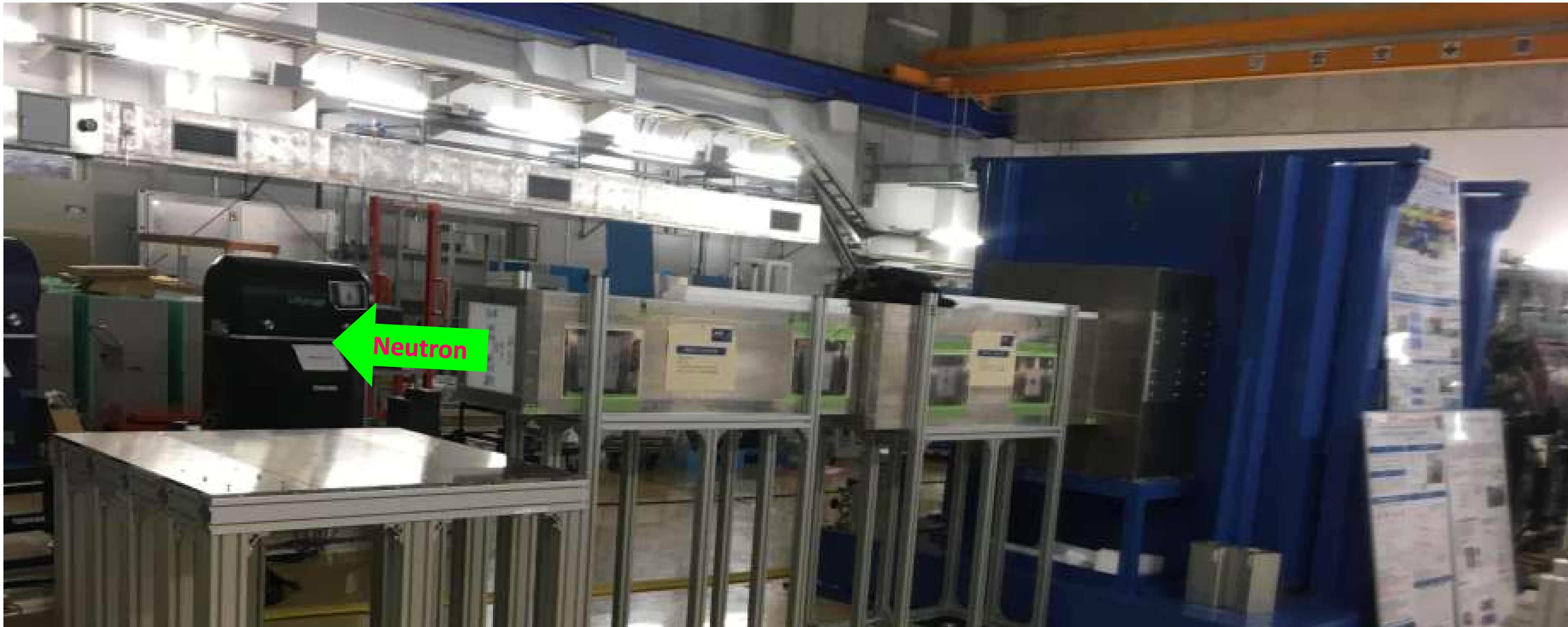
Compact neutron system for practical use !

neutrons, anytime, anywhere

compact neutron source

R&D

Instruments design, analytical methods **especially with CANS** should be based on user's strong requirements



1. Imaging experiments special resolution, 0.5mm, 0.2mm,
2. Diffraction, iron steel samples, residual austenite phase fraction
3. PGNAA, elemental analysis
4. Fast neutron transmission imaging for thick samples
5. Fast neutron reflected imaging from the surface layer with 6~20cm
6. SANS will come with Ibaraki Univ.

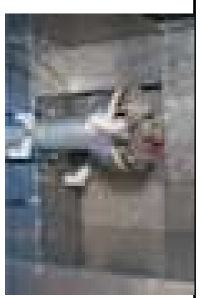
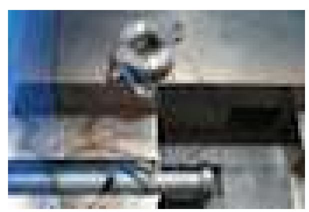
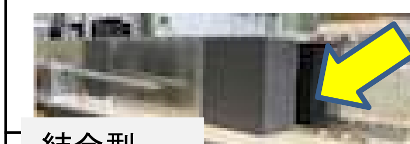
7.Cold source development, and focusing SANS, Dr. Y.Yamagata

RANS upgrade2017

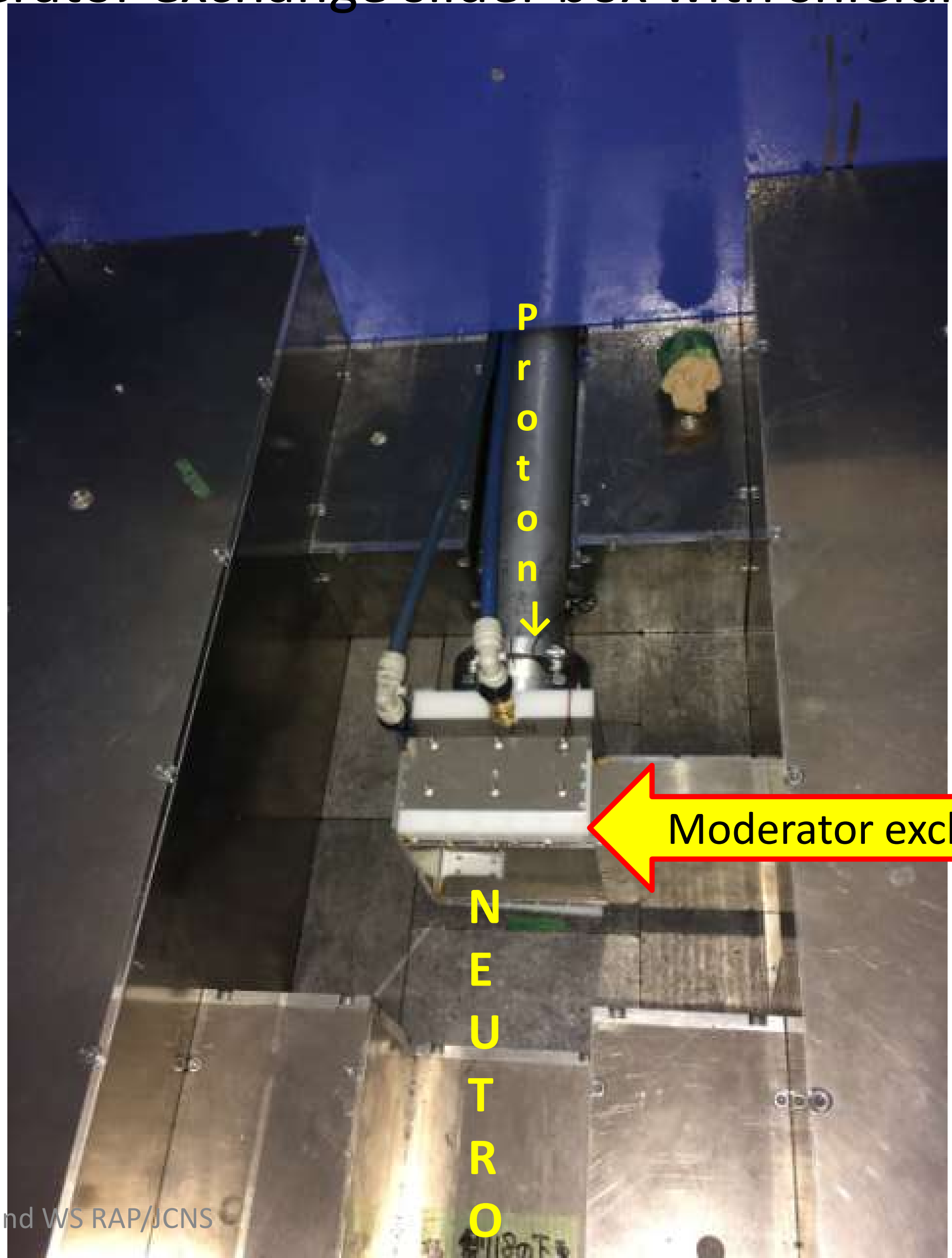
New Be target, V-baking, Ti cavity, moderator exchange system

2017 Exchange of Be target, Ti cavity, Moderator exchange guide installation

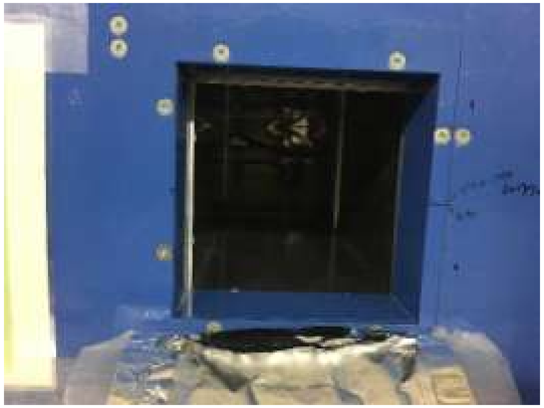
28th March 2017 3月28日		30 March (After radiation doze decrease)	
			Moderator exchange guide 
Opening the target station	Measurement radiation doze and check the safety	Check the position of moderator exchange guide	Moderator exchange guide position from out side

8th July Exchange the target, Ti Cavity, Moderator				30th July Moderator exchange system
				 結合型 
Removal of cooling tubes, target current monitor	Removal of moderator	Target removed	Proton wire monitor	Without moderator Coupled moderator 2cm Poison

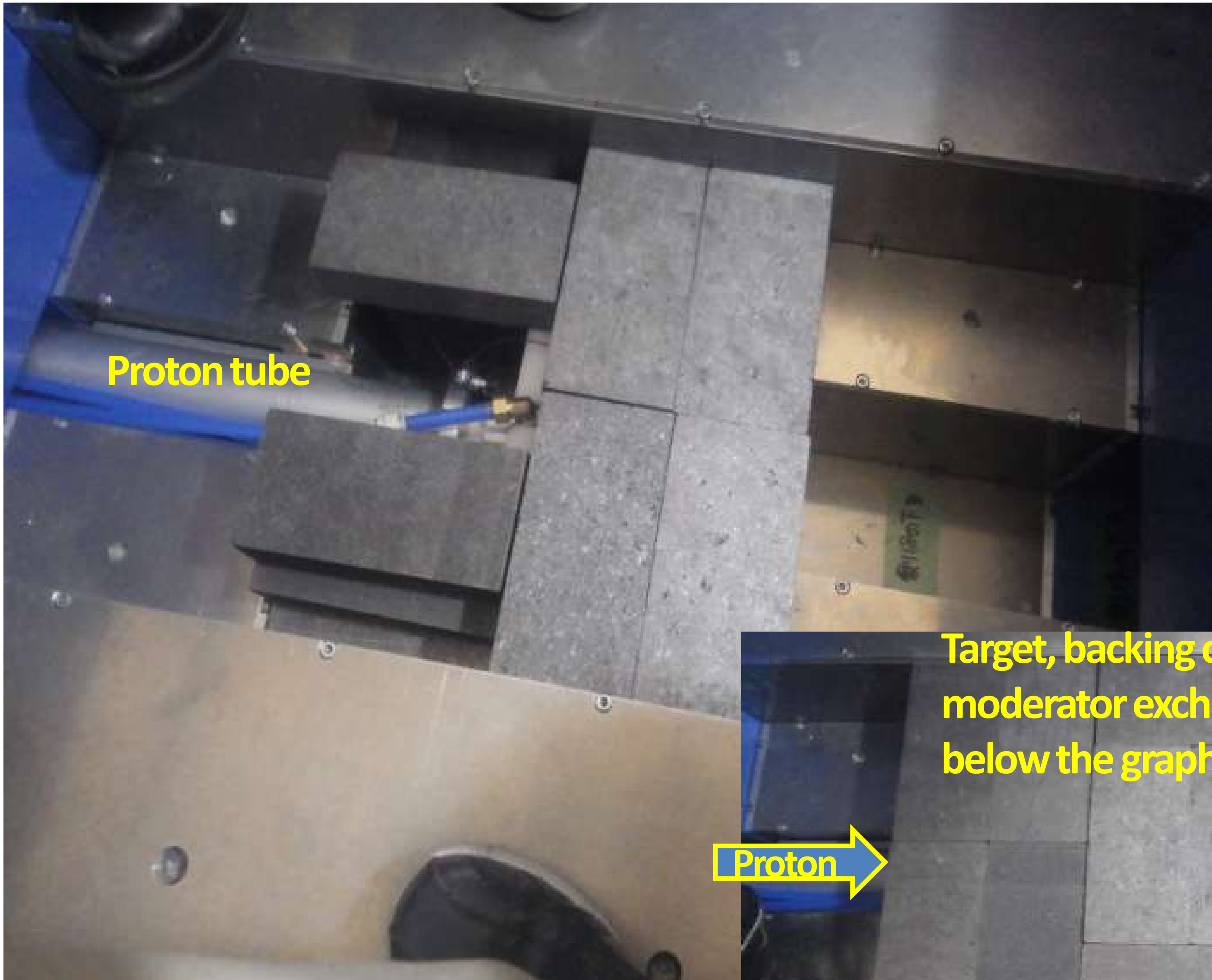
New Be target, backing, cooling cavity, are installed,
Moderator exchange slider box with shielding are placed from side

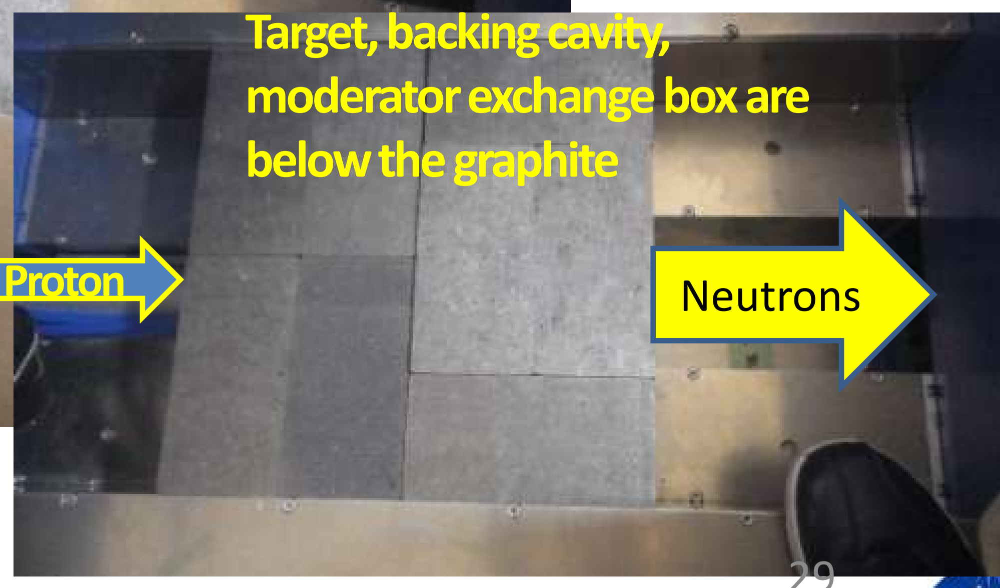


Moderator exchange from aside

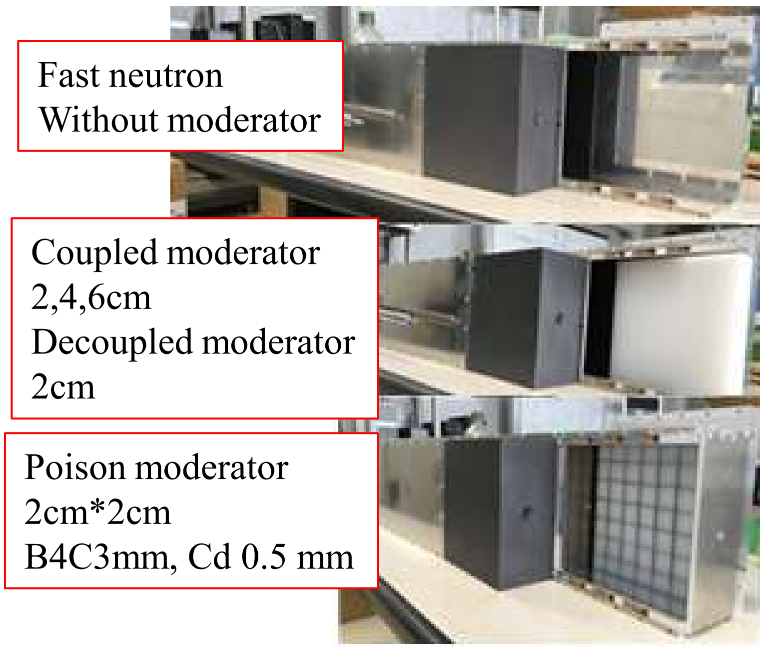


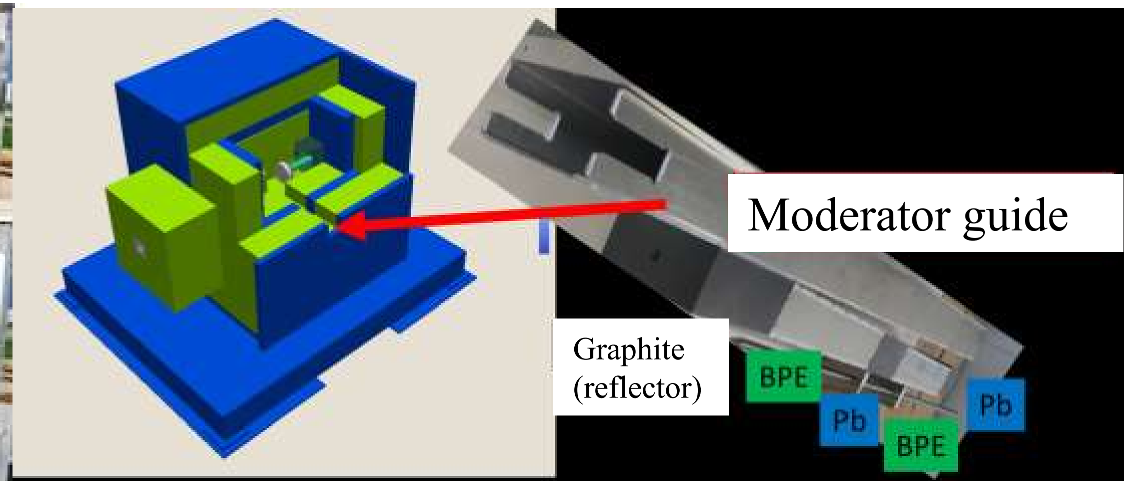
Filing around the target and moderator with reflector, graphite blocks





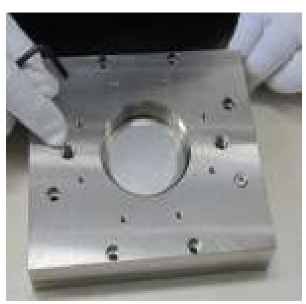
RANS up-grade（moderator）2017





New　target+backing
V Φ90mm
＋Be Φ50mm

New Ti cooling cavity



insulation flange

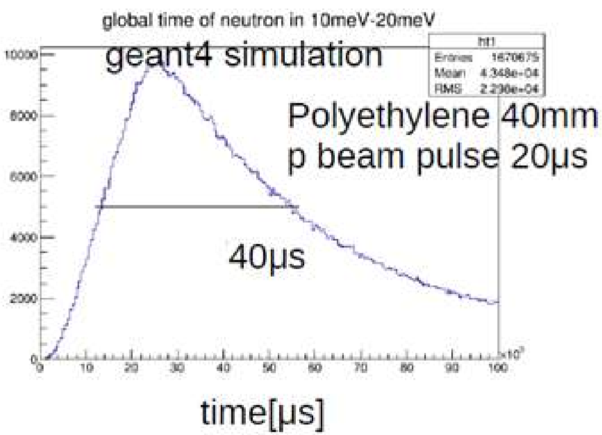
Moderators,

Energy	category	thickness	Exchange
Thermal Polyethylene	Coupled	2, 4, 6cm	Side hole exchange system
	decoupled	2cm B4C	
	Poison	2cm +B4C Cd	
Cold mesitylene	Coupled	Pre-mod 2~3cm Mod 3.5 cm	Opening the target station (Dr.Yamagata)

Thermal moderators and its intensity and moderation time

[redacted]

