Evaluation of Radionuclide Production and Neutron Transportation inside the Concrete Wall at the J-PARC Main-Ring Synchrotron

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J-PARC Symposium

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Activation at accelerator facilities

Neutrons are generated when proton beam irradiates to substance

Substance has reaction with generated neutrons

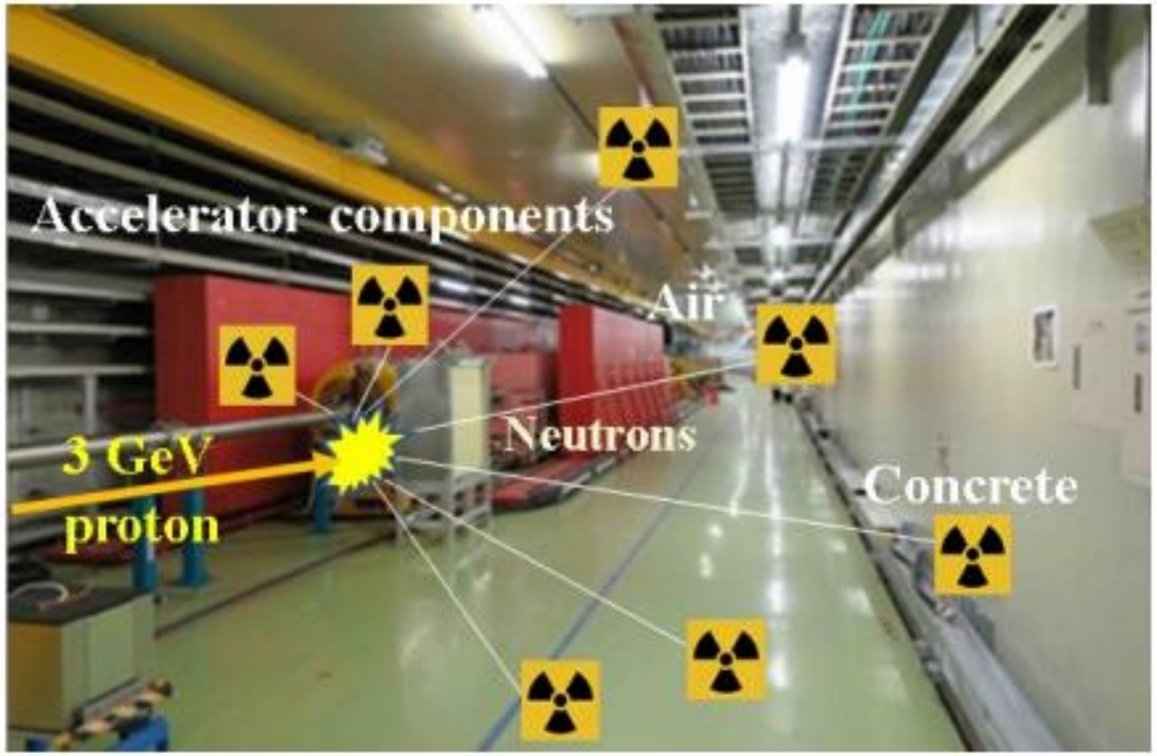
Reaction with fast neutron

Reaction with thermal neutron

Radionuclides are produced

(^{3}H, ^{7}Be, ^{22}Na, ^{24}Na, ^{54}Mn, ^{60}Co, ^{152}Eu, etc.)

Activation at accelerator facilities

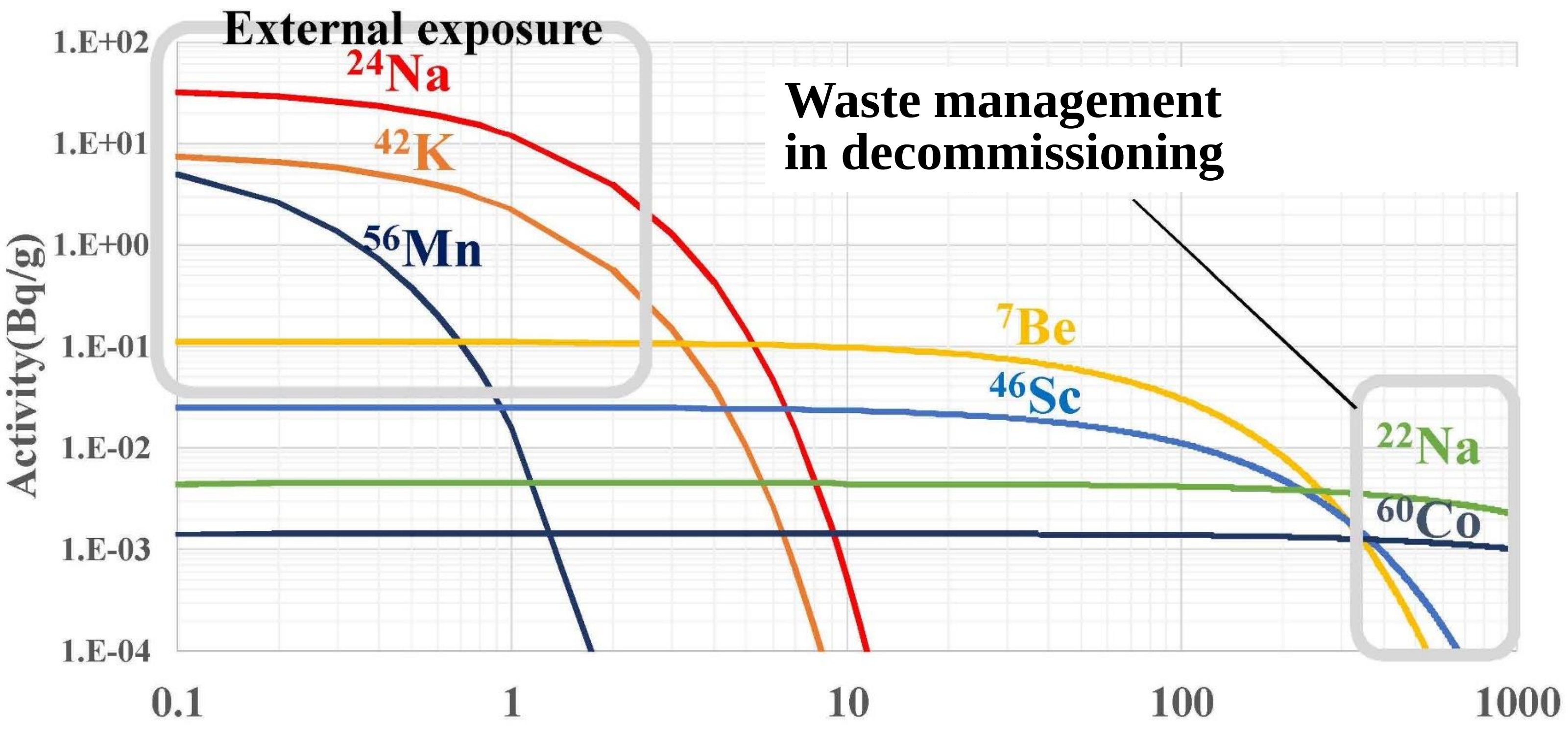


Activation inside accelerator tunnel (image)