- <u>Moderator thickness and time resolution</u>

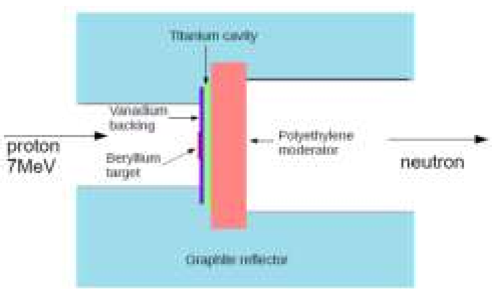


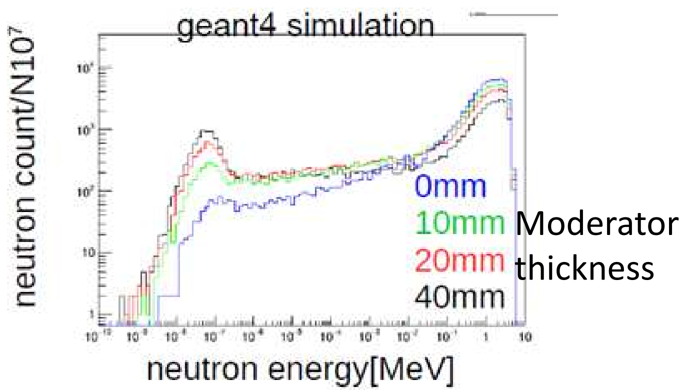
5m flight path=>3.5ms

<u>Δt~ 40μs->1% resolution</u>

->change the moderator with poison

<u>(de-coupled) with 2cm-> 10μs</u>



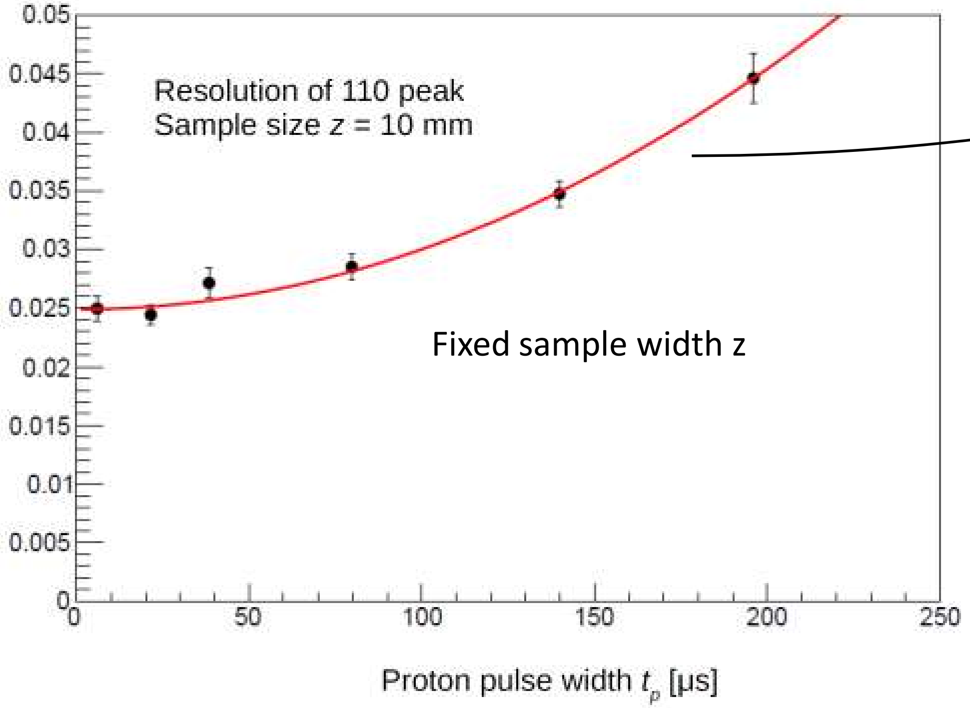


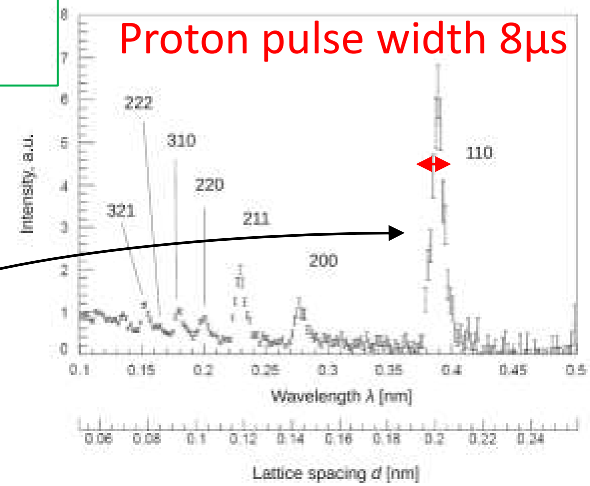
Estimation of the moderation time σ based on the diffraction peak width

$$\sigma = \sqrt{\sigma_{mod}^2 + \sigma_p^2 + \sigma_{sample}^2}$$

Change in the resolution of the 110 reflection as a **function of proton pulse** width t_p from 8 to 190μs

$$\sigma = \sqrt{\sigma_{mod}^2 + \sigma_p^2 + \sigma_{sample}^2}$$





Standard deviation by fitting the plots with

$$\sigma = \sqrt{\sigma_{mod}^2 + \sigma_p^2 + \sigma_{sample}^2}$$

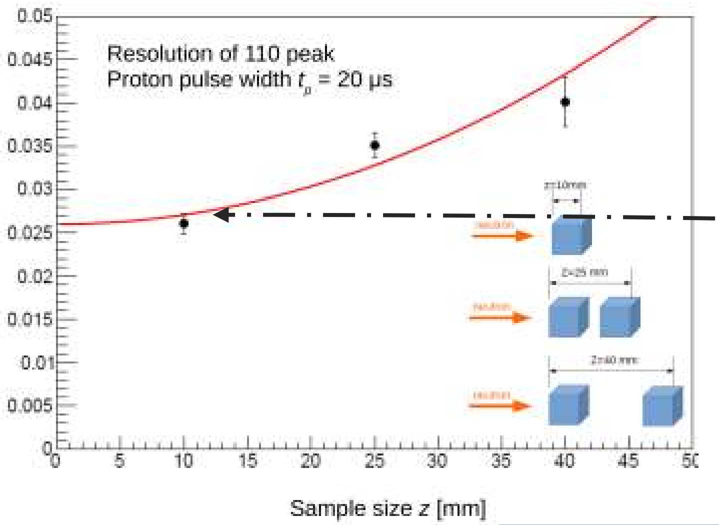
$$\sigma_p \propto t_p$$

$$\sigma_{sample} \propto z$$

Y. Ikeda, et al Nucl. Instr. Meth. A833 (2016) 61-67

- Change in the resolution of the <u>110 reflection</u> as a **<u>function of sample size</u>**

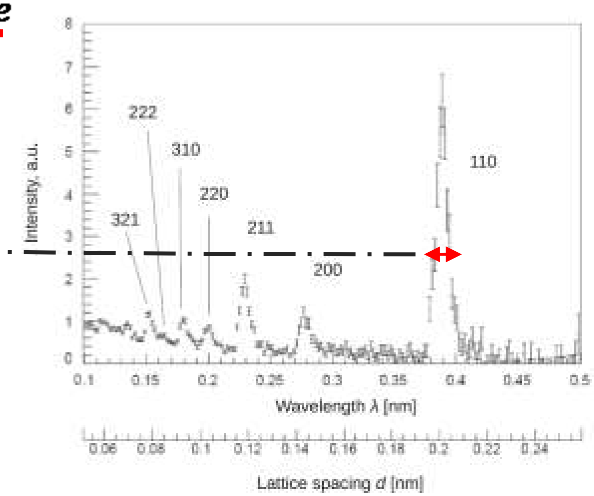
$$\sigma = \sqrt{\sigma_{mod}^2 + \sigma_p^2 + \sigma_{sample}^2}$$



Standard deviation by fitting the plots with

$\sigma_p \propto t_p$

$\sigma_{sample} \propto z$



The moderation time for RANS with coupled moderator is estimated to be **<u>30μs</u>**

Y. Ikeda, et al Nucl. Instr. Meth. A833 (2016) 61-67

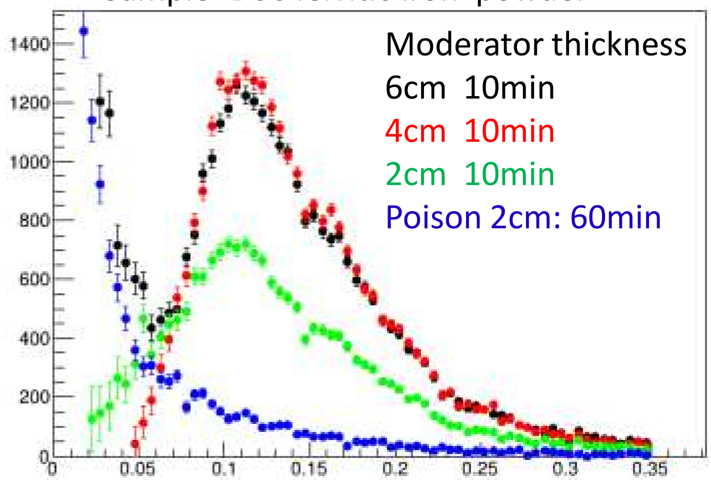
<u>With decoupled moderator; 20μs</u>

<u>-> Poison, 10μs</u>

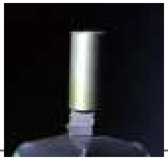
Intensity comparison with 2,4,6 coupled and poison

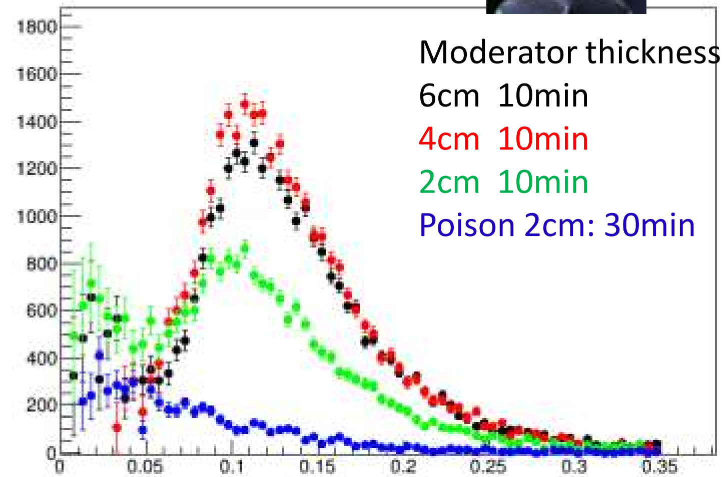
Preliminary results

Sample : BCC ferritic iron powder

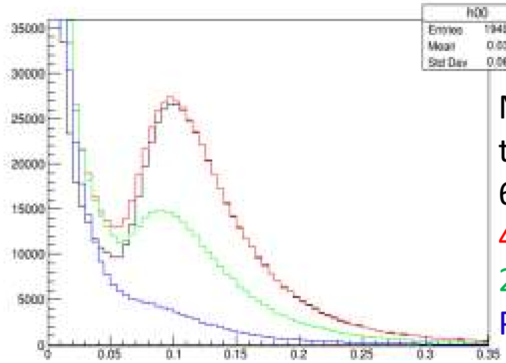


Sample : Vanadium Colum





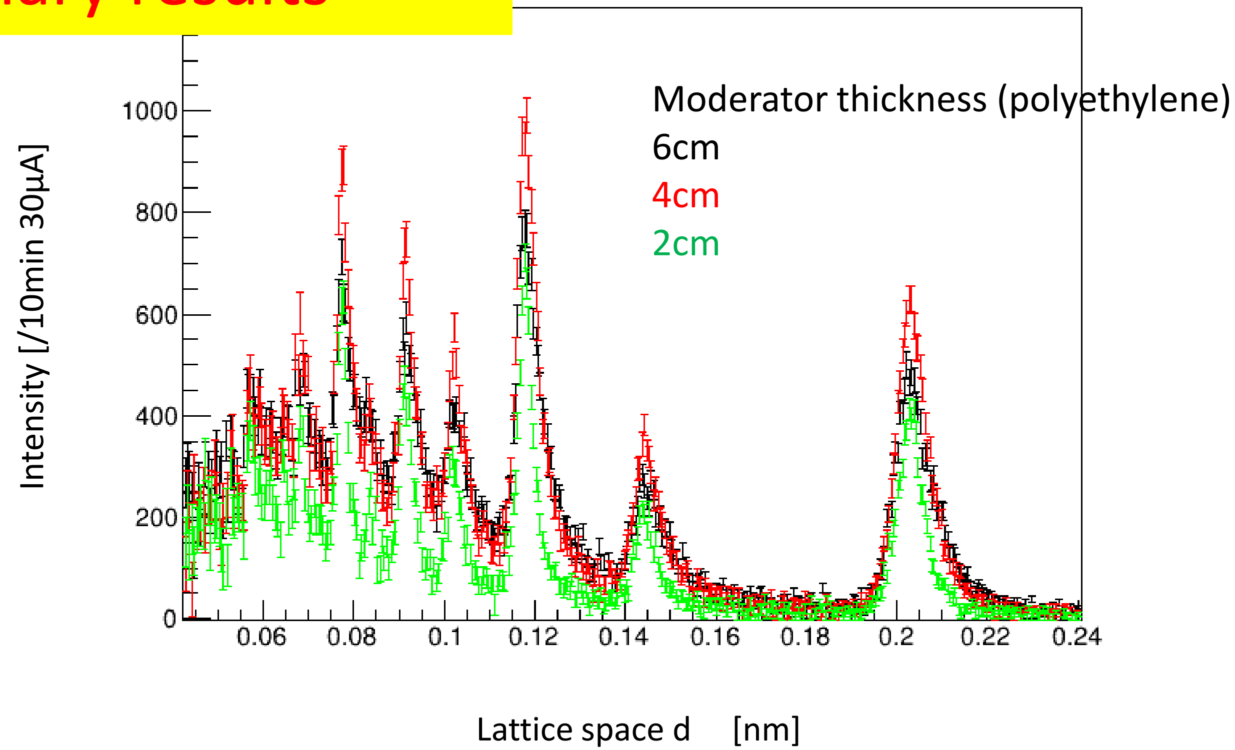
MC simulation (Geant 4)



Experimental results with coupled moderator with different thickness, 2,4,6cm

Ferrite steel powder sample, 2θ=90deg

Preliminary results



Dr. Yutaka Yamagata

Development of cold neutron source using methyl-benzene derivatives for compact neutron source＋α

Yutaka Yamagata, Shin Takeda, Takuya Hosobata, Toshihide Kawai,
RIKEN Center for Advanced Photonis RIKEN(Japan)

Masahiro Hino, Yutaka Abe,
Kyoto University (Japan)

Hirota Katsuya, Hirohiko M. Shimizu,
Nagoya University (Japan)

Yasuo Wakabayashi, Tomohiro Kobayashi, Atsushi Taketani, Yoshie Otake
RIKEN Center for Advanced Photonics, RIKEN (Japan)

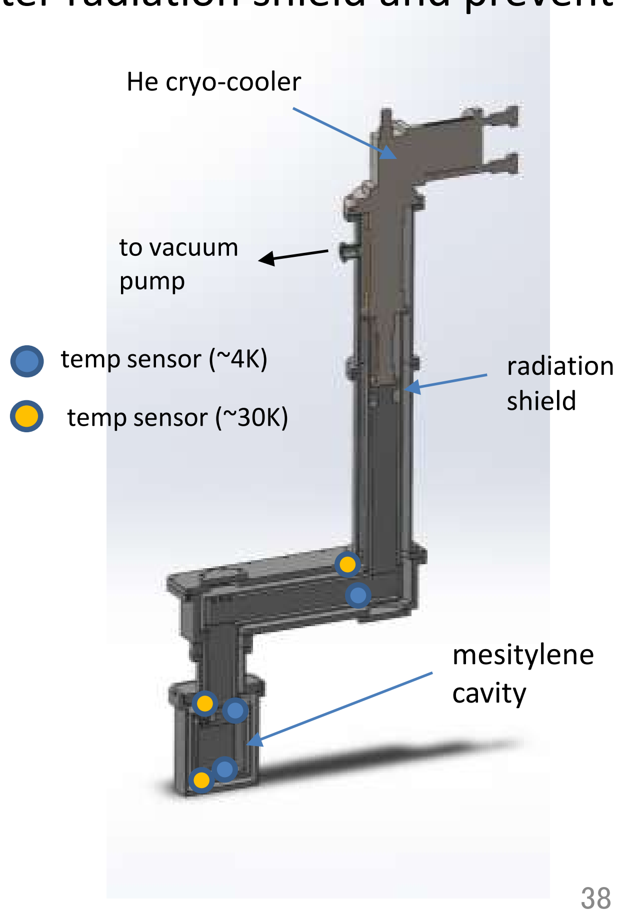
RAP

Dr. Yutaka Yamagata

Cryo system for cold moderator (Indiana U. method)

- Closed cycle He cryo-cooler (GM type) with two stage using heat transfer by aluminum bar is adopted.
- Most components are made of aluminum for low activation
- Mesitylene cavity will be cooled below 20K, radiation shield around 80K
- L-shaped structure for better radiation shield and preventing cryo-cooler activation

Mesitylene cavity (10cmx10cmx2.5cm)



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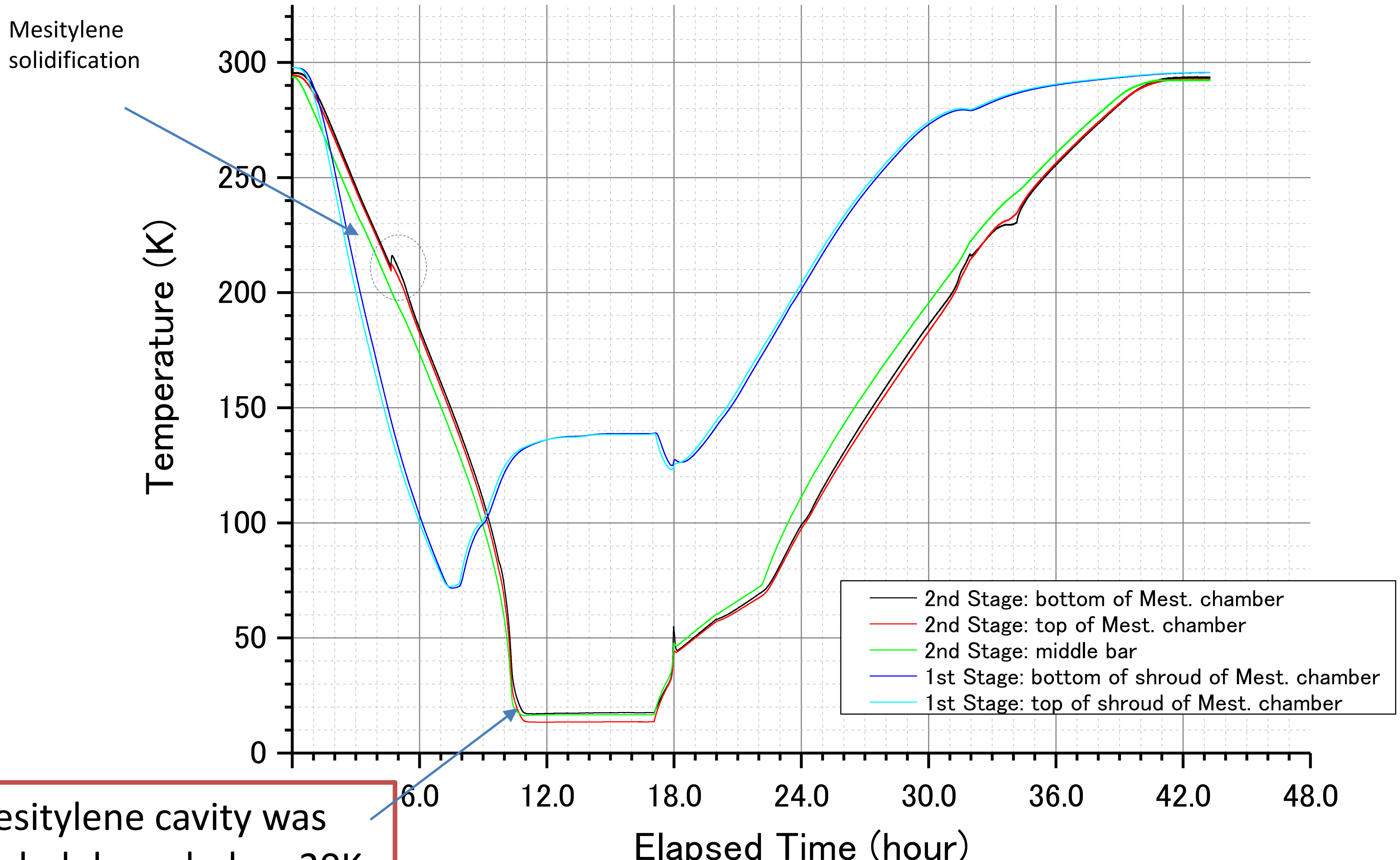
Cooling and warming up

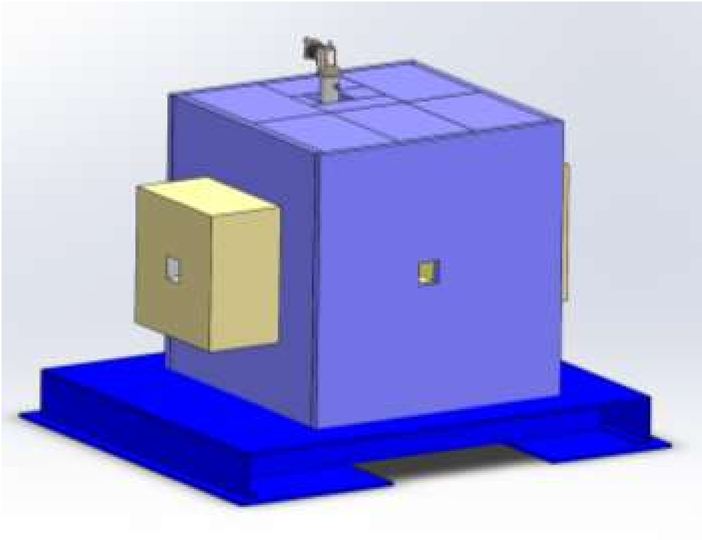
cooling down for 11 hours, warming up for 18 hours

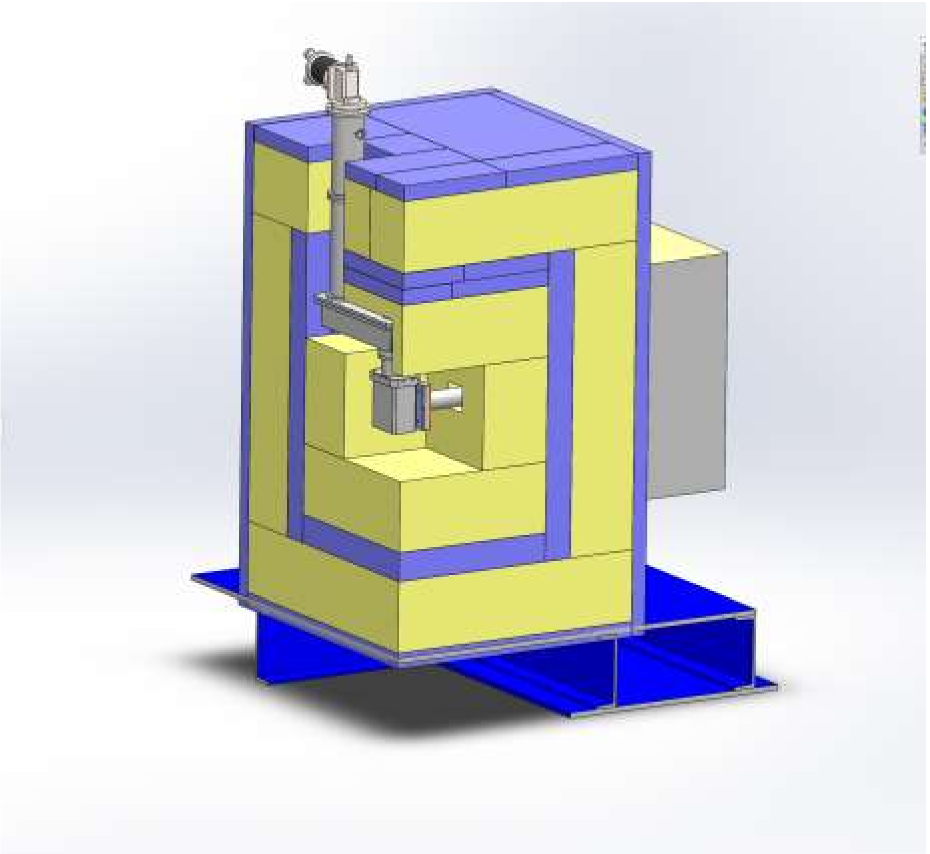


Mesitylene cavity was cooled down below 20K

Dr. Yutaka Yamagata

Mounting cold moderator to RANS target station



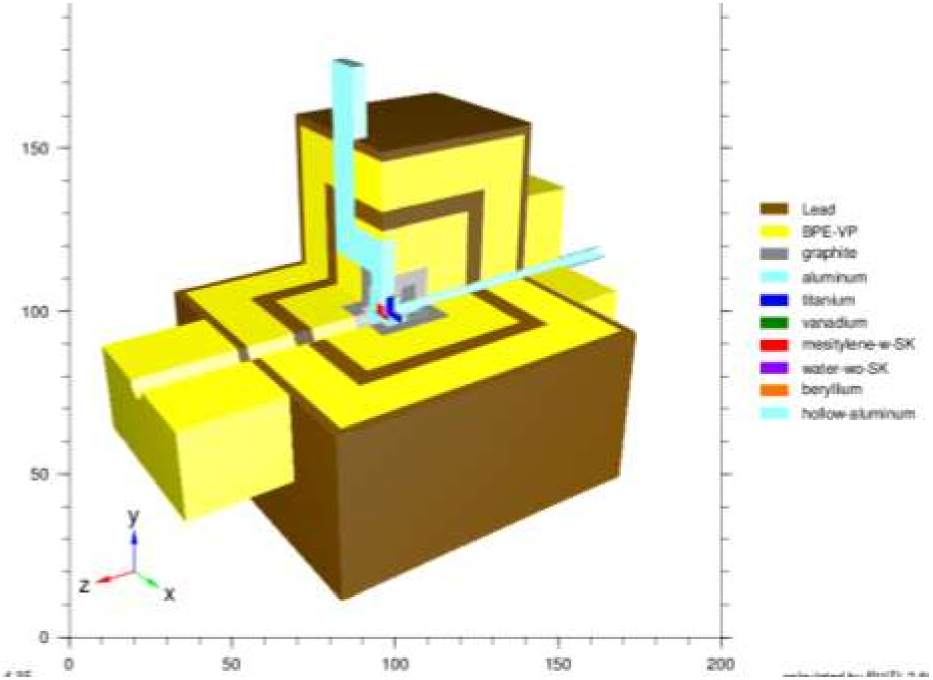


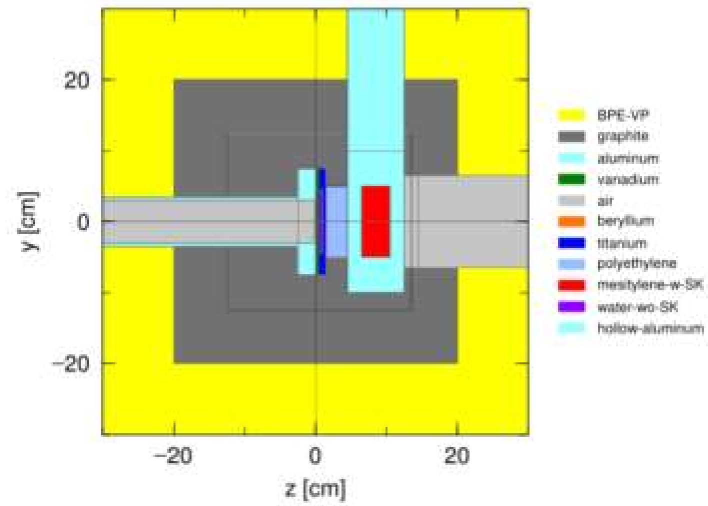
- RANS is used with many different types of moderators depending on the experiments.
- New radiation shielding block was made to enable "quick" installation and removal of cold modeator

Installation of cold moderator takes about one day and removal will take one day.
It will be a convenient platform for moderator test

Dr. Yutaka Yamagata

Monte carlo simulation of cold moderator by Dr. S.Takeda



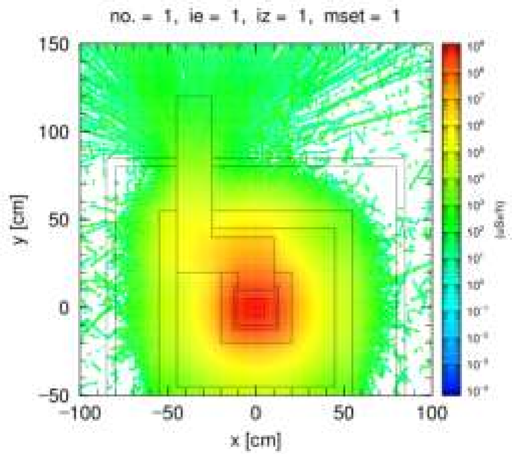


- phitsコード(2.88) was used
- Scattering kernel provided by Dr. Granada is used
- Aluminum duct and chamber is modled as aluminum with half density.

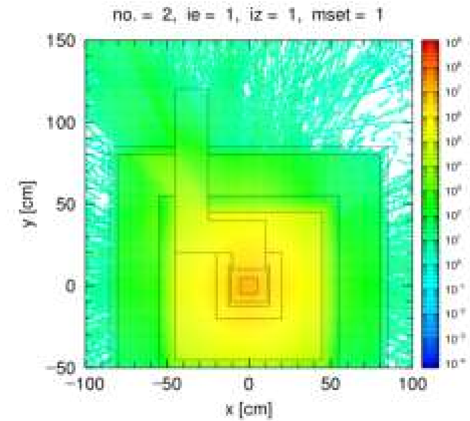
Dr. Yutaka Yamagata

Shielding evaluation

XY cross section
around cold moderator

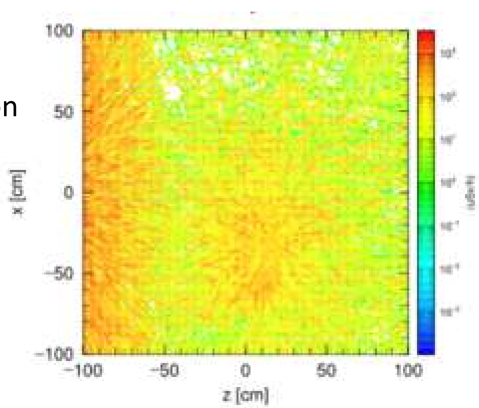


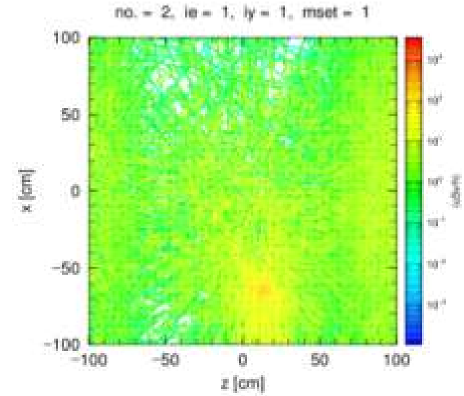
Neutron



Photon

XZ plane 50cm above target station

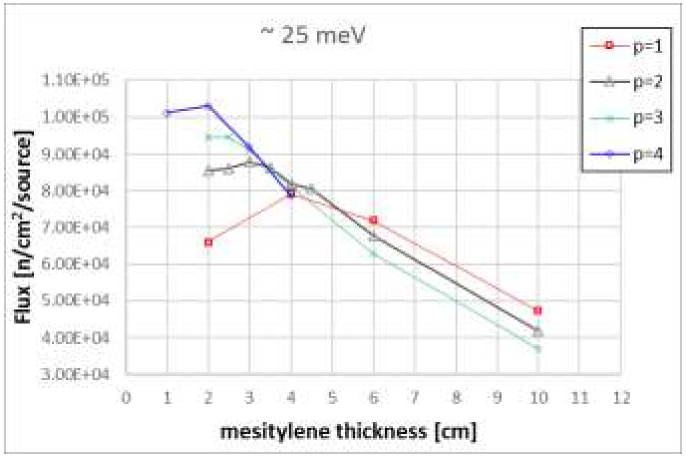


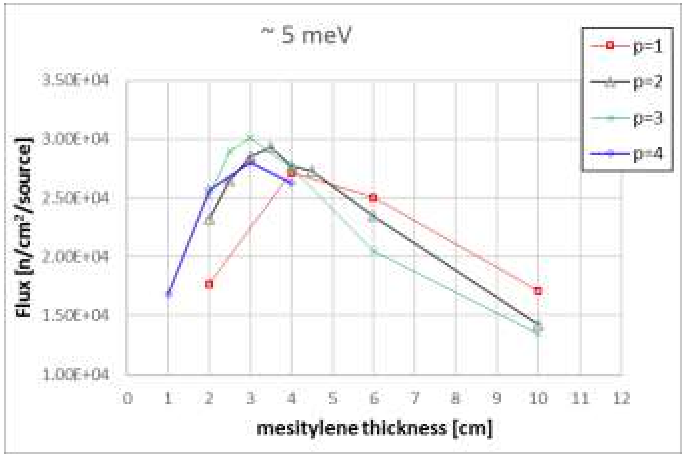


At the entrance of cold moderator, radiation dose is about 100uSv/h。

Optimization of pre-moderator and moderator dimension

Neutron flux was evaluated in thermal neutron region (<25meV) and cold neutron region (<5meV) by varying the thickness of pre-moderator(polyethylene) and cold moderator(mesitylene)





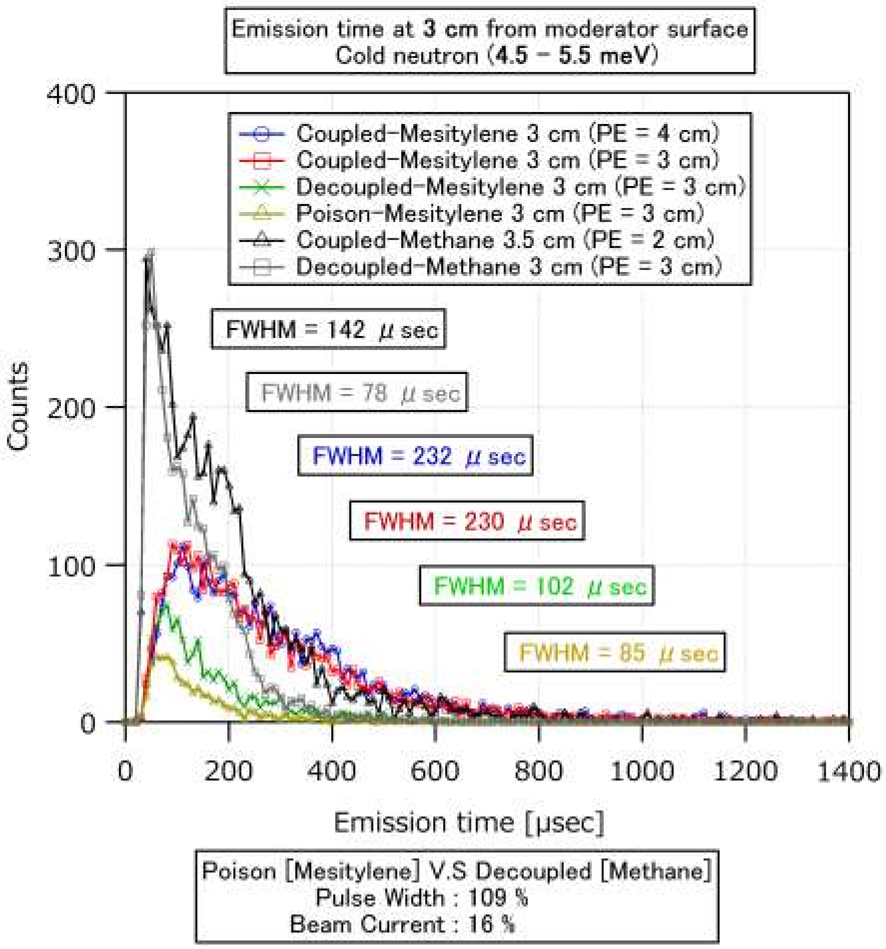
- Pre-moderator thickness (p) 2-4cm, Mesitylene thickness 1-10cm
- Pre-moderator= 3 cm Mesitylene = 3.5 cm seems to be the optimum

Dr. Yutaka Yamagata

Pulse width simulation of cold neutron beam using various moderator materials and configurations

- Pulse width was evaluated at 3cm from moderator surface with cold neutrons(4.5 to 5.5meV 4Å) for solid methane and mesitylene
- For solid methane, coupled and decoupled was evaluated. For Mesitylene, coupled, decoupled and poisoned moderator was evaluated

- Results show that solid methane has high peak intensity and short pulse width
- Wavelength resolution is 4.5%@5m (Coupled) and 2.0%@5m.
- Poisoned mesitylene moderator does not have any benefit considering FOM.



Dr. Yutaka Yamagata

Setting up cold moderator on RANS target station

- RANS target station shielding is modified to accommodate cold neutron moderator with cryo unit

cryo module setup on target

completed setup of cold moderator

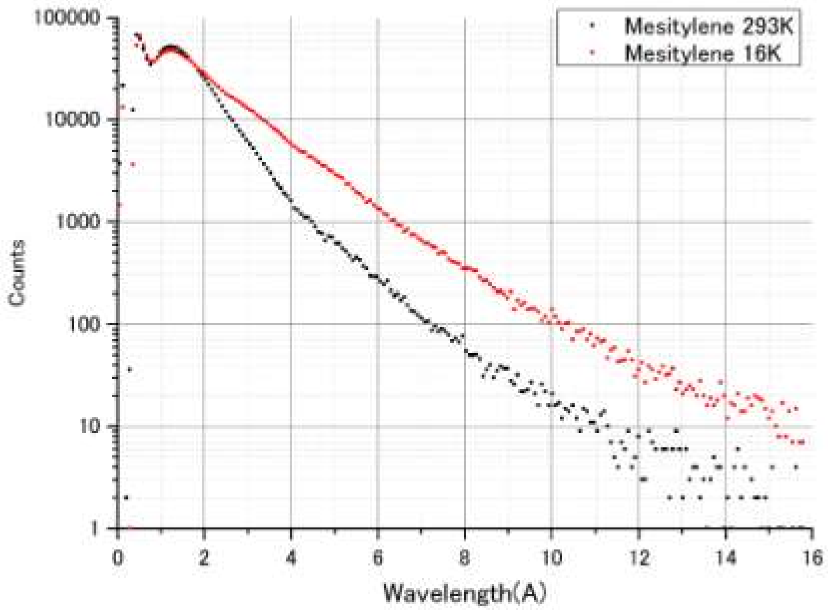
Making customized shielding block

Dr. Yutaka Yamagata

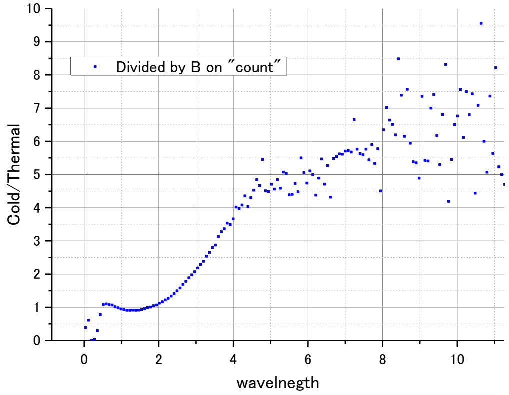
Spectrum measurement in March

preliminary

Spectrum of neutron beam is measured by TOF using RPMT detector.
x3.5 gain at 4A, x7 gain at 10 A



measured area 1cm^2



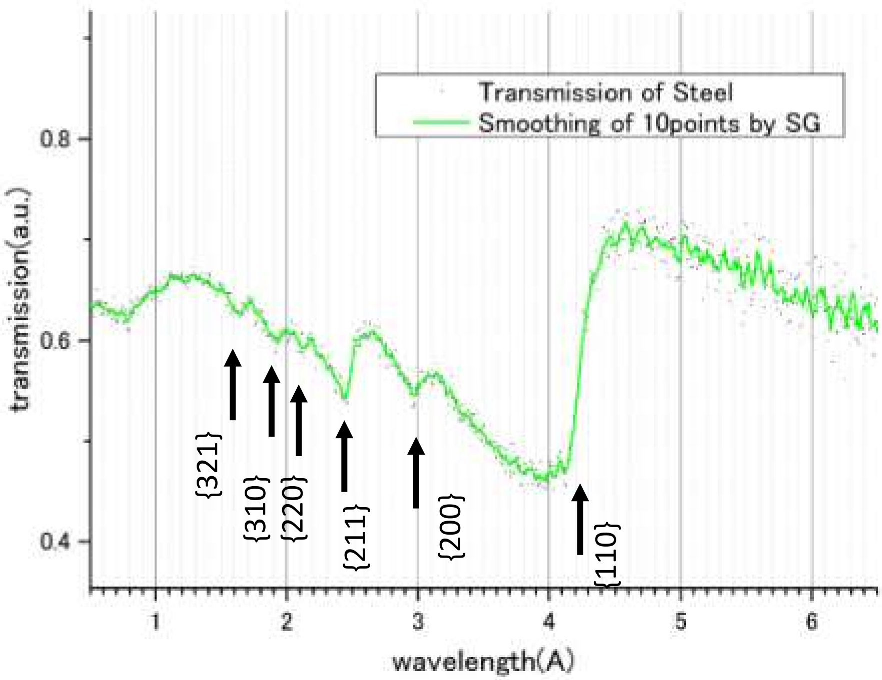
Accelerator parameters
Pulse width 40us
Peak current 9mA
Average current 12uA
Rep. Frequency 30Hz
Meas. time 30min
L=5m
Estimated cold neutron flux:
2.3x10^{3}n/cm^2/s @ 100uA L=5m (>4Å)

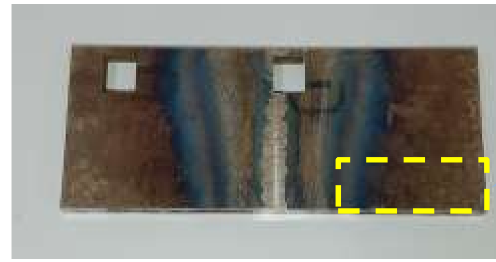
Dr. Yutaka Yamagata

Bragg edge test in March

preliminary

- A steel plate (t=6mm) was measured by RPMT detector for 60 min.
- Transmission was measured.





measured area:
15x48mm (7.2cm²)

Steel sample (provided by Dr. H.Sato,Hokkaido Univ.)

Bragg edge data obtained at J-PARC TAKUMI (Ph.D Thesis of Dr. H.Sato)

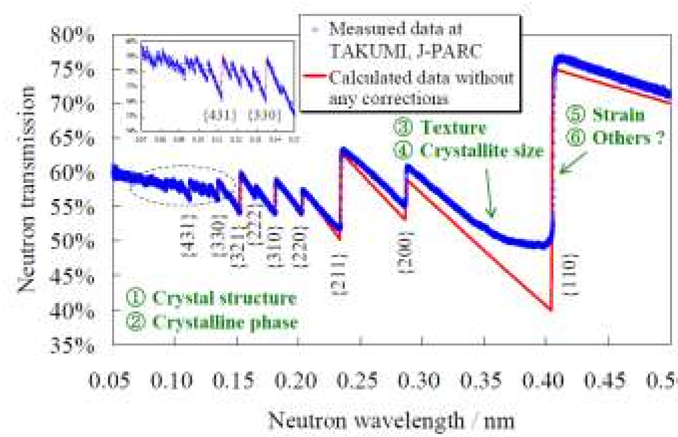


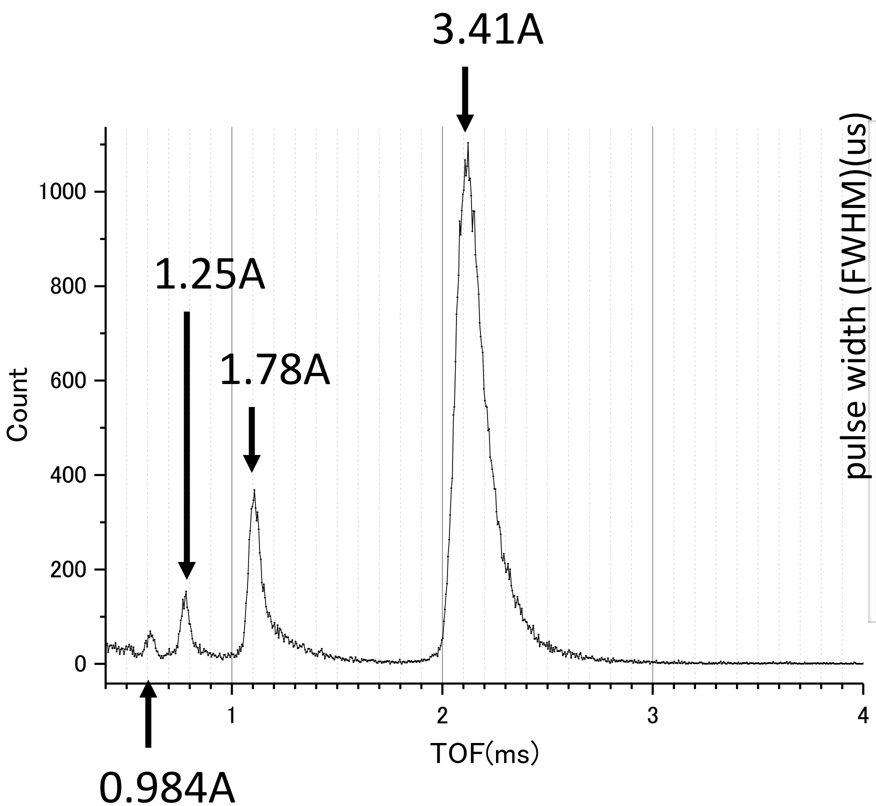
図1.16：ブラッグエッジ透過率スペクトルに含まれている結晶組織構造情報のまとめ。

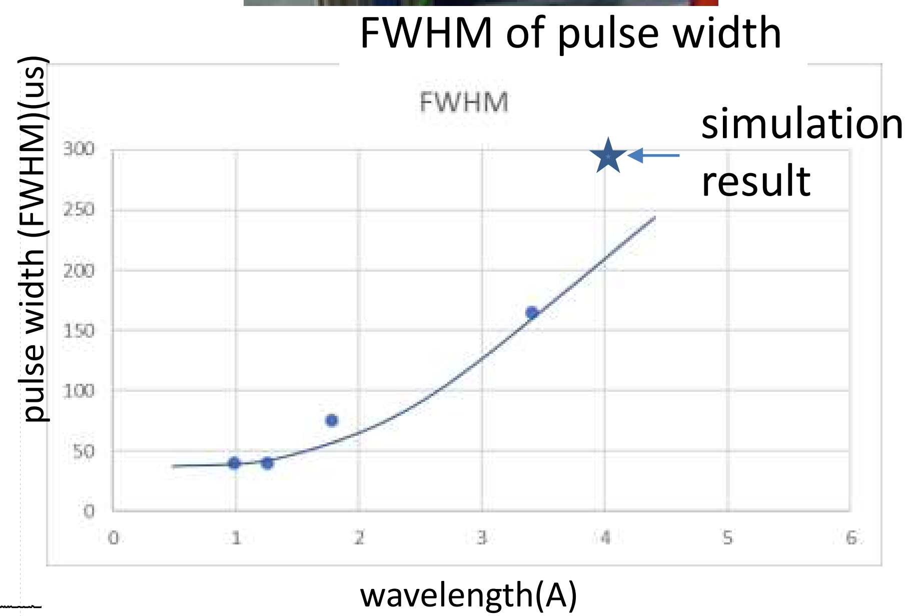
Pulse width test

preliminary

Dr. Yutaka Yamagata

Pulse width of cold neutron moderator was measured by using diffraction by HOPG (d=6.62A, t=1mm mosaic spread 0.4 to 0.5 deg), slit 5cm-2cm at 1.8m distance.