Issues regarding activation at accelerator facilities

Important in reduction of the radiation exposure for workers

Important in radioactive waste management in decommissioning



Day after termination of accelerator operation

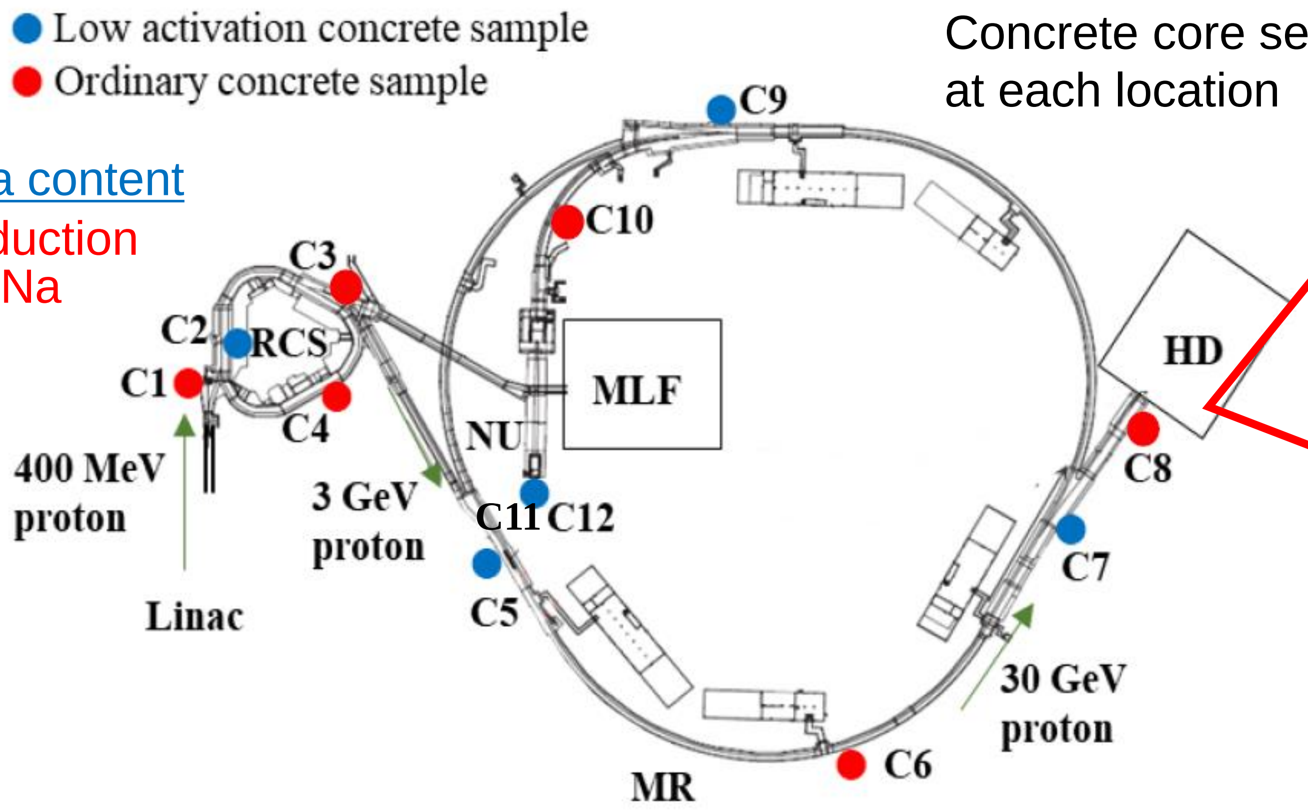
To clarify the mechanism of radionuclide productions in concrete at accelerators

Typical time profiles of radionuclides produced in concrete at proton accelerators.

Experiment setup for studying radioactivity production in concrete at J-PARC

Low Na content

Less production of ^{24}Na, ^{22}Na



Concrete core setup at each location

Plane view of the J-PARC accelerator tunnel for the beam-line

(K. Nishikawa, et al. (2021). JPS Conf. Proc. , 011148 (2021))

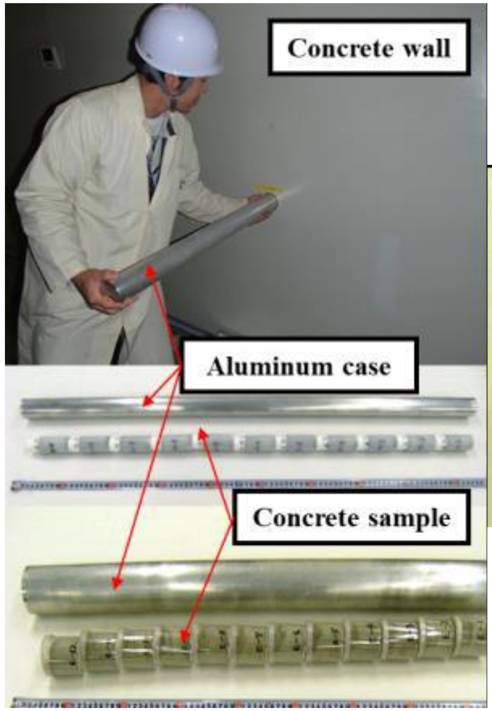
C1~C12 indicate the locations of the concrete samples installed

Concrete core samples are collected, measured and reinstalled at summer shutdown period every year (July-October)

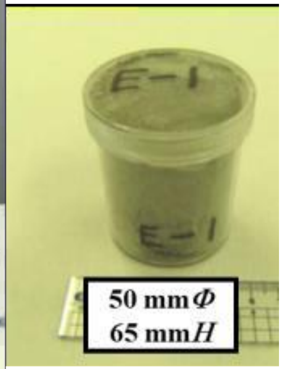
Experimental setup since 2010

(by J-PARC Radiation Control Section)