Compared with simulation result (tw=230us) including pulse width of proton beam (40us), experimental result seems to be a little bit smaller.

RAN development for practical use on site

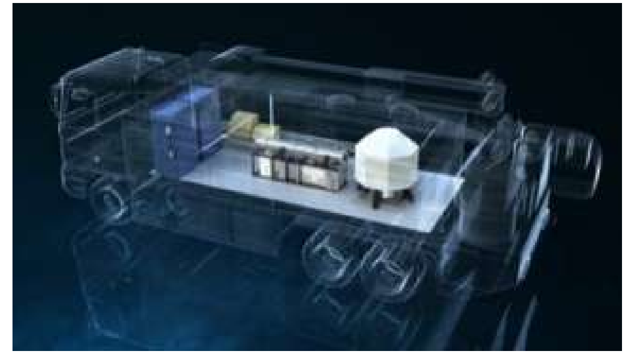
➢ **Social safety with fast neutrons**

infrastructure non-destructive inspection technique

1. **Transmission neutron experiment through thick concrete**
2. **Reflected neutron imaging under the pavement**
3. **Chloride damage detection：PGAA**
4. Fast neutron transmission imaging

➢ Industrial use –

1. **Diffractometer,** texture evolution, austenite volume fraction estimation
2. Imaging: corrosion in the steel and water visualization



Fast neutron for Social safety

infrastructure non-destructive inspection technique

1. Visualization in the thick concrete slab
2. Reflected neutron imaging
3. Chloride damage detection

Background

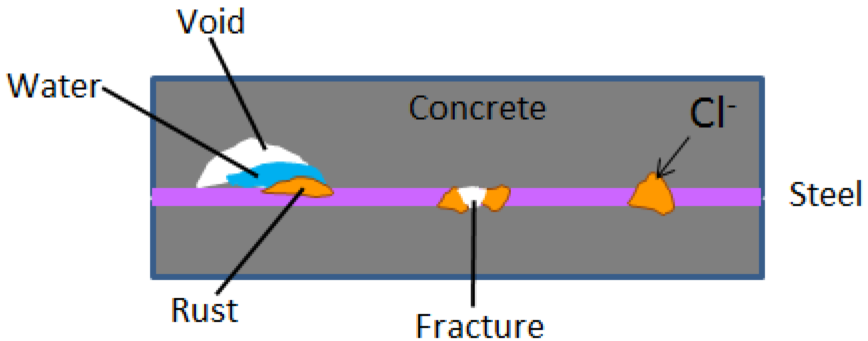
Collapse of the Ynys-y-Gwas brg.
(UK, 1985)

- Aging deterioration of large-scale concrete structures
  - Lifespan of concrete ~ 60 years → peak in 2025 in Japan
    → Lifetime expiration 42,000 bridges
  - New construction of bridges/highways is impossible

    → Diagnosis, preventive maintenance, life extension

Deteriorated concrete

- Assessment of concrete deterioration



- Width of Steel bar
- Void
- Water
- Fracture of steel bar

→Required resolution ~ 3 cm

Fast neutron transmission imaging

as on-site nondestructive inspection technique

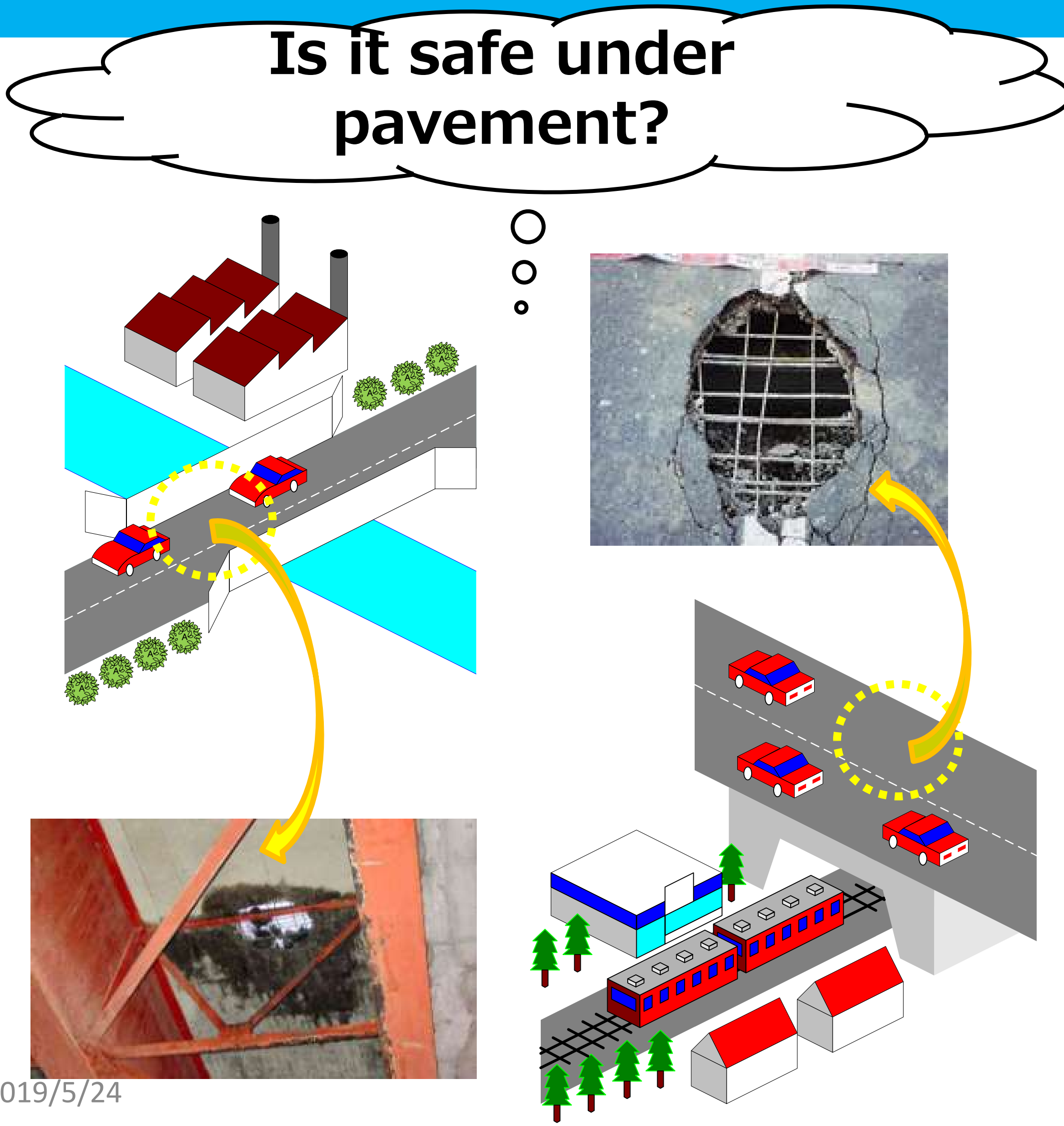
High penetration power

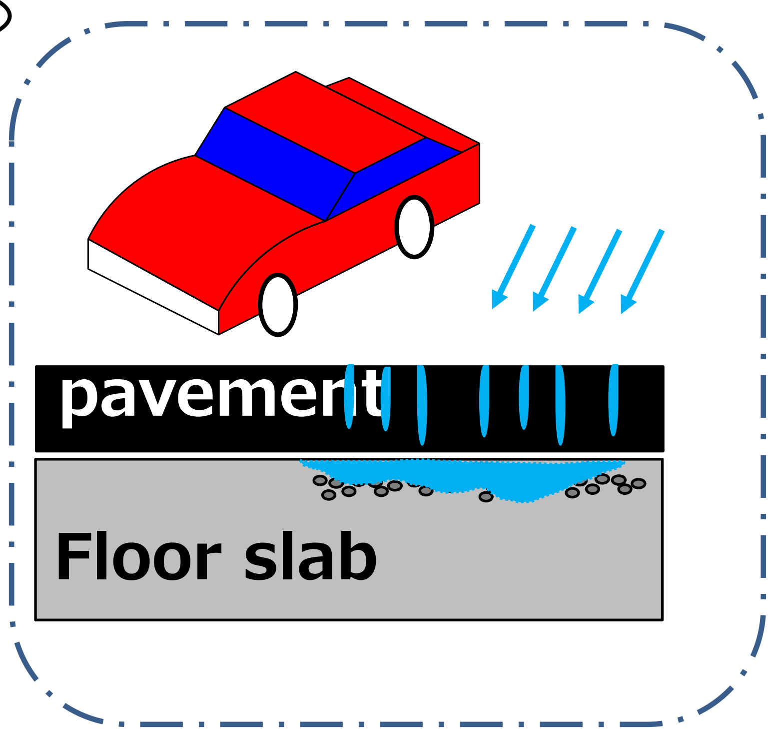
Sensitivity to water

New method to observe under pavement with fast neutron

Defects visualization in concrete slabs

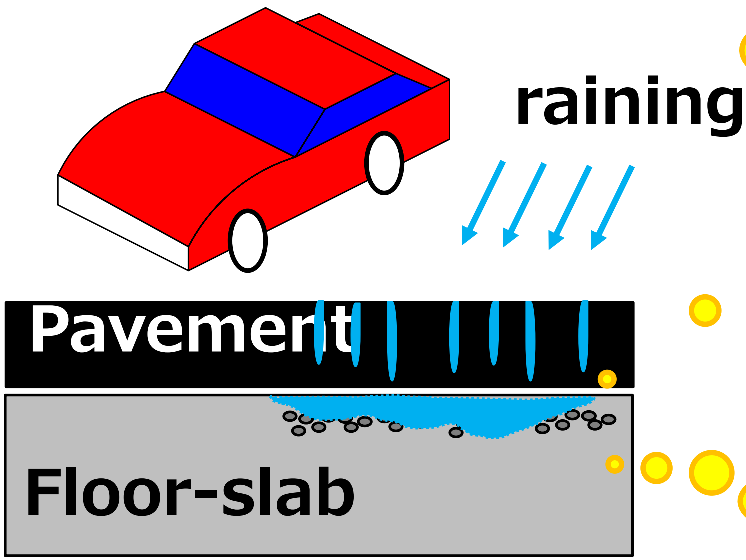
Y.Ikeda, Y.OTAKE, M.Mizuta





Defects of floor-slab under the pavement

- Traffic load affects fatigue of floor slab



Water accelerates degradation

Water weaken concrete strength

Under the pavements degradations are growing

Visualization is needed

- degradation ・・・

Defect visualization under pavement with fast neutron ！

Transmission method

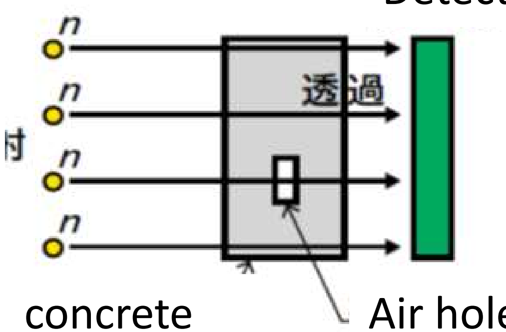
Detector set behind the objects
→Application place limitation

Reflection method

Detection place is the same as source→roads, tunnels, high-way

Detector

Incident neutrons



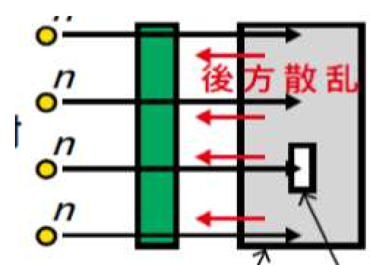
concrete

Air hole, water, etc.

Transmission neutron measurement

Detector

Incident neutrons

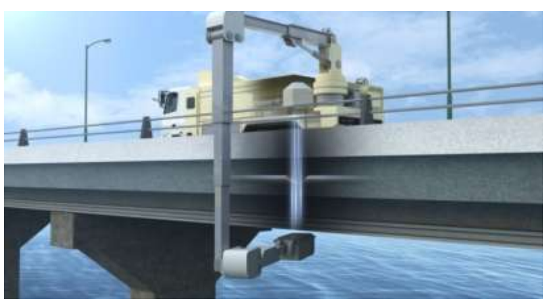


Back-scattered Neutron

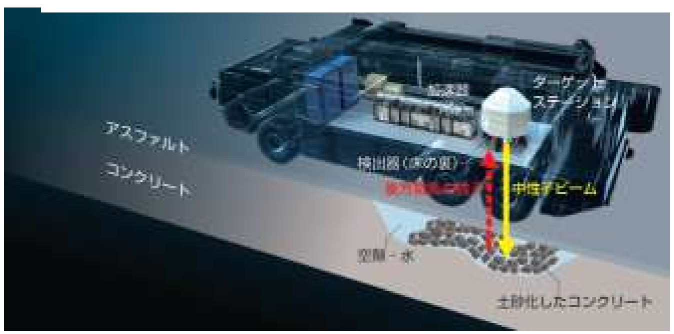
concrete

Air hole, water, etc.

Back scattered neutron measurement



Future image of transmission method
（未来図）

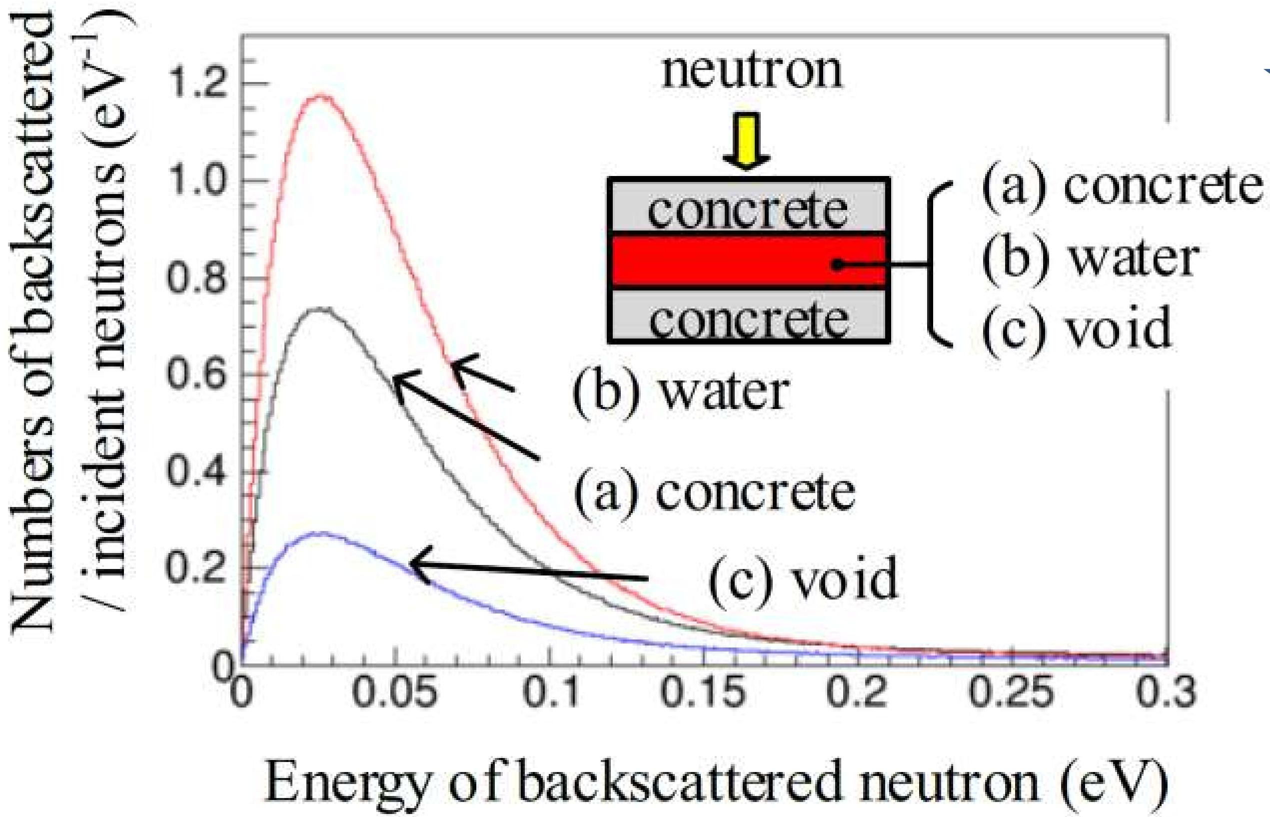


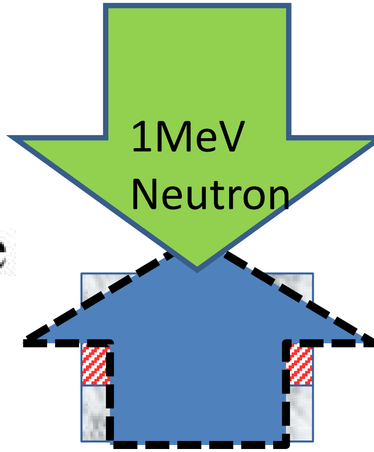
Future image of reflection method
（現在の未来図）

Development of reflected neutron imaging method

Simulation study of back scattered neutron from concrete

Reflected neutron energy

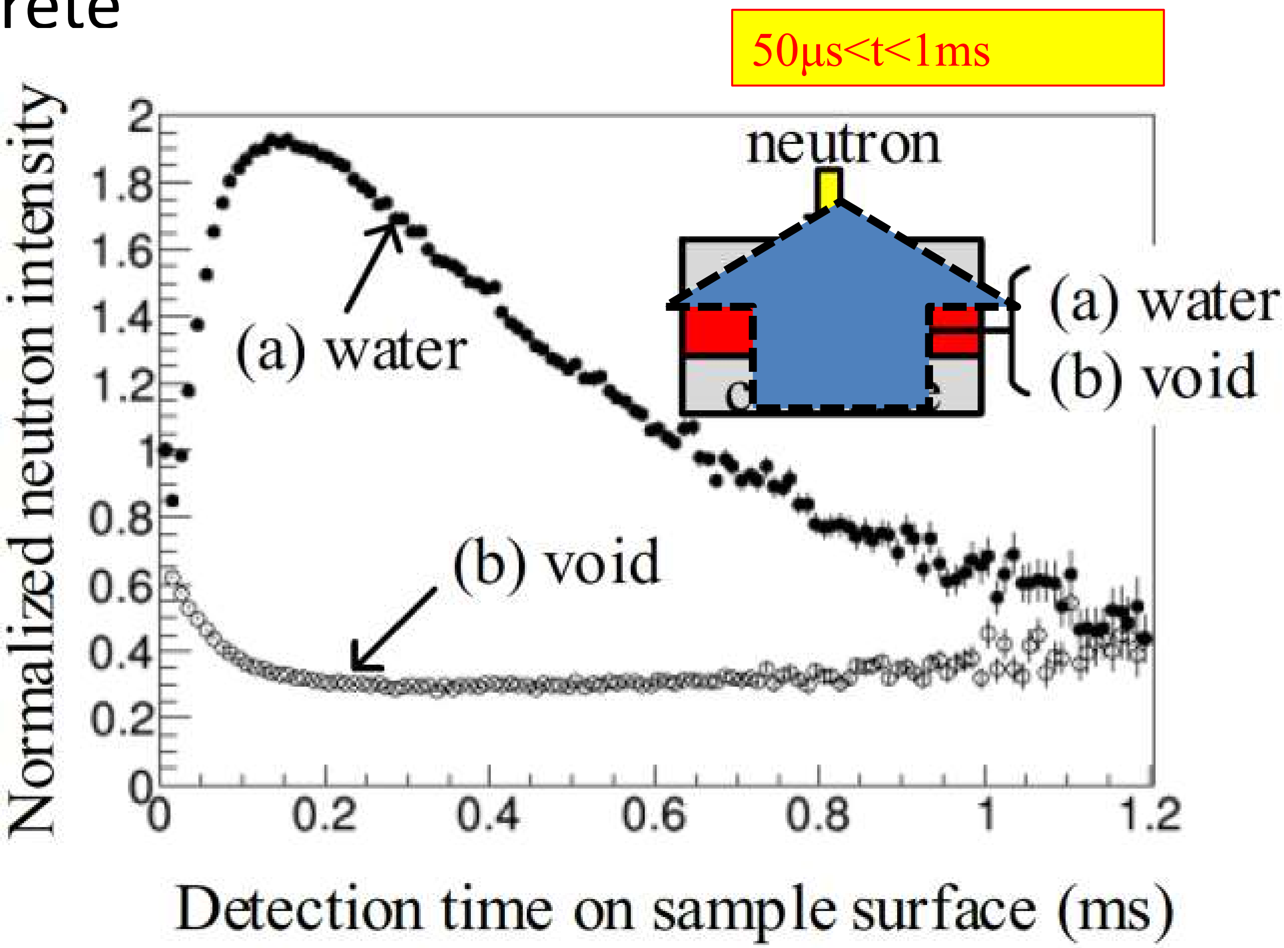




Simulation results of energy spectrum of backscattered neutrons

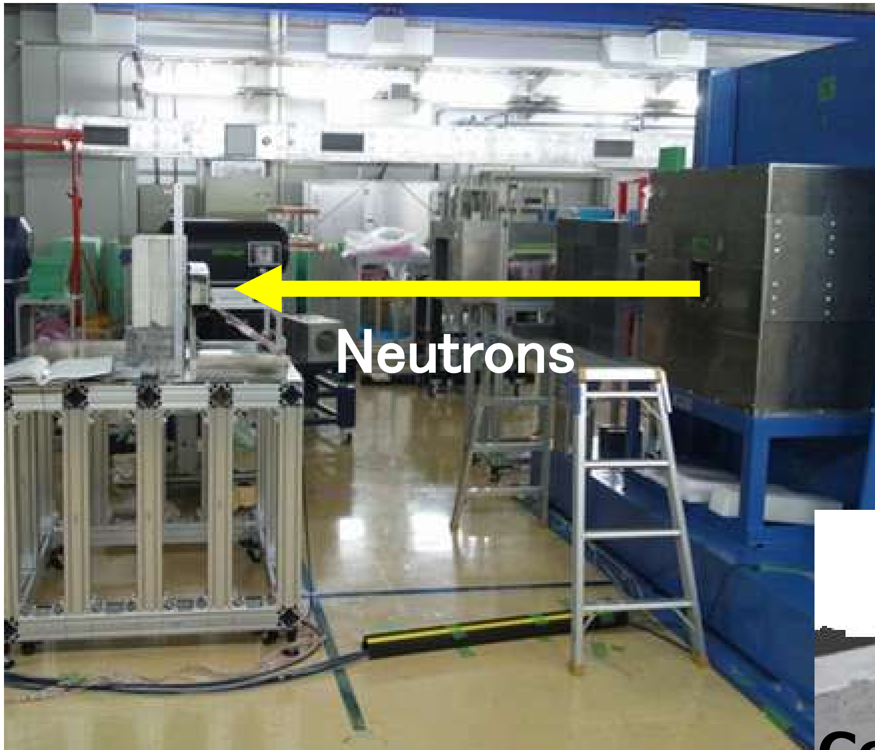
Development of reflected neutron imaging method