To survey the depth profile of radioactivity inside concrete walls



Density: 1.7 g/cm^3



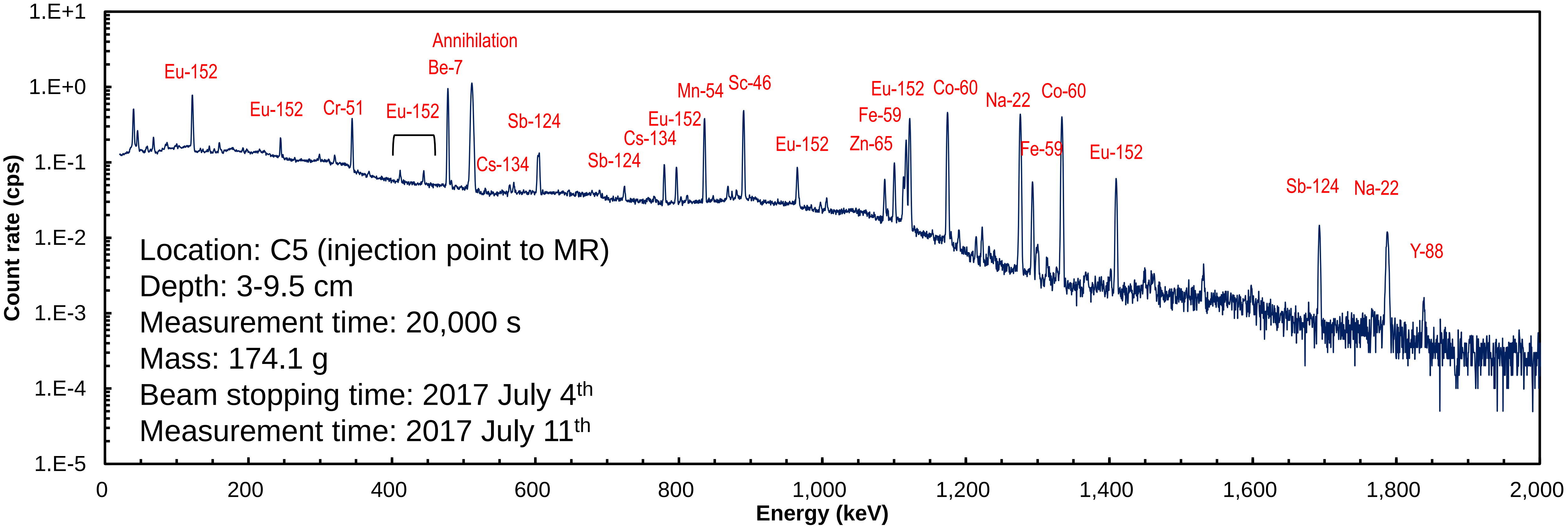
Sealed in the case

- Boring the concrete walls
- Pulverizing into powder

Stacked concrete samples were installed in the holes bored on the walls

Analysis of gamma-emitting nuclides in concrete

- Measurement time: 20,000 s
- Specific activity: corrected to the beam-stop time at corresponding beam-lines
- Efficiency calibration: mixed γ-ray source with same geometry of the concrete samples



An example of γ-ray spectra of concrete sample with HPGe detector at the injection point to MR

Objectives

- **Aim**

  To clarify the activation mechanism in the concrete at high-energy accelerator facilities.

- **Key issues of this report**

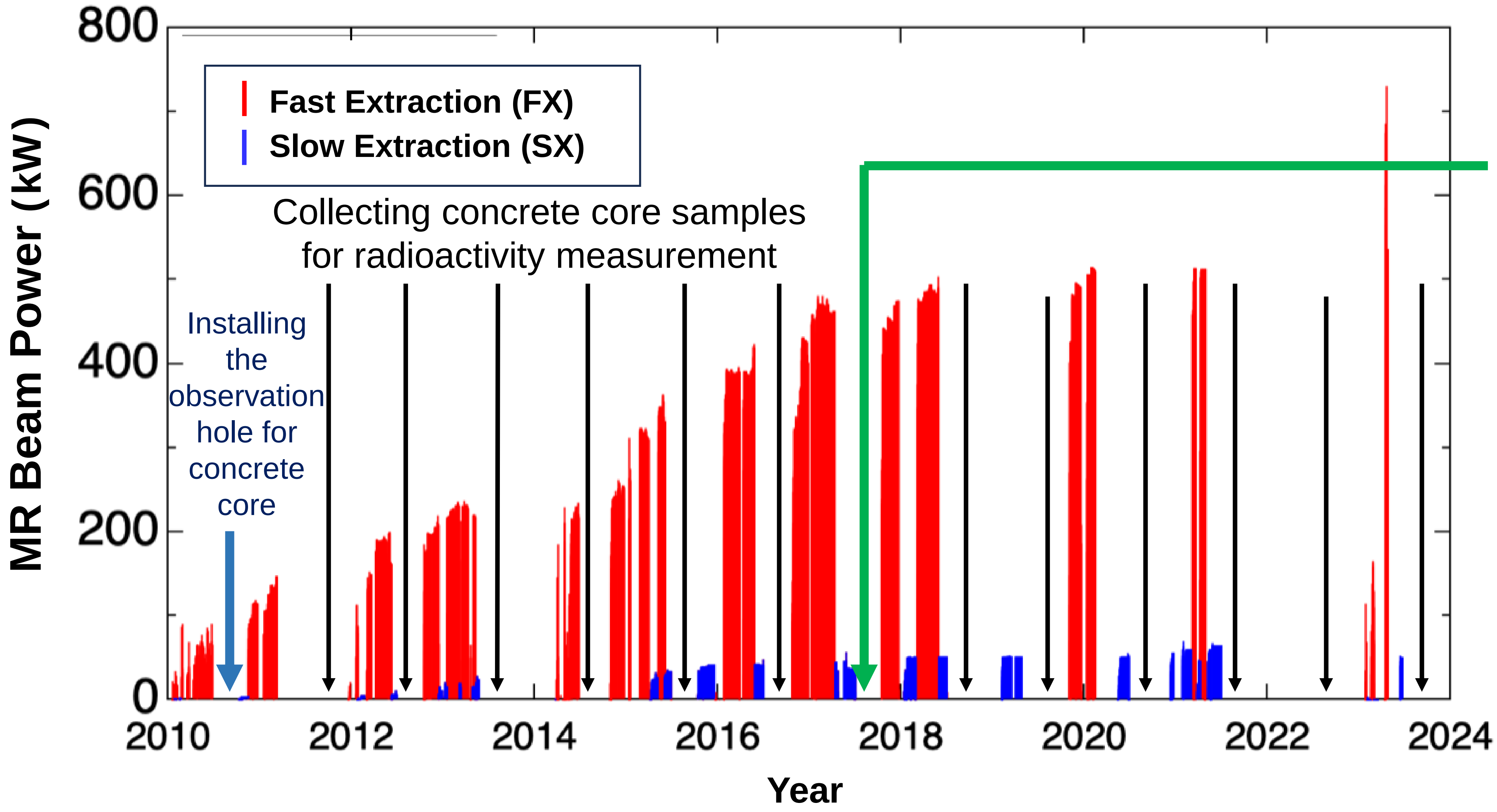
  - Transportation of neutrons in concrete at Main Ring injection point:

    → Depth profile of neutron-induced radionuclides

    → Comparison of depth profile of radionuclides and neutron fluence

    → Neutron attenuation behaviors (energy dependence of incident neutrons) in the concrete

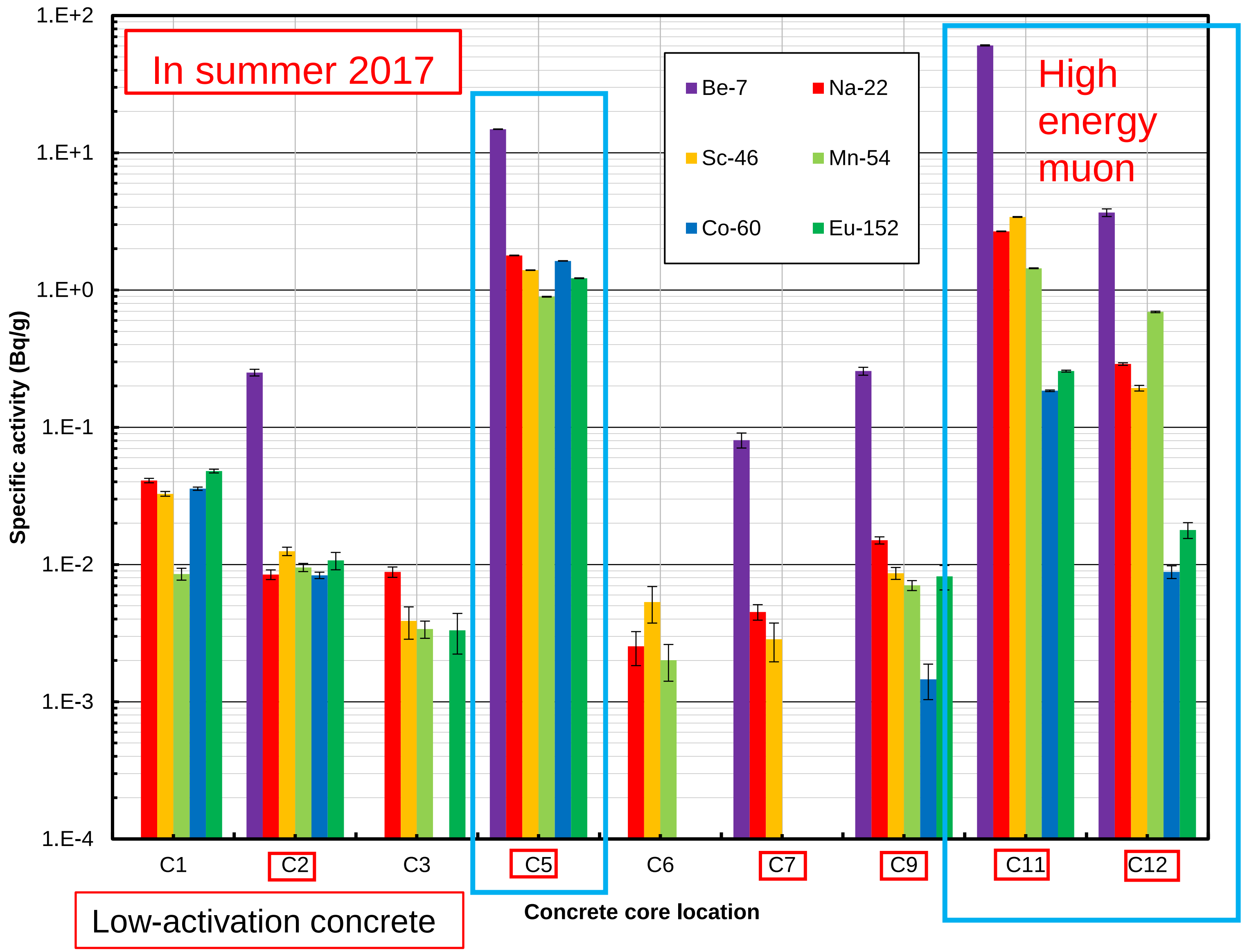
Timeline for collecting and measuring concrete samples



Beam operation history of MR (by J-PARC Center)

Experiment data in summer 2017 with detailed collimators configuration are used for discussion in this report

Activation status of concrete at J-PARC accelerator facilities



Activation status of the surface concrete at 12 locations J-PARC (2017)
(Radionuclides were not detected in C4, C8 and C10)

Typical neutron-induced reactions in different energy ranges:

- $^{16}O(n, x)^{7}Be$ (Threshold energy: 30 MeV)
- $^{23}Na(n, 2n)^{22}Na$ (Threshold energy: 13 MeV)
- $^{54}Fe(n, p)^{54}Mn$ (Threshold energy: 1 MeV)
- $^{59}Co(n, \gamma)^{60}Co$ (Thermal neutron capture), similar for ^{46}Sc, ^{152}Eu, etc.