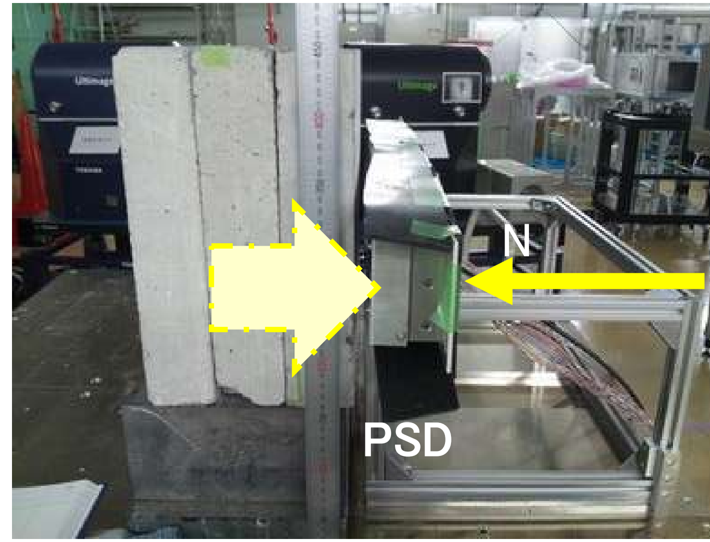
<u>Timing distribution</u> reflected neutron emitted from the surface of concrete

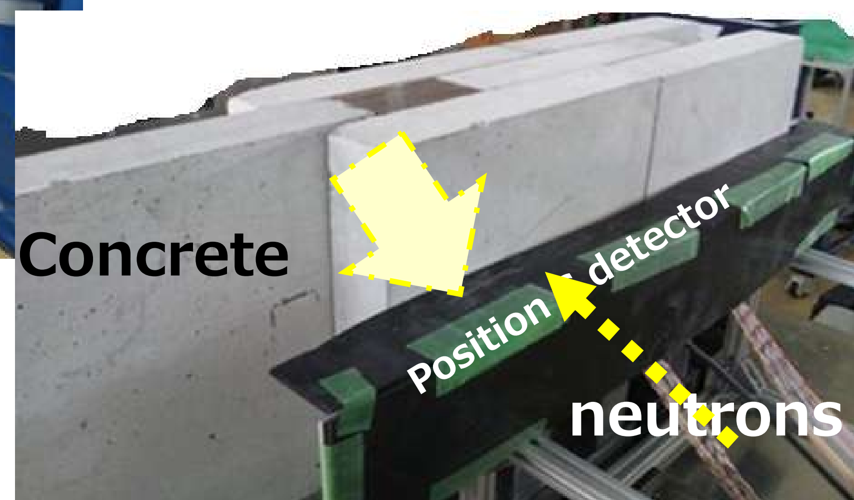


Simulation results: time distribution of normalized intensity of backscattered neutrons with normal state

Development of reflected neutron imaging method: experiment at RANS



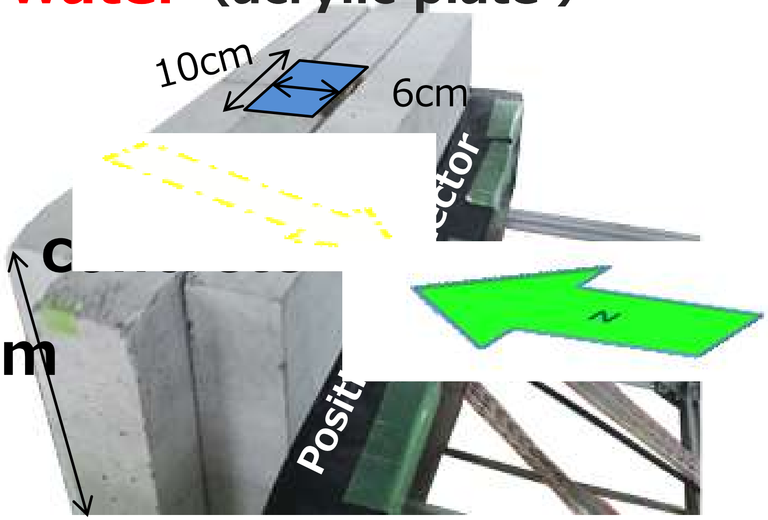


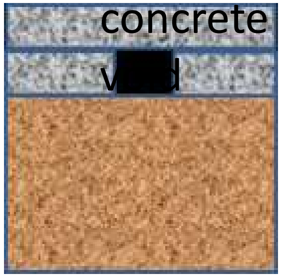


＜Concrete slabs with void, water＞

Reflected neutron imaging method: Results

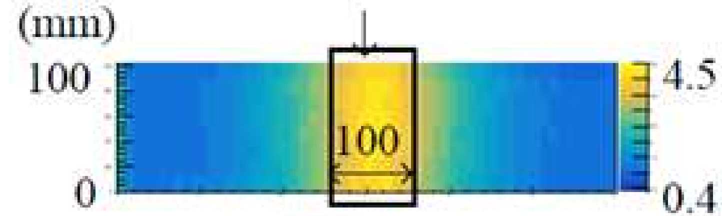
water **(acrylic plate)**



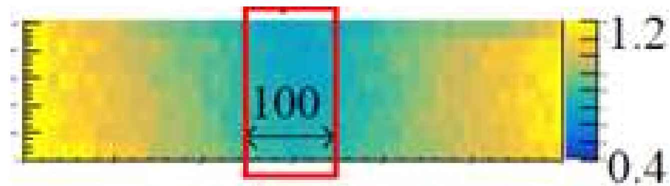


Degradation : water

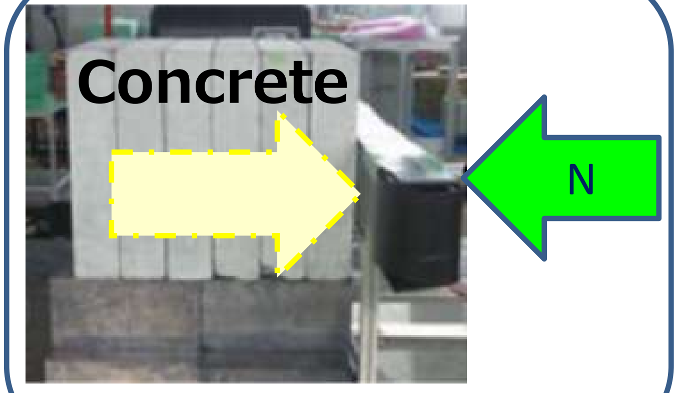
Neutrons increase 4~8 times



Healthy condition



Void, decrease 20~40%

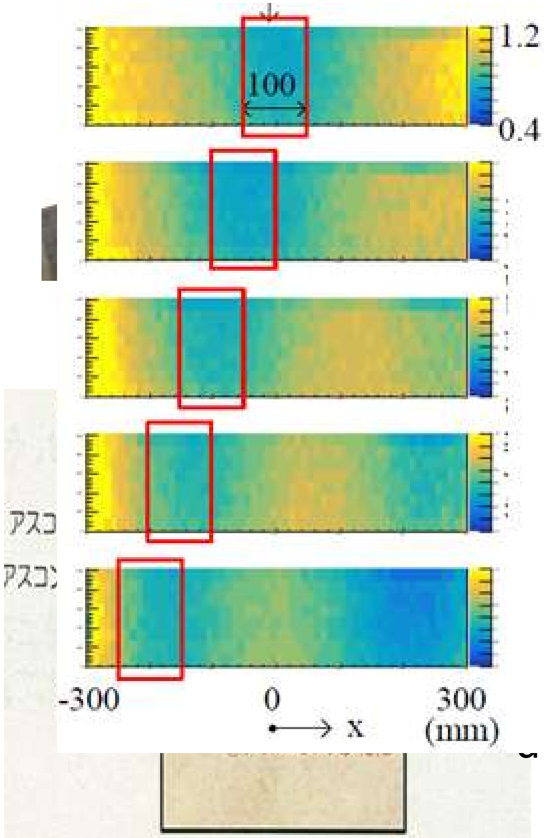


30cm thickness case

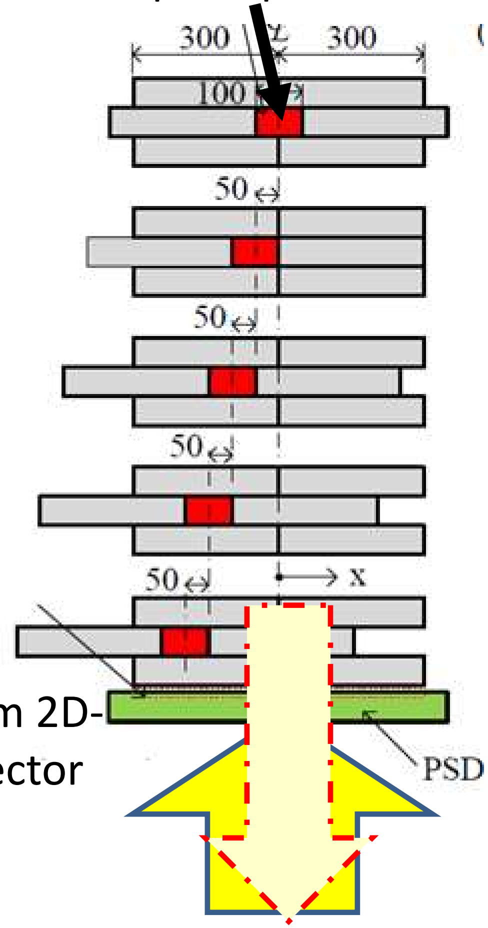
Timing(TOF), energy, intensity ratio
->non-destructive inspection inside concrete degradation

Position sensitive measurement of water, air void with reflected neutron imaging method

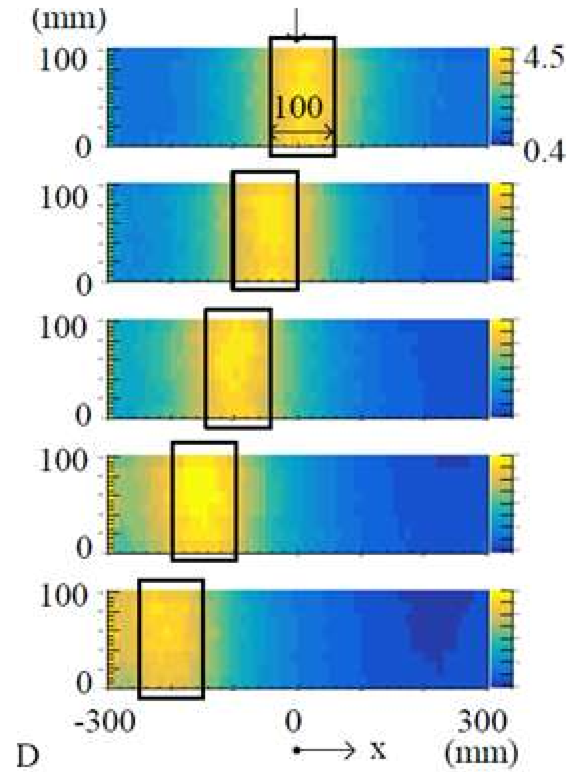
Air



Moving acrylic plate position



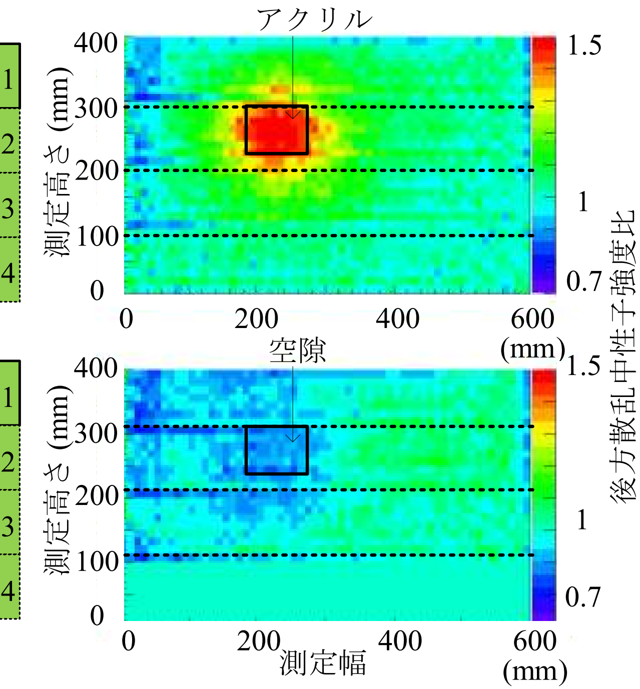
Acrylic plate



Fast neutron

Water and air hole in a floor slab with asphalt

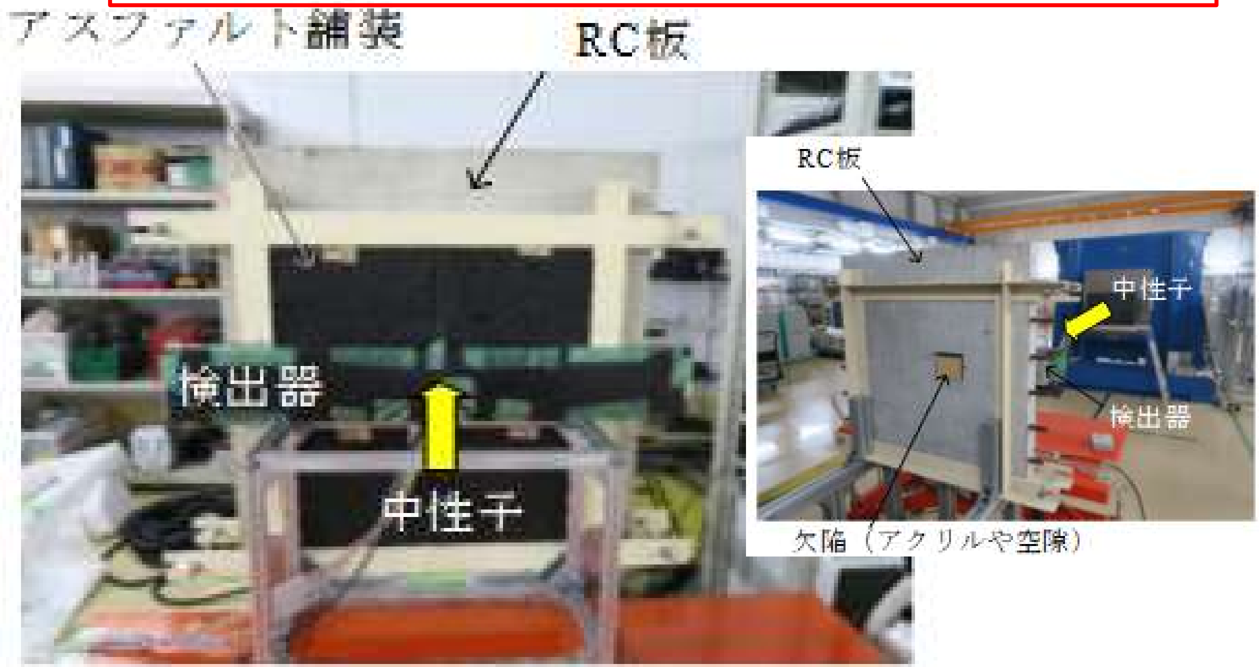
·Reflected (backscattered) Neutron imaging method



床版模擬サンプルの測定結果

Success of visualization of water, void with realistic sample

- Void under asphalt 5cm
- 5cm, 3cm air hole, acrylic plate

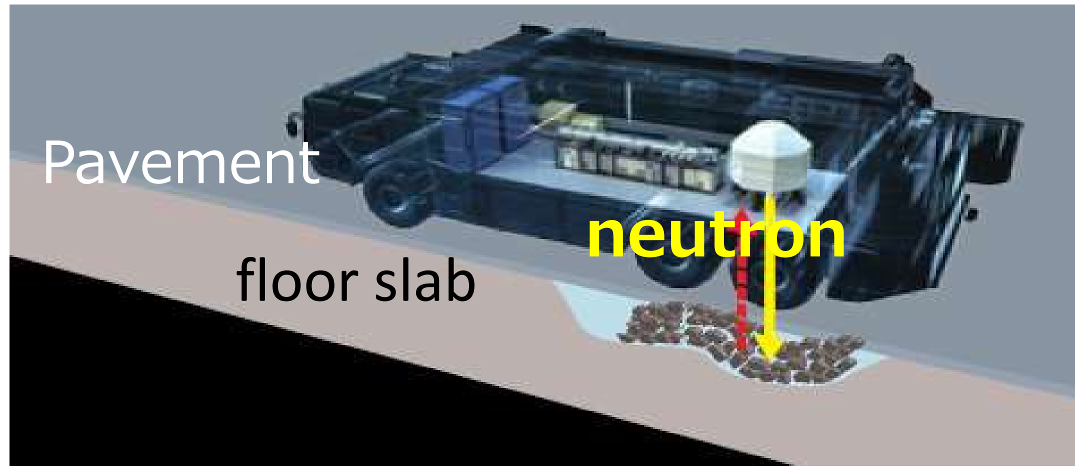


・Yoshimasa Ikeda, Yoshie Otake and Maki Mizuta Journal of Advanced Concrete Technology, Vol.15 (2017) pp.603-609, 2017, doi: 10.3151/jact.15.603
・Y.Ikeda, Y.Otake, M.Mizuta, CLES/LANSA`17 (Conference on Laser Energy Science / Laser and Accelerator Neutron Sources and Applications 2017)

Further RANS development for practical use

compact neutron system in 5ton truck

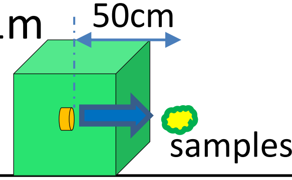
Non-destructive inspection system

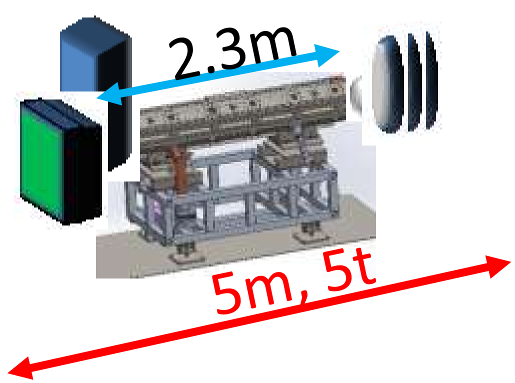


- **放射線障害等防止法第10条 および 関連規定(平成17年7月改定)**Japanese regulation 4MeV>linac
  - 橋梁等の非破壊検査に用いる**直線加速器で4メガ電子ボルト**以上のエネルギーを有する放射線を発生しないものは、放射線発生装置の使用の場所の変更を都度許可を得る必要がなく届出で足りることとする。(ただし、設備については、事前に原子力規制委員会原子力規制庁の届け出許可が必要。)
  - **実行線量:(3か月で1.3mSv)**
  - **労働安全衛生法令による管理区域**
  - **人事院規則による管理区域**

RIKEN : RANS2 development Dr.T.Kobayashi

1. Prototype of transportable neutron source development; fast neutron (without moderator)
2. Smaller system realization for the practical use as floor standing type (with moderator)

Power	Neutron yield at the target	Size of Target station shielding	Beamline length	Neutrons at the sample	
RANS: 7MeV 700W	10^{12} n s^{-1}	<2m	1.5m	*10^{5} n s^{-1}	RANS 1.3% (RF Duty cycle)
			5m	*10^{4} n s^{-1}	
RANS2 2.49MeV 250W	*10^{11} n s^{-1}	<1m 	0.5m	*10^{4}~10^{5} n s^{-1}	RANS2 3% (RF Duty cycle)
			1.5m	*10^{4} n s^{-1}	



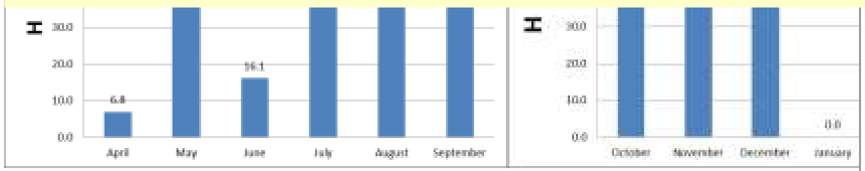
The collaboration,
<u>RFQ, with Prof. N.Hayashizaki, Tokyo Institute of Technology</u>

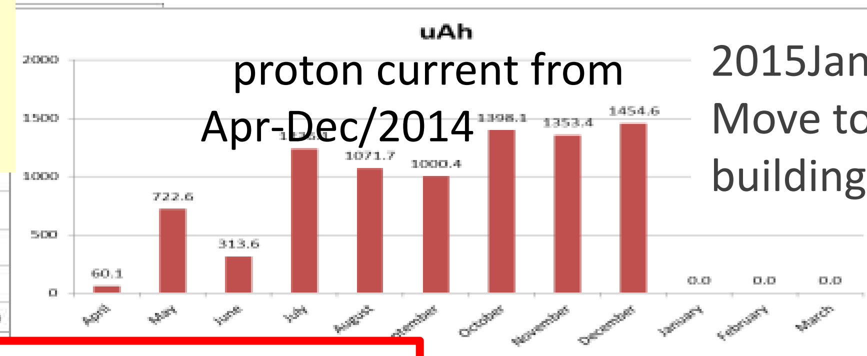
RANS record of beam on time with proton current monitor at the target

- 陽子線放射稼働月別累積時間

42929=25312+17607 μAH：2013-2018 March Jul.