❖ High activation status: C2, C5, C11, C12

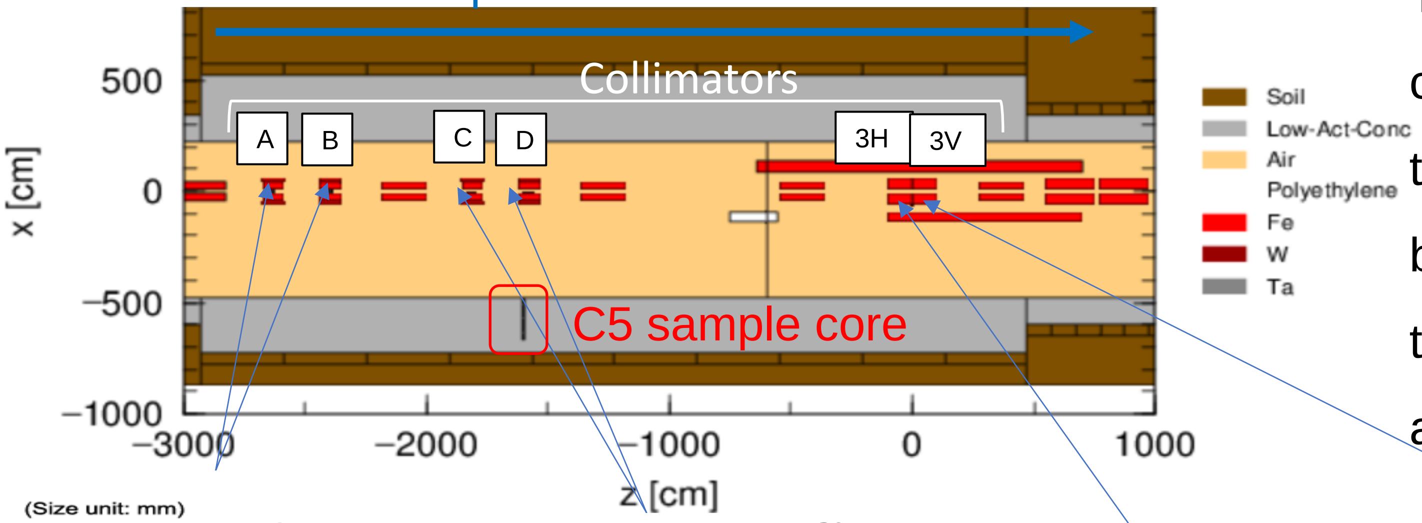
❖ Beam loss situation and beamline structure of C5 location (injection point to MR) are reported in previous studies

=> C5 location was chosen to study in detail

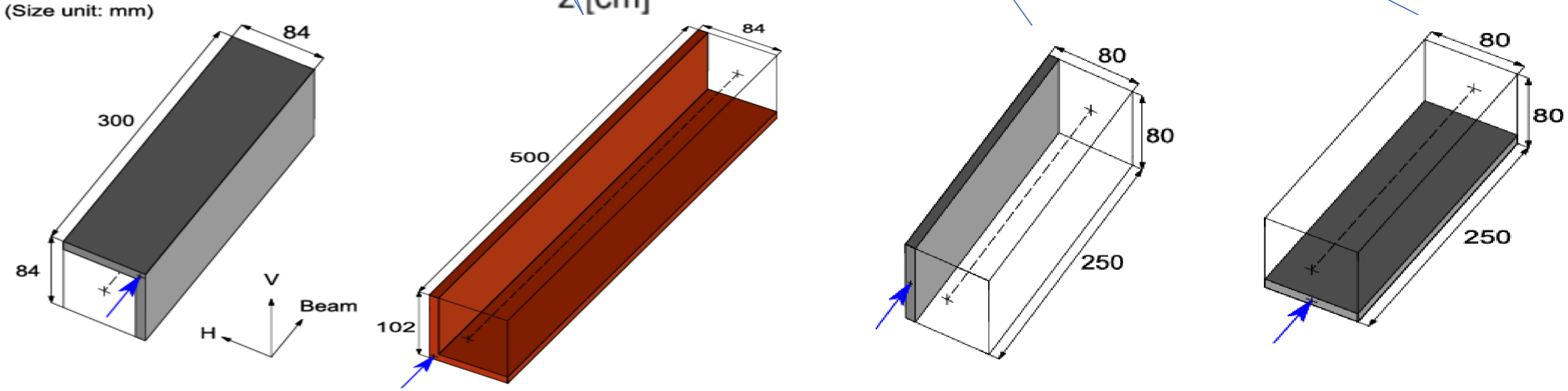
Collimators configuration of the injection point from RCS to MR

Injection point from RCS to MR in the MR accelerator tunnel

3 GeV proton beam



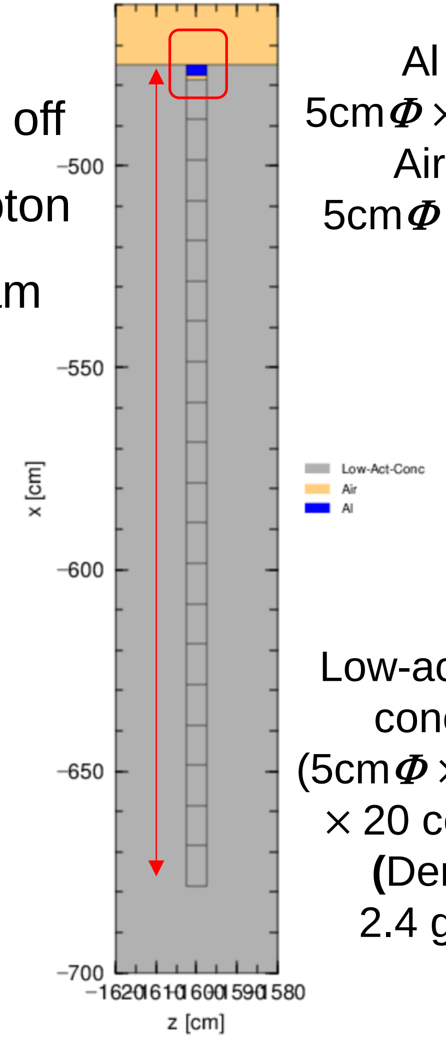
The collimators continuously scraped off the halo of 3 GeV proton beam to stabilize beam transport in the MR accelerator.



Col.A, Col. B
L-shaped, Ta, 30 cm

Col.C, Col. D
L-shaped, W, 50 cm

Col. 3H, Col. 3V
I-shaped, Ta, 25 cm



Al cap
5cmΦ × 2.5cm$H$
Air gap
5cmΦ × 1cm$H$

Low-activation concrete
(5cmΦ ×10cm$H$)
× 20 cell units
(Density: 2.4 g/cm^3)