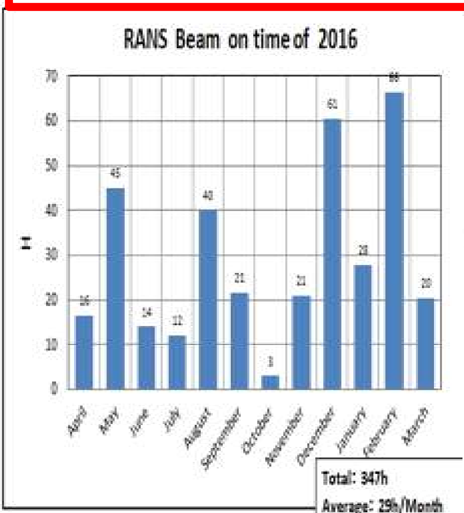
RANS実験 beam on time (メンテナンス年2回)
Mon-Fri. 10:00-17:00
Collaboration (人の手当がある)基本

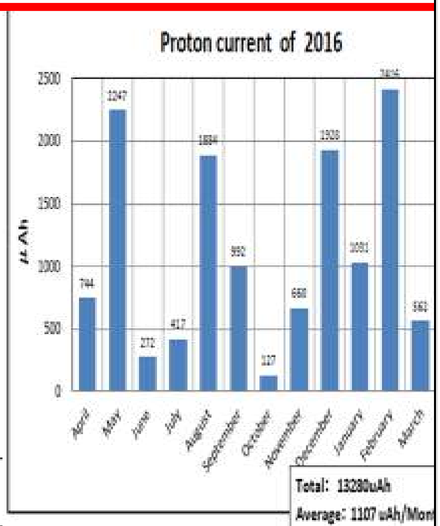


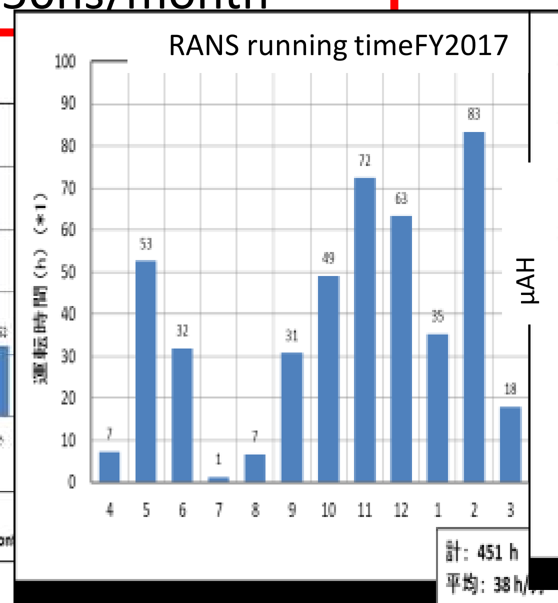


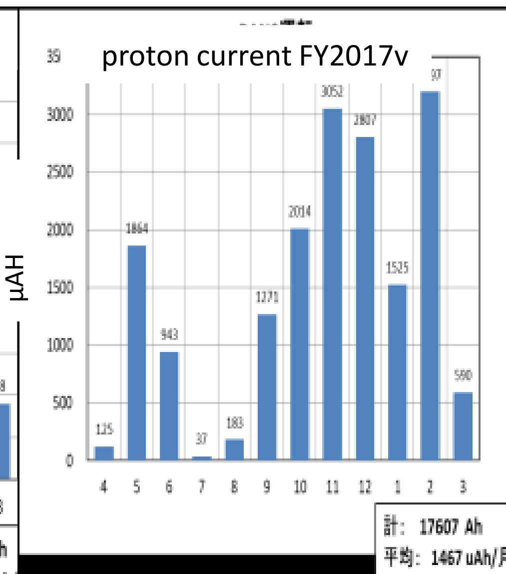
2015Jan-2016Jan Move to new building

Beam on total **898h**=347＋451h('17) ~36h/month
Operation time =proton beam＊4.5～150hs/month







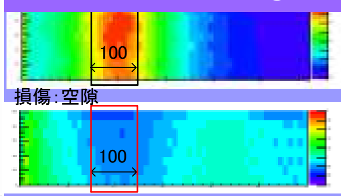


RIKEN Accelerator-driven compact Neutron sourcesRANS,RANS2

Non-destructive inspection; infrastructure


See through concrete
In the pavement :
reflected imaging

Visualization of degradation



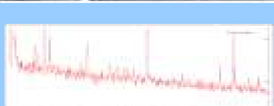
Transmission imaging : thicker than30cm

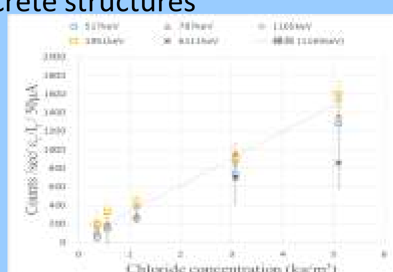
Salt detection of concrete

Prompt-Gamma Neutron Activation Analysis (PGAA)

Salt Concentration Measurement of concrete

1.6～2kg/m^3 Japanese standards for concrete structures





Compact Neutron

Anytime, anywhere

RANS : 15m, 25ton MeV～meV

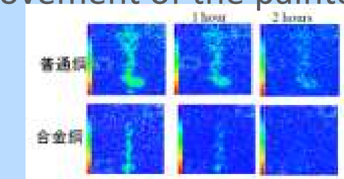
RANS2 :
~5m
~5ton
E=500keV～meV

Transportable, Floor standing

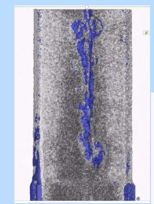
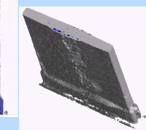
Iron and steel: Corrosion visualization

Corrosion;2~% of GDP is spent for anti-corrosion

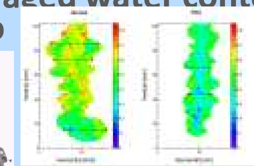
Visualization of the corrosion and its related water movement of the painted steel



3D visualization

Averaged water content ratio

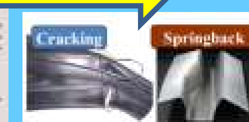


-> J-PARC experiment

Towards strength and formability

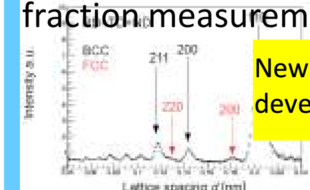
Texture evolution

On-site use

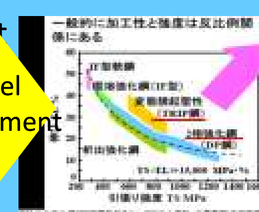


1~2%agreement with J-PARC

retained austenite fraction measurement



New steel development



Thank you for your attention!

This work was partially supported by the Council for Science, Technology and Innovation (CSTI), the Cross-Ministerial Strategic Innovation Promotion Program (SIP), "Infrastructure Maintenance, Renovation and Management" (funding agency: JST), and the Photon and Quantum Basic Research Coordinated Development Program from the Ministry of Education, Culture, Sport, Science and Technology, Japan. It was also supported by JSPS KAKENHI Grant Numbers 25289265 and 25420078. Authors would like to thank the Iron and Steel Institute of Japan (ISIJ) Research Group for their beneficial assistance.

Pre-stressed concrete bridge from Niigata-Toyama

- **<u>放射線障害等防止法第10条　および　関連規定（平成17年7月改定）</u>**
  - 橋梁等の非破壊検査に用いる<u>**直線加速器で4メガ電子ボルト**</u>以上のエネルギーを有する放射線を発生しないものは、放射線発生装置の使用の場所の変更を都度許可を得る必要がなく届出で足りることとする。（ただし、設備については、事前に原子力規制委員会原子力規制庁の届け出許可が必要。）

Observation of water distribution on under-film corroded steels by using RANS

RIKEN Atsushi Taketani, Y. Wakabayashi, Y. Otake

Kobelco Research Inst. Inc. T. Wakabayashi, K. Kono

Kobe Steel, Ltd. T. Nakayama

Cost of corrosion including economy loss was about 100 billion US$ / year in Japan at 1997. (3% of GDP)
Paint costed 30B US$. This values are common in the world.

$\underline{Fe}$-> $Fe^{2+} + 2e^-$

$1/2\underline{O_2} + \underline{H_20} + 2e^- \rightarrow 2OH^-$

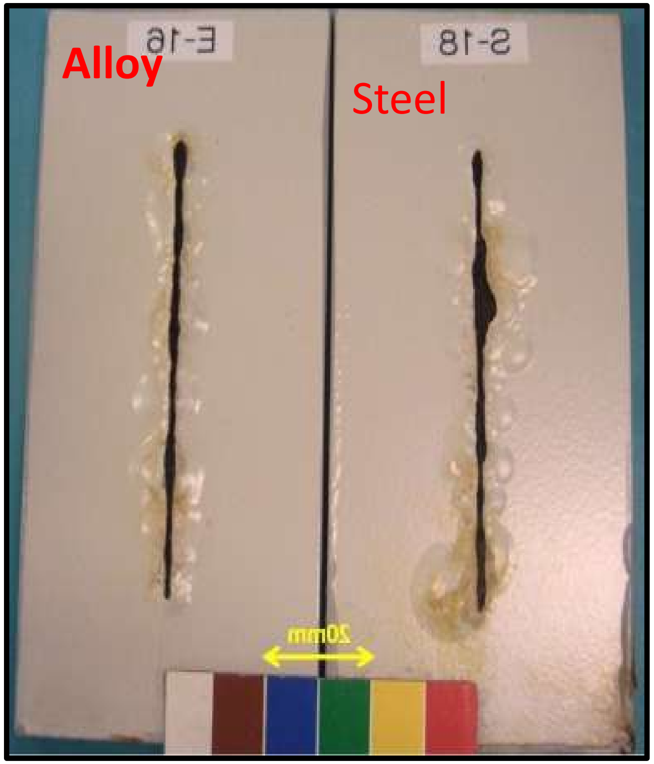
$Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2$

$Fe(OH)_2 + 1/4\underline{O_2} \rightarrow FeOOH + 1/2\underline{H_2O}$

1.Industrial application- Iron and steel

Corrosion and water Visualization

Kobe Steel A.Taketani H.Sunaga, M.Yamada
Proposed by Dr. T . Nakayama



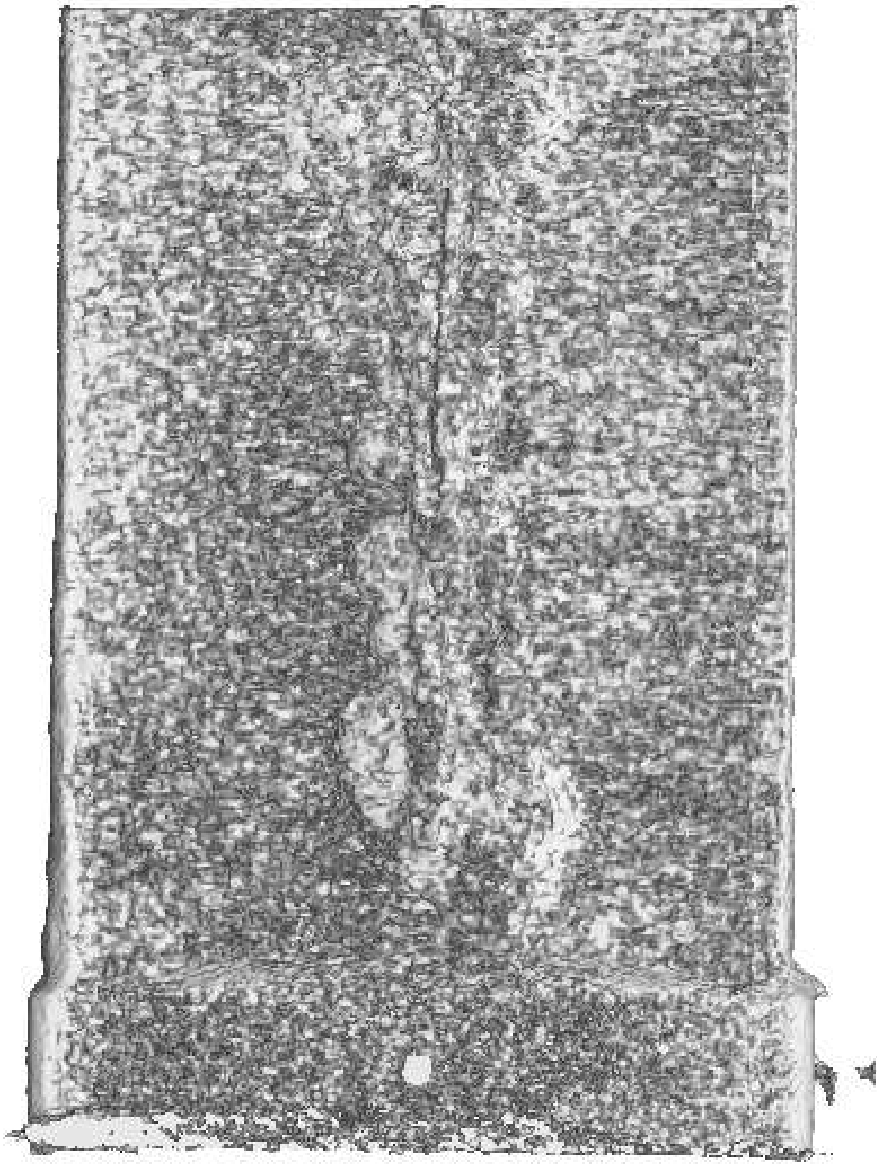
Non-destructive visualization of the corrosion in the steel under the film, with the water movement

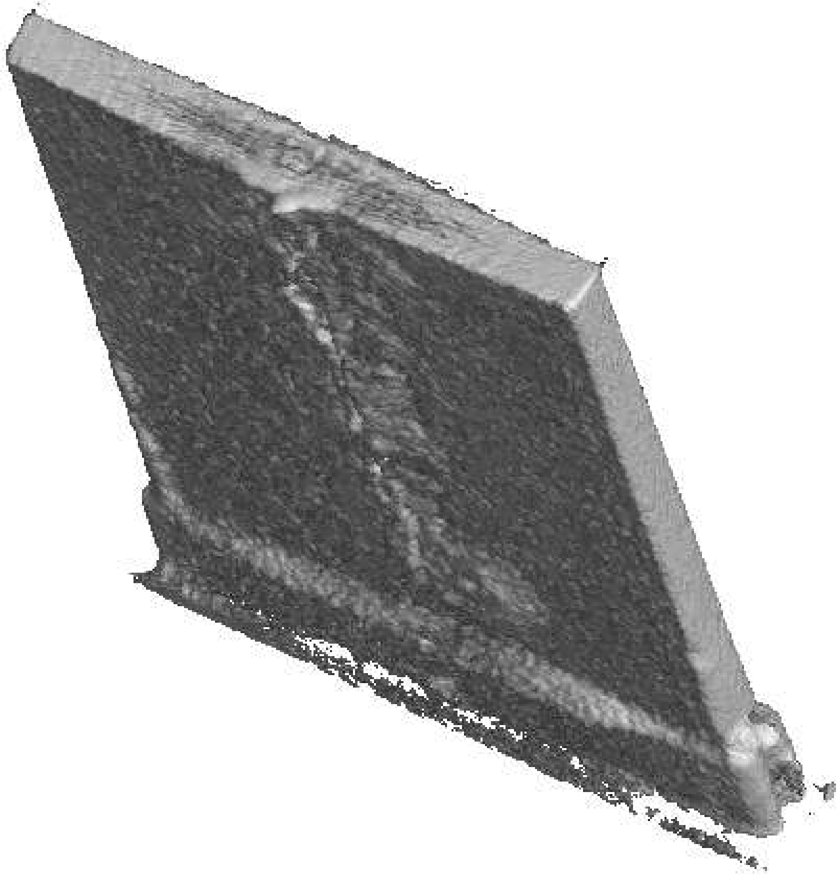
Cost of corrosion including economy loss was about 100 billion US$ / year in Japan at 1997. (3% of GDP)
Paint costed 30B US$. This values are common in the world.

Using neutrons can we distinguish corrosion, rust under the film, difference between normal steel and corrosion resistant alloy?

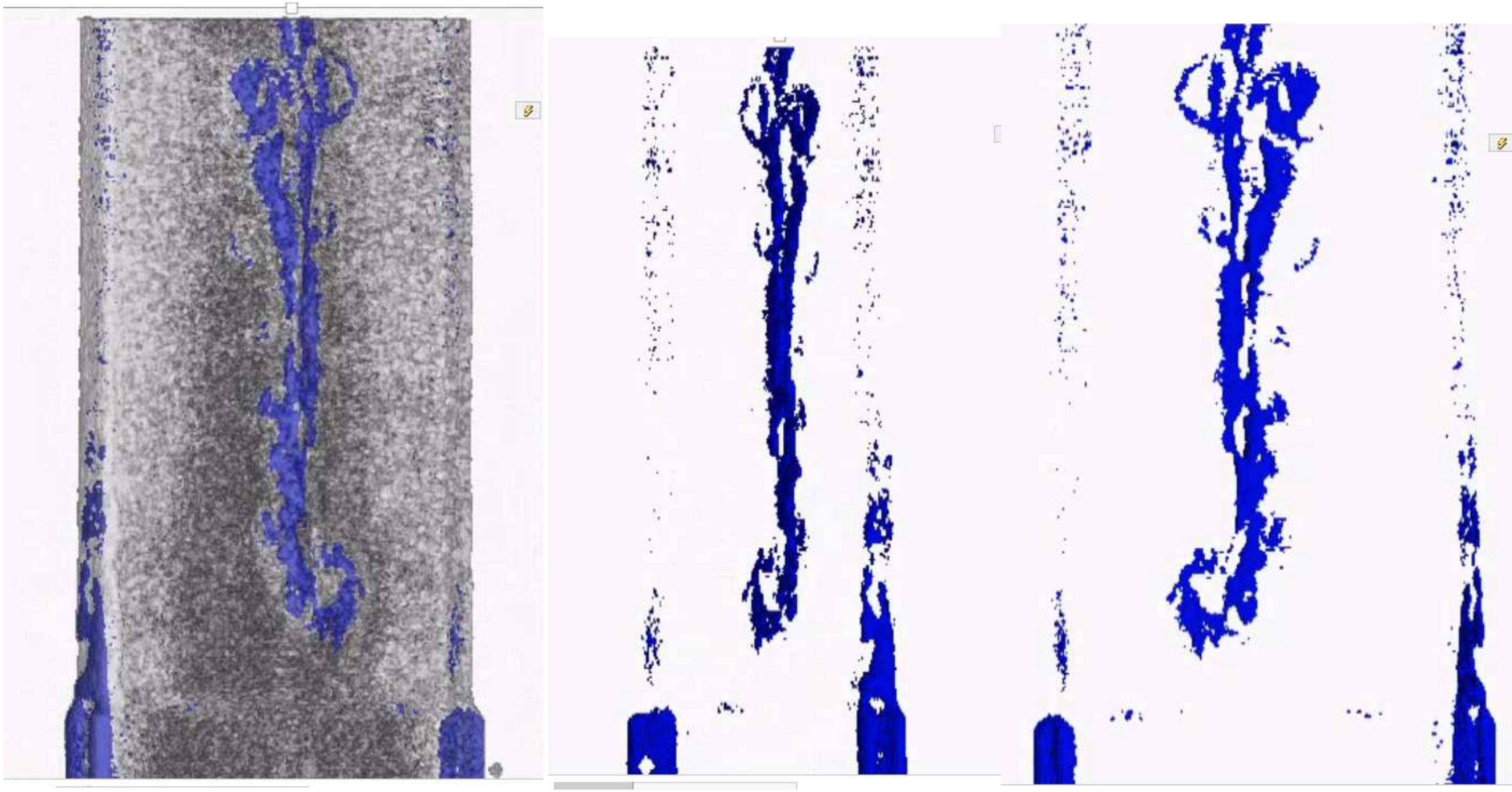
RANS imaging exposure time 1~5 min.

Corrosion and water visualization with RANS, normal steel sample, Kobe steel



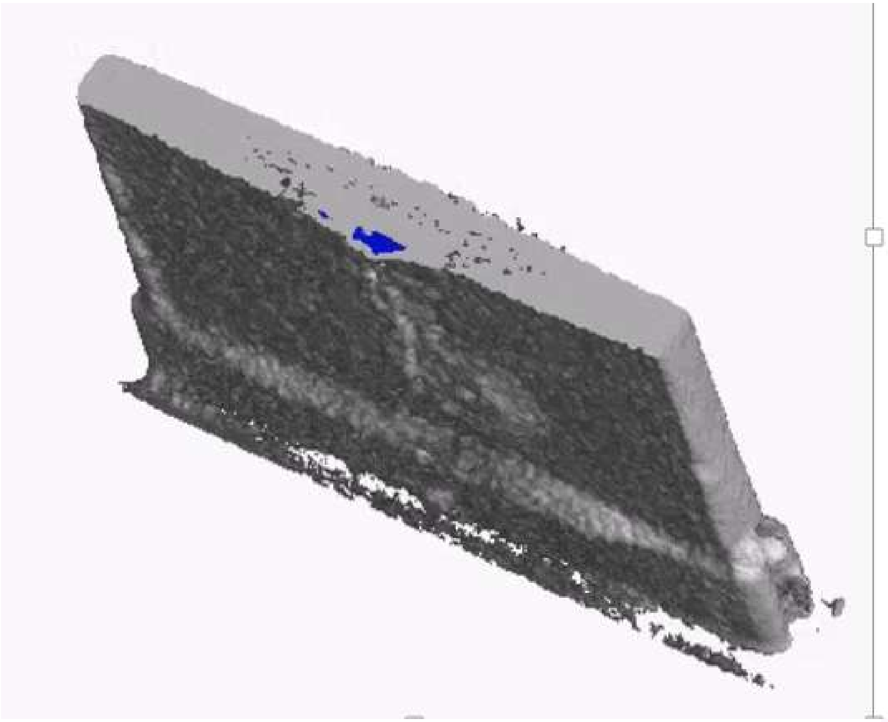


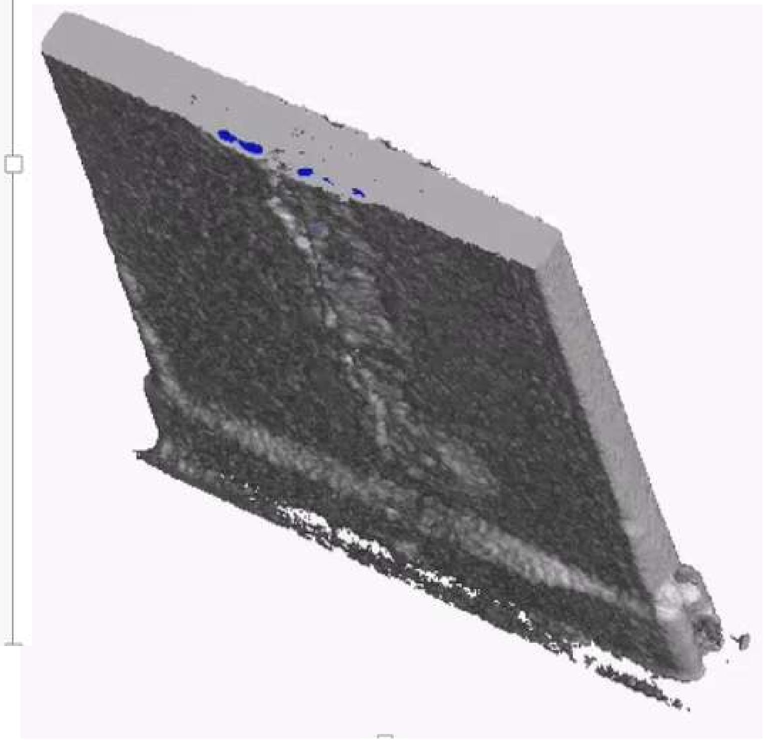
3D imaging of corrosion of normal steel



Cross section imaging after reconstruction

Time dependent corrosion change can be observed non-destructively on-site





Time-dependent water images of painted steel samples

Dr.T.NAKAYAMA,
Kobe Steel co

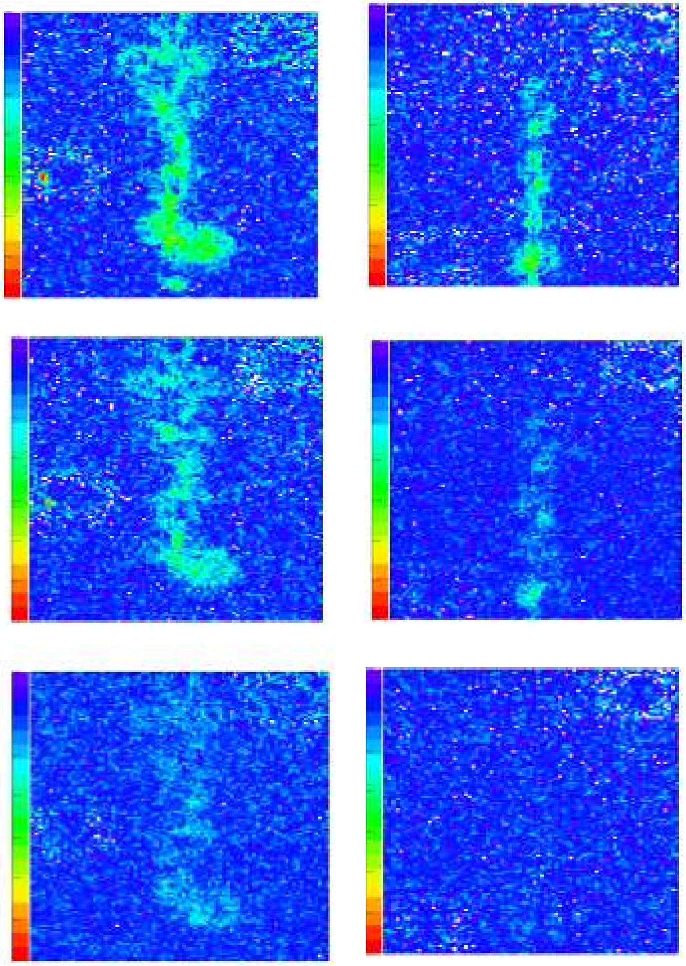
After 2 hours water soak

Air blow for 2 hours

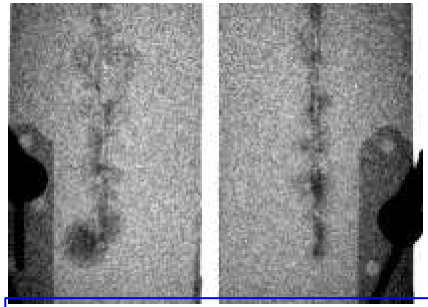
Normal steel | Corrosion resistant alloy steel

1 hour

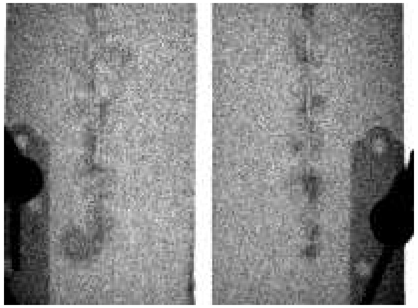
2 hours



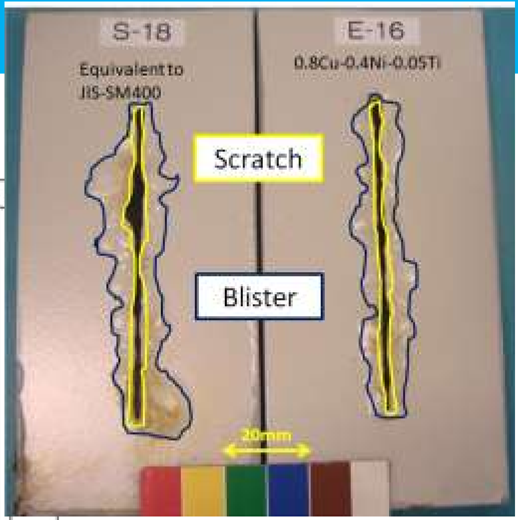
After wet process

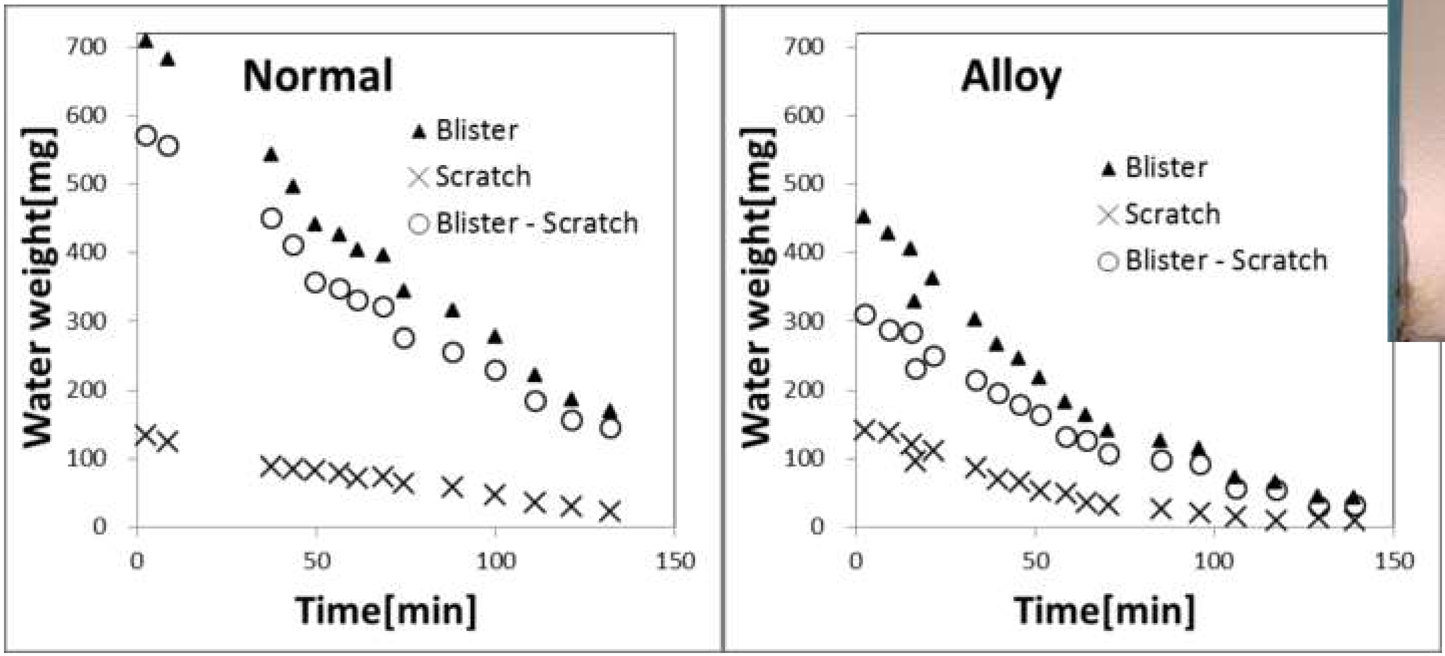


After 2 hours air blow



The time dependences of the amount of water in each region estimated by RANS





Most of the water is distributed in the blister region. The blister region in the normal sample contains more water than that in the alloy
＝corrosion resistance alloy contains less water

A.Taketani et al. ISIJ International DOI: 10.2355/ ISIJINT-2016-448

Prompt gamma neutron activation analysis

Sensitivity of each element for PGNAA[1]

AP2-2Y.Wawkabayashi talk

高感度 <0.01 mg | 良感度 0.01～1mg | 中感度 1 ～ 100mg | 低感度または測定不可

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pb	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac															
				Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
				Th	Pa	U											

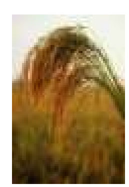
Major elements of concrete are **not so sensitive as Cl for PGAA**

Deterioration of concrete structure has been drawing a greater social attention and severe chloride damage has been observed.

Corrosion of steel bars causes spalling of concrete

Example of Port structure

Target element : Cl

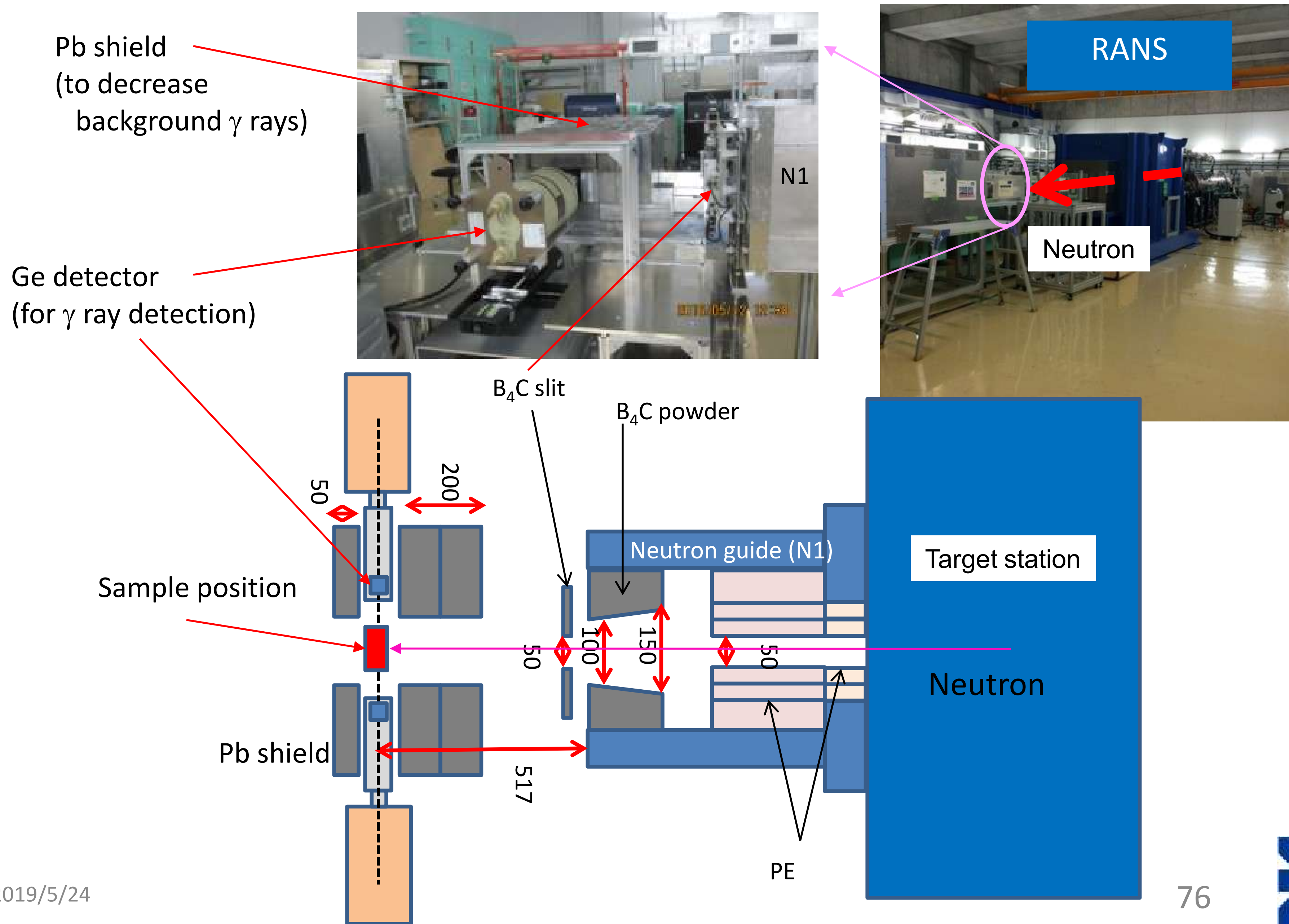


Example of sample : Rice

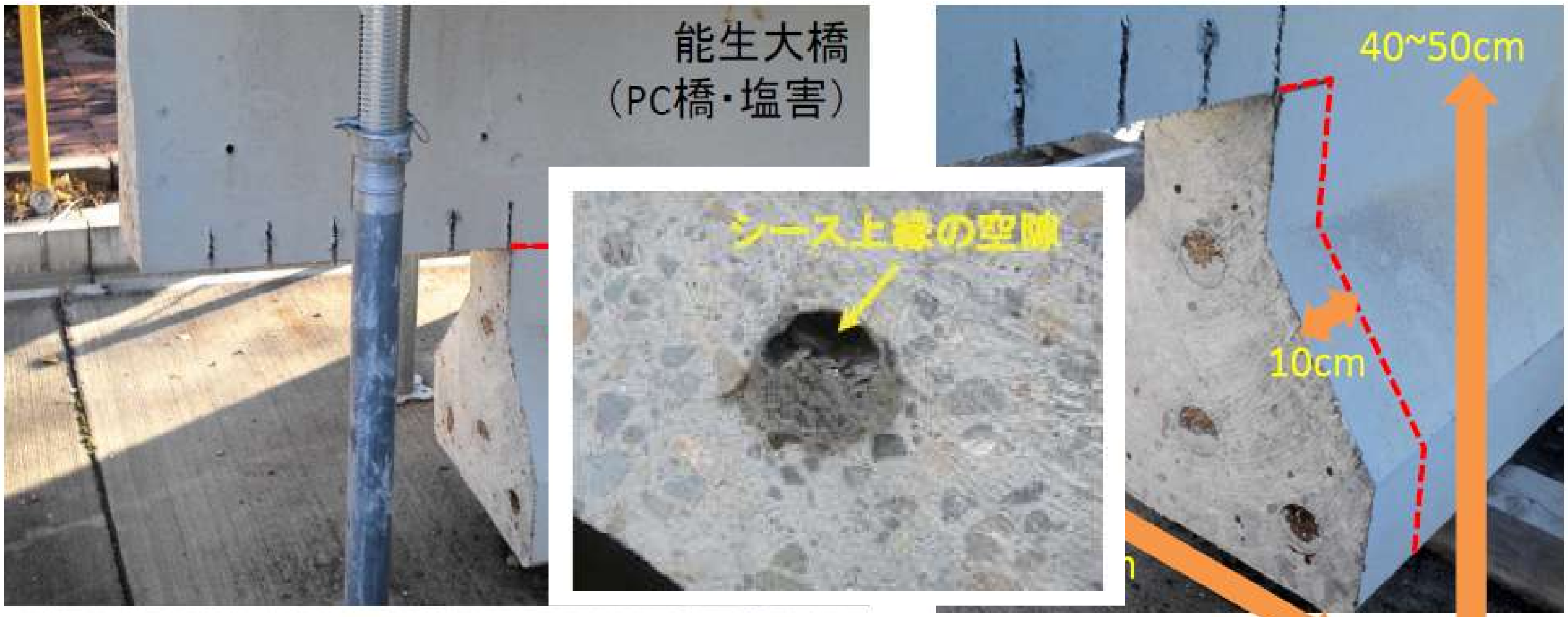
Target element : Cd, Hg, etc.

[1]Hitachi-Naka tech..Center technical report

Experimental setup and its schematic view



Pre-stressed concrete bridge from Niigata-Toyama



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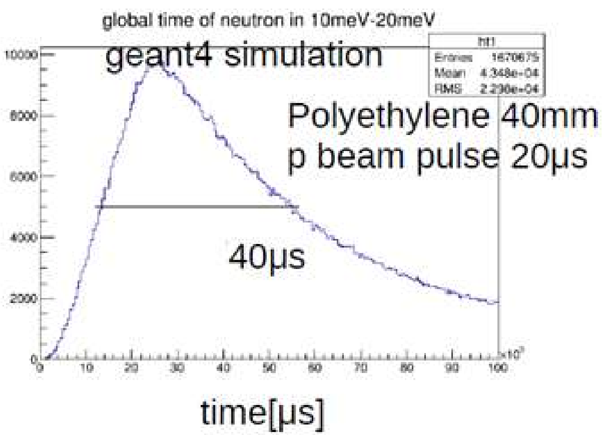
Towards higher resolution measurements of engineering diffraction

[redacted]

- Moderator thickness and time resolution

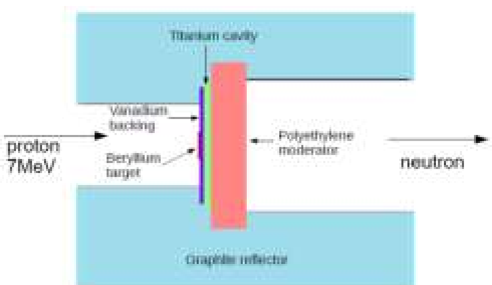


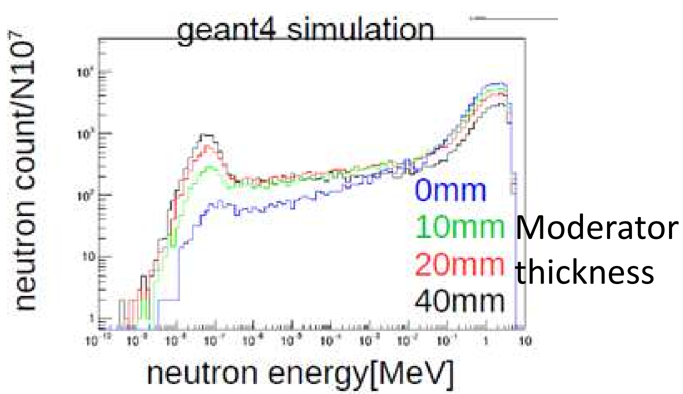
5m flight path=>3.5ms

Δt~ 40μs->1% resolution

->change the moderator with poison

(de-coupled) with 2cm-> 10μs



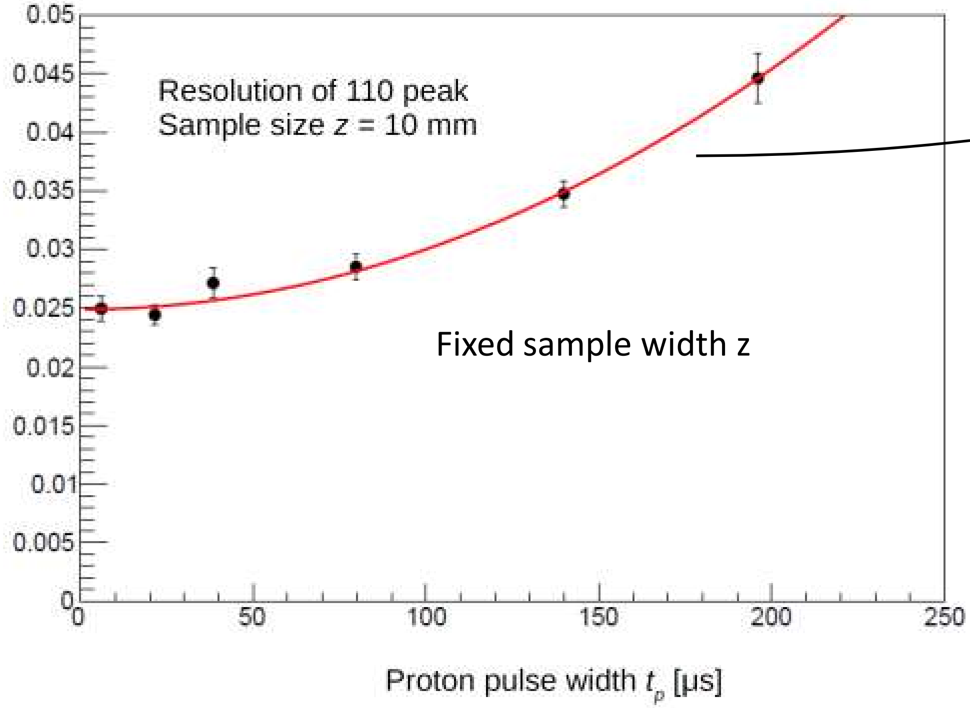


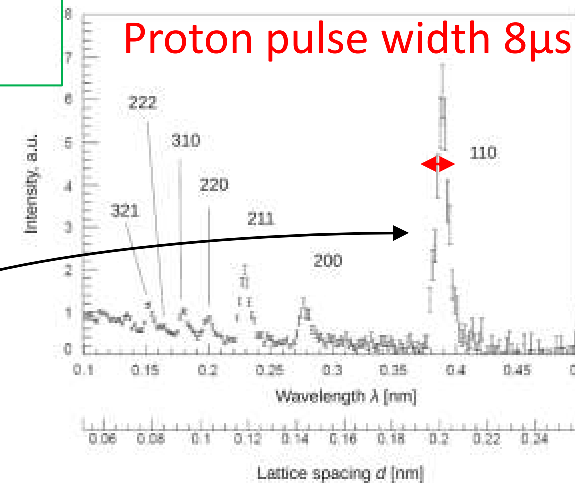
Estimation of the moderation time σ based on the diffraction peak width

$$\sigma = \sqrt{\sigma_{mod}^2 + \sigma_p^2 + \sigma_{sample}^2}$$

Change in the resolution of the 110 reflection as a **function of proton pulse** width t_p from 8 to 190μs

$$\sigma = \sqrt{\sigma_{mod}^2 + \sigma_p^2 + \sigma_{sample}^2}$$





Standard deviation by fitting the plots with

$$\sigma = \sqrt{\sigma_{mod}^2 + \sigma_p^2 + \sigma_{sample}^2}$$

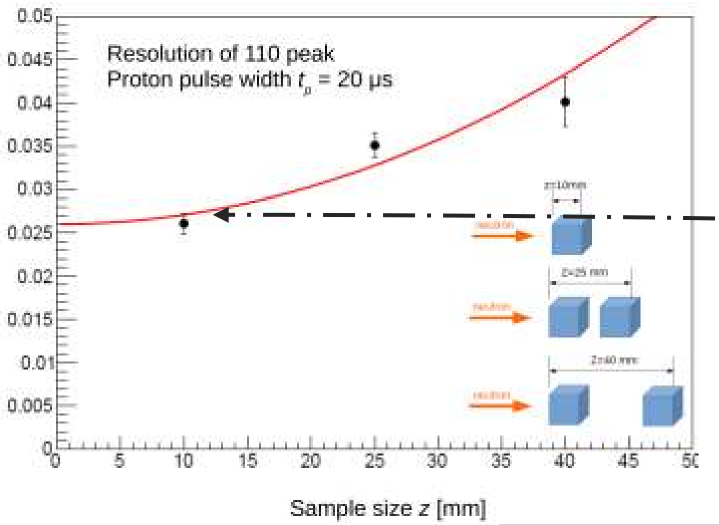
$$\sigma_p \propto t_p$$

$$\sigma_{sample} \propto z$$

Y. Ikeda, et al Nucl. Instr. Meth. A833 (2016) 61-67

- Change in the resolution of the 110 reflection as a **function of sample size**