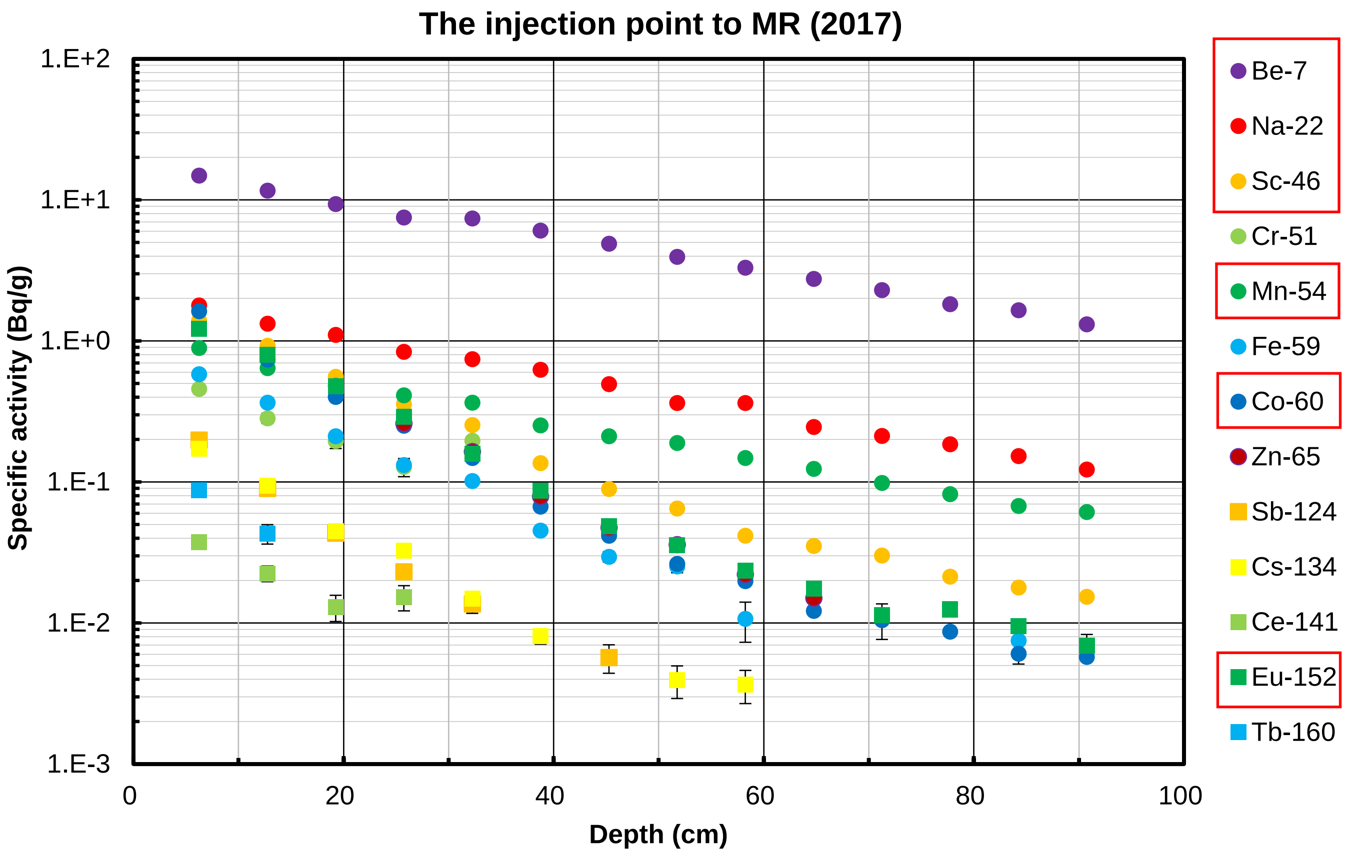
T.Oyama et al., Nucl. Instrum. Methods Phys. Res., Sect. A **937**, 98 (2019)

Geometry and materials of collimators in the injection point from RCS to MR (Oyama et al., 2019)

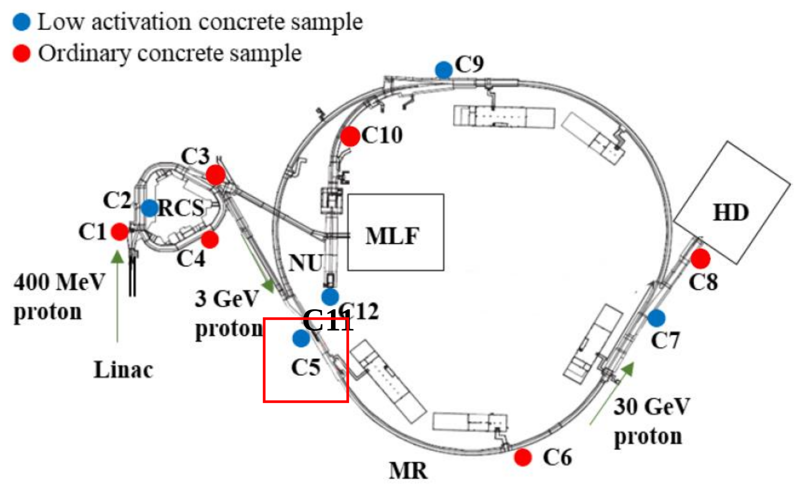
---- Center of the beam duct

→ 3.0 GeV proton source in PHITS calculation

Depth profile of radionuclides in concrete at the injection point to MR



Depth profile of radionuclides induced in concrete at the injection point from RCS to MR (2017)



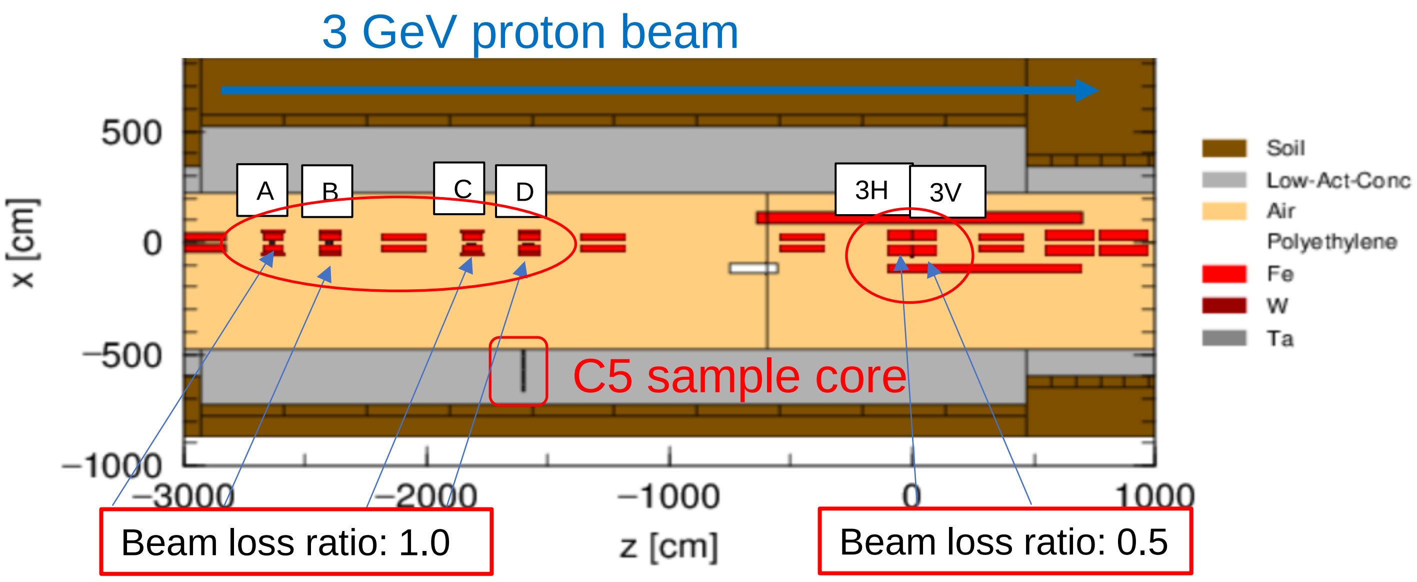
- Fast neutrons-induced nuclides (^{7}Be, ^{22}Na, ^{54}Mn)
- Thermal neutrons-induced nuclides (^{46}Sc, ^{51}Cr, ^{59}Fe, ^{60}Co, ^{65}Zn, ^{124}Sb, ^{134}Cs, ^{141}Ce, ^{152}Eu, ^{160}Tb)

Different slopes:

- ❑ Fast neutrons-induced nuclides (^{7}Be, ^{22}Na, ^{54}Mn):
  - Gradually decreased along the depth
  - Can be fitted as single exponential function
- ❑ Thermal neutrons-induced nuclides (^{46}Sc, ^{60}Co, ^{152}Eu):
  - Rapidly decreased from 0-60 cm, gradually decreases from 60-100 cm along the depth
  - Can be fitted as double exponential functions

Calculation of neutron fluence inside concrete: Calculation methods, conditions

Injection point to MR in the MR accelerator tunnel



Geometry of calculation in the MR tunnel

Particle and HeavyIon Transport code System (PHITS) Ver. 3.31

Calculate the particle transportation immediately after irradiation

➢ Neutron fluence and spectra inside concrete

(n) 1 meV～20 MeV: JENDL-4.0

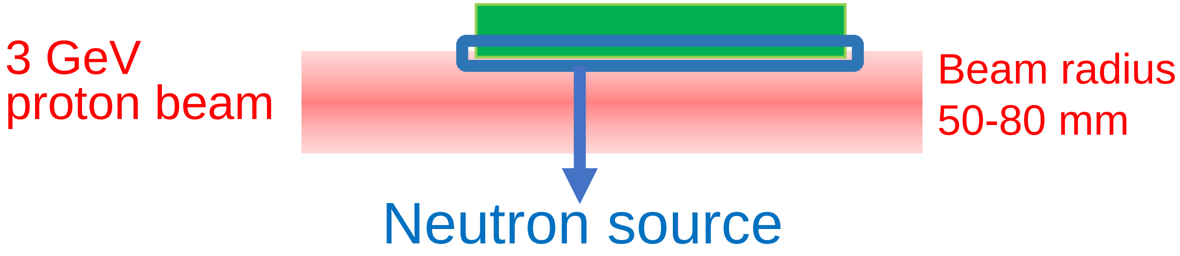
20 MeV～3 GeV: INCL-GEM

(p, π+, π-) 1 keV～1 MeV: Bertini-GEM

1 MeV～3 GeV: INCL-GEM

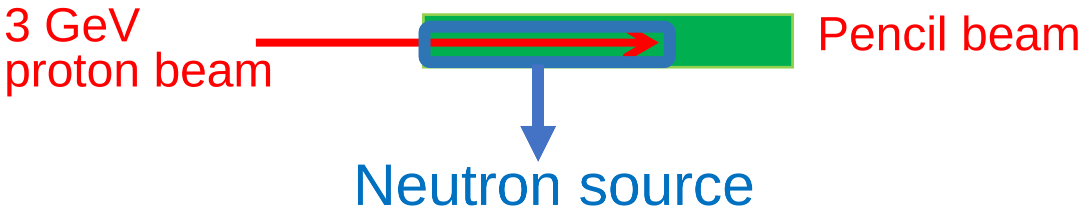
Image for real beam operation

Ta, W collimator jaws (250-500 mm*L*)