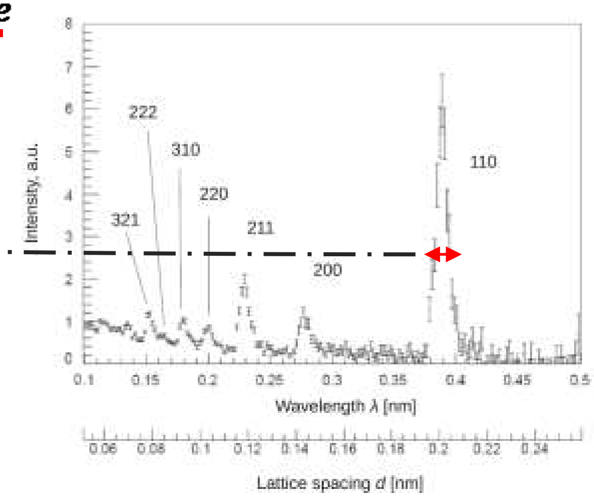
$$\sigma = \sqrt{\sigma_{mod}^2 + \sigma_p^2 + \sigma_{sample}^2}$$



Standard deviation
by fitting the plots with

$$\sigma_p \propto t_p$$

$$\sigma_{sample} \propto z$$



The moderation time for RANS with coupled moderator is estimated to be **30µs**

Y. Ikeda, et al Nucl. Instr. Meth. A833 (2016) 61-67

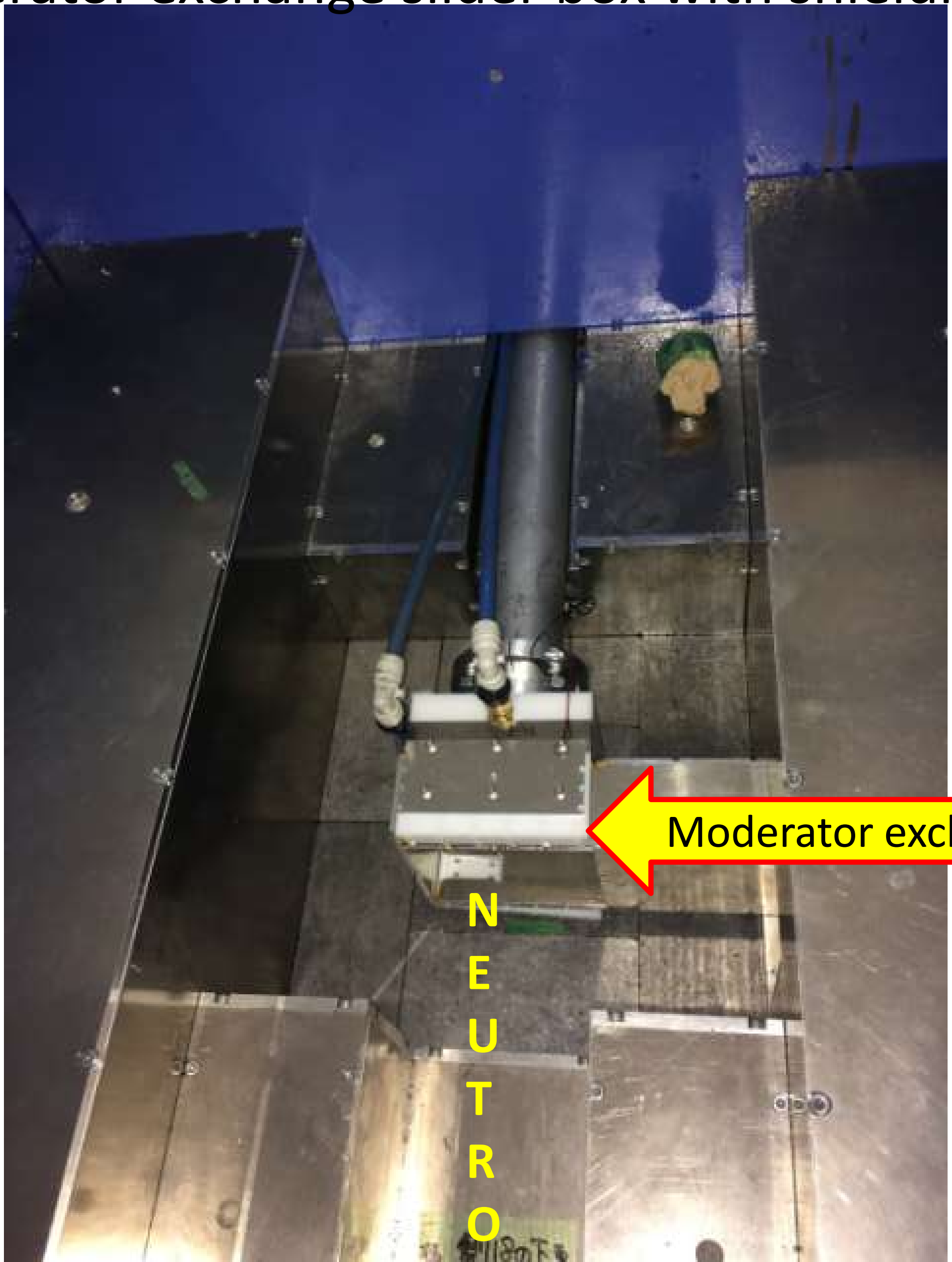
With decoupled moderator; 20µs

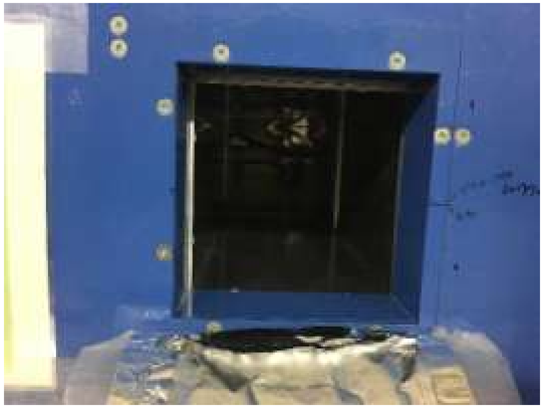
-> Poison, 10µs

RANS upgrade2017

New Be target, V-baking, Ti cavity, moderator exchange system

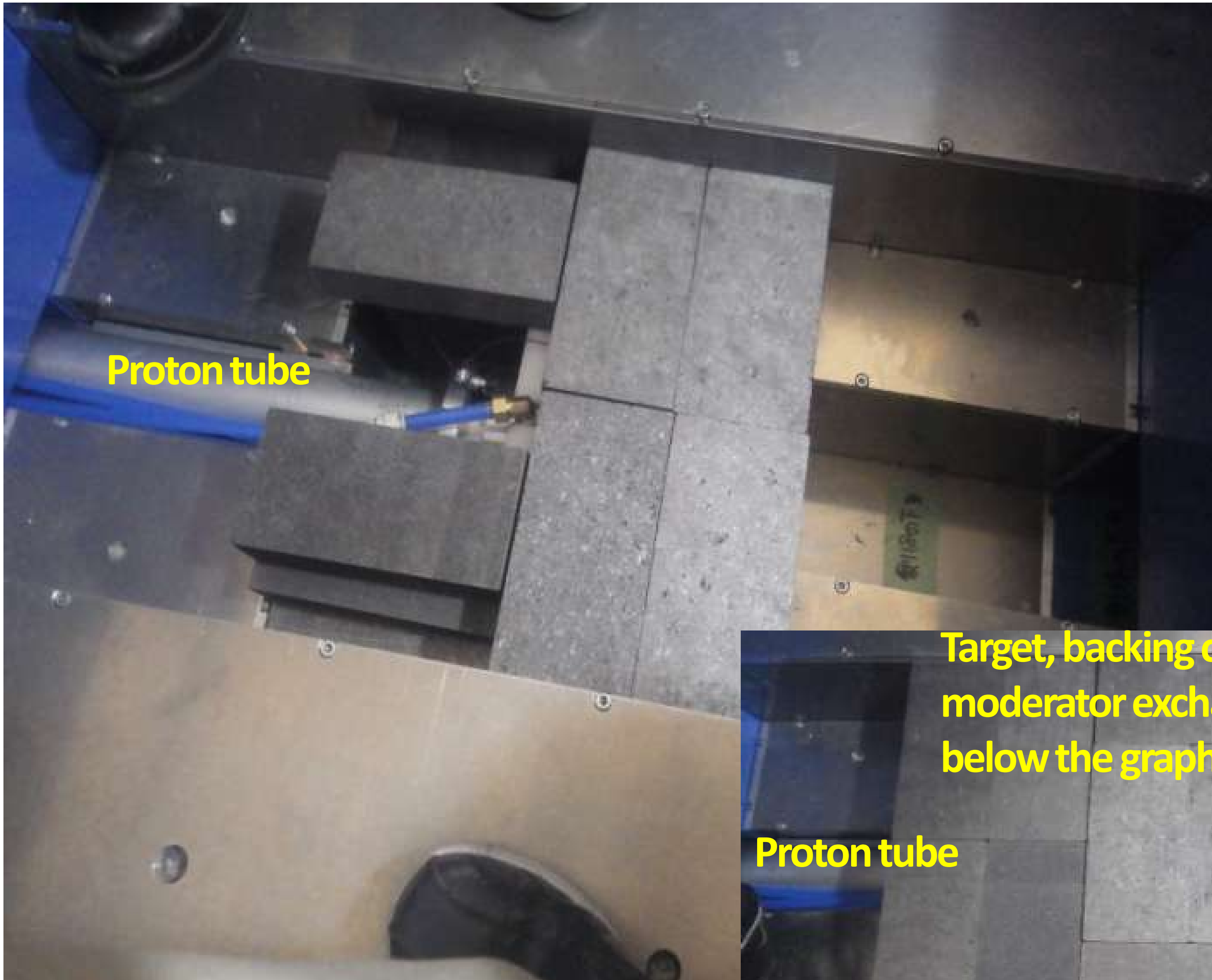
New Be target, backing, cooling cavity, are installed,
Moderator exchange slider box with shielding are placed from side

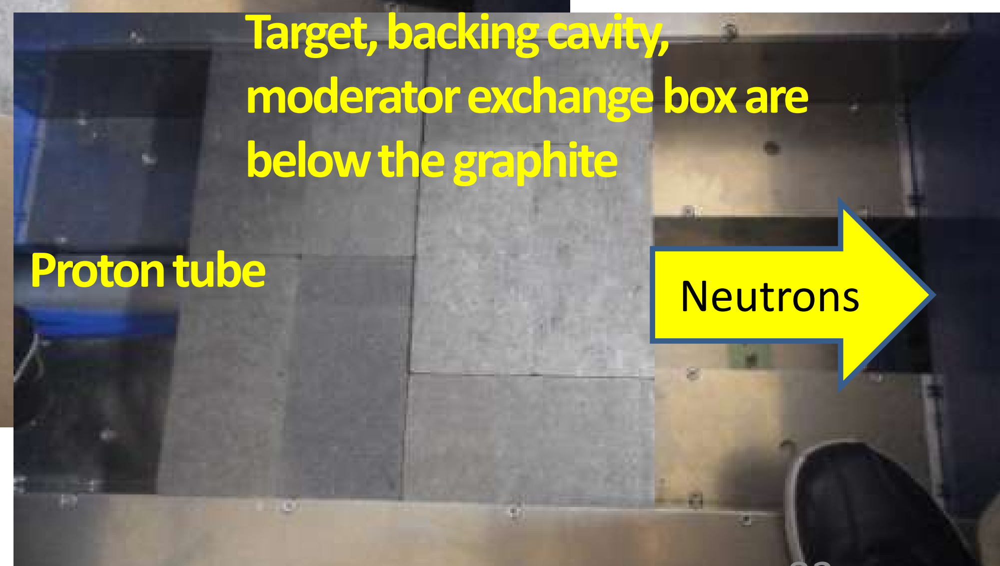




Moderator exchange from aside

Filing around the target and moderator with reflector, graphite blocks

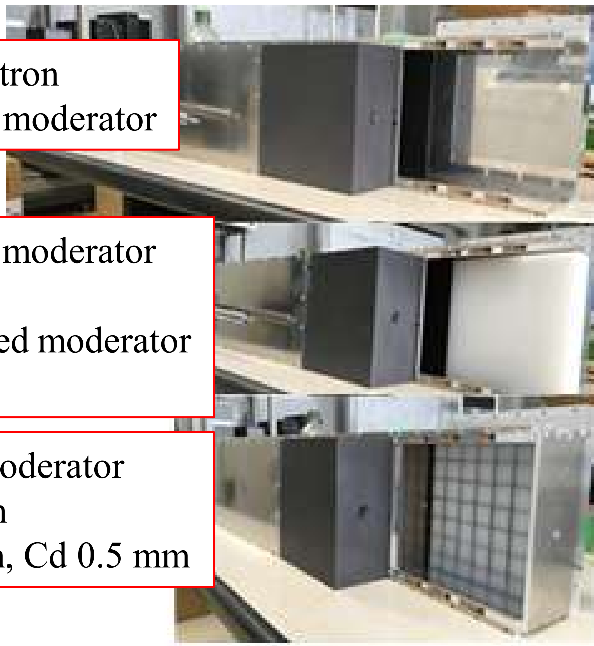


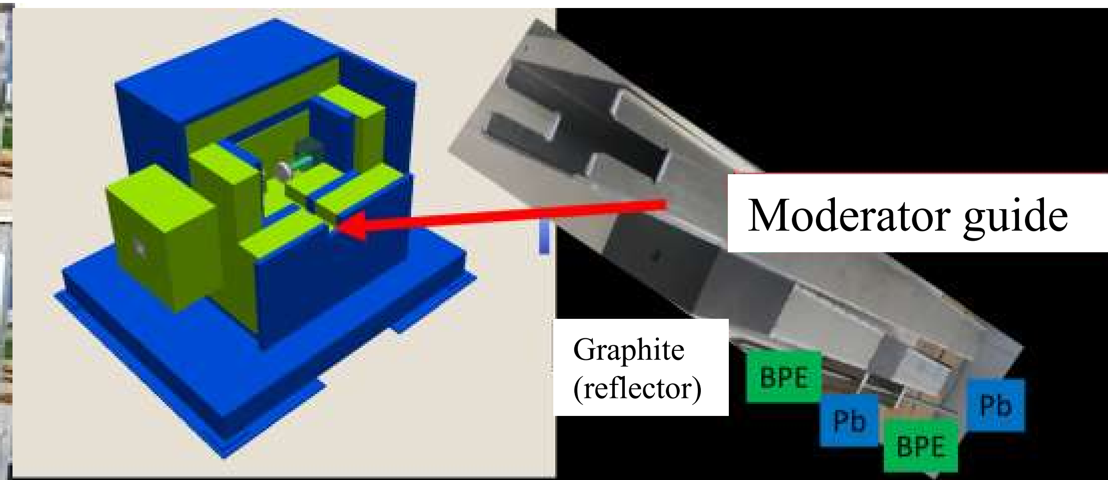


Moderators,

Energy	category	thickness	Exchange
Thermal Polyethylene	Coupled	2, 4, 6cm	Side hole exchange system
	decoupled	2cm B4C	
	Poison	2cm +B4C Cd	
Cold mesitylene	Coupled	Pre-mod 2~3cm Mod 3.5 cm	Opening the target station (Dr.Yamagata)

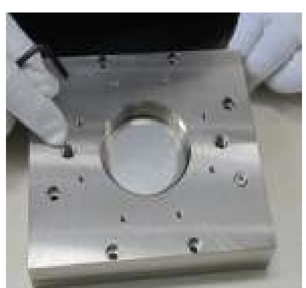
RANS up-grade（moderator）2017





New target+backing
V Φ90mm
+Be Φ50mm

New Ti cooling cavity

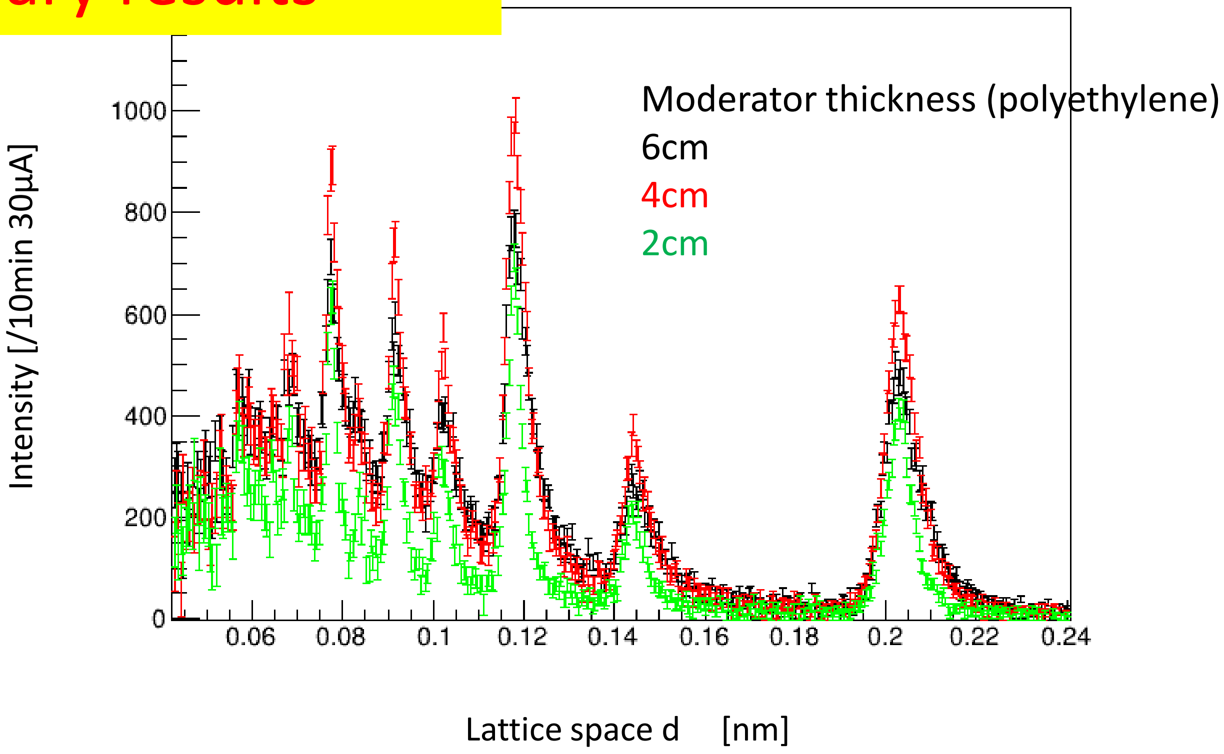


insulation flange

Experimental results with coupled moderator with different thickness, 2,4,6cm

Ferrite steel powder sample, 2θ=90deg

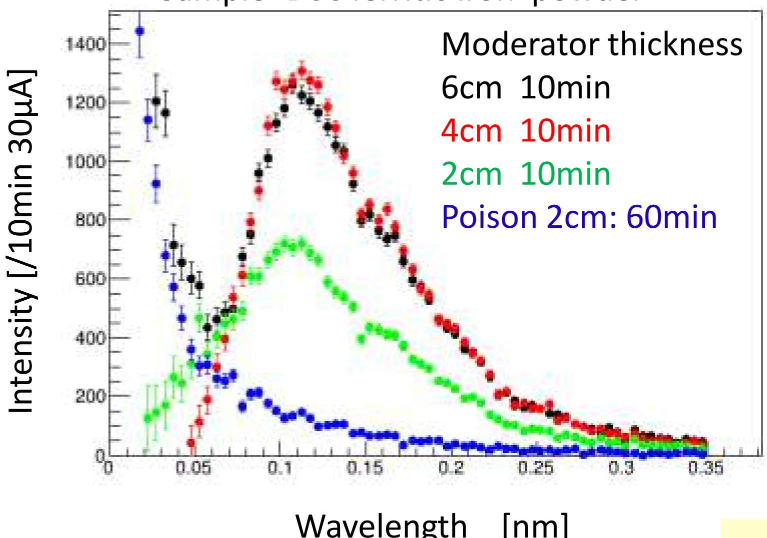
Preliminary results



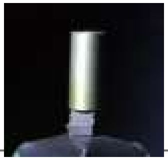
Intensity comparison with 2,4,6 coupled and poison

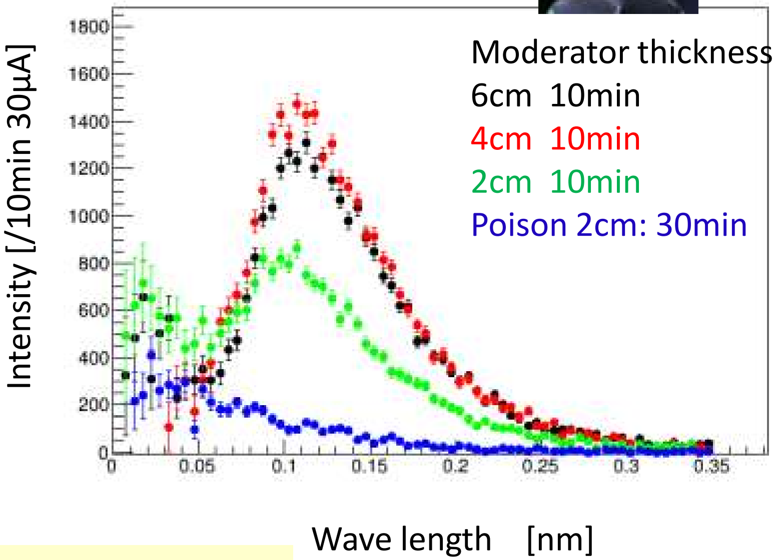
Preliminary results

Sample : BCC ferritic iron powder



Sample : Vanadium Colum





MC simulation (Geant 4)