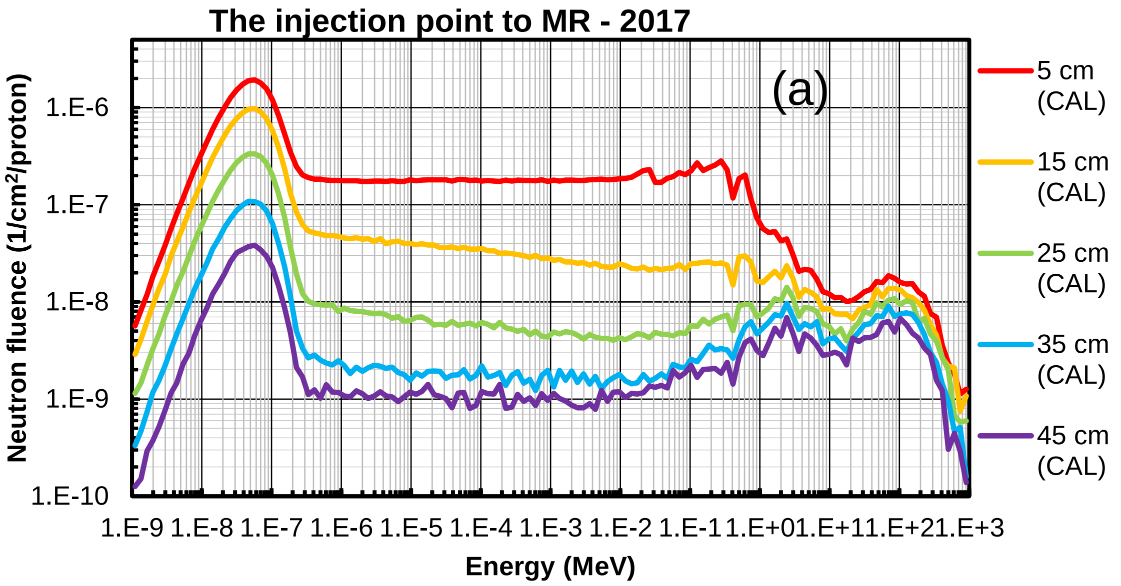


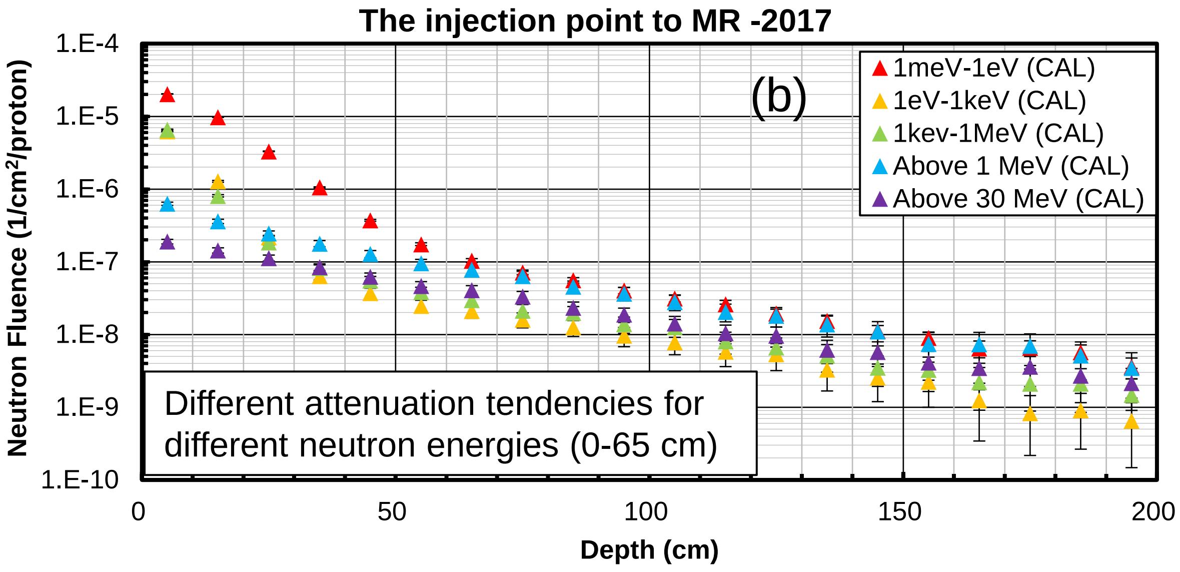
Simplified calculation model at this work

Ta, W collimator jaws (250-500 mm*L*)

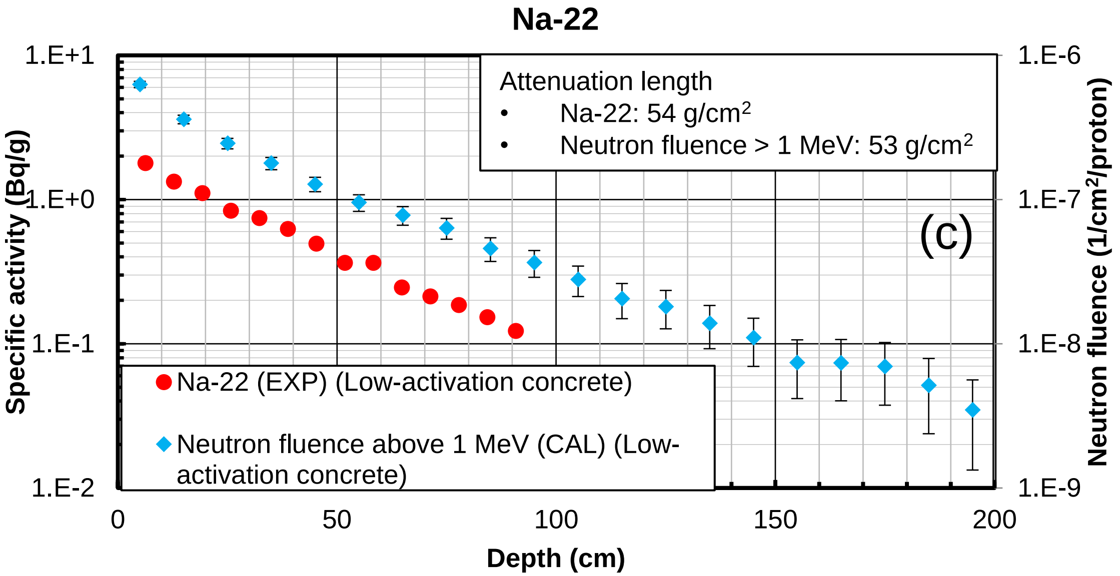


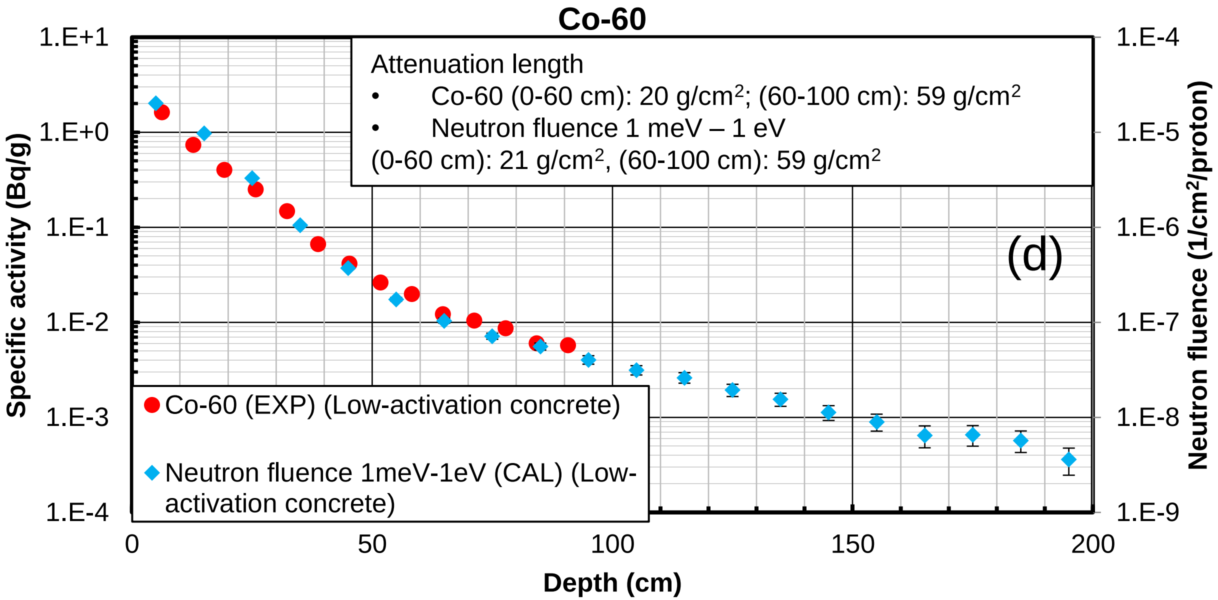
Neutron spectra and depth profile of neutron fluence at the injection point to MR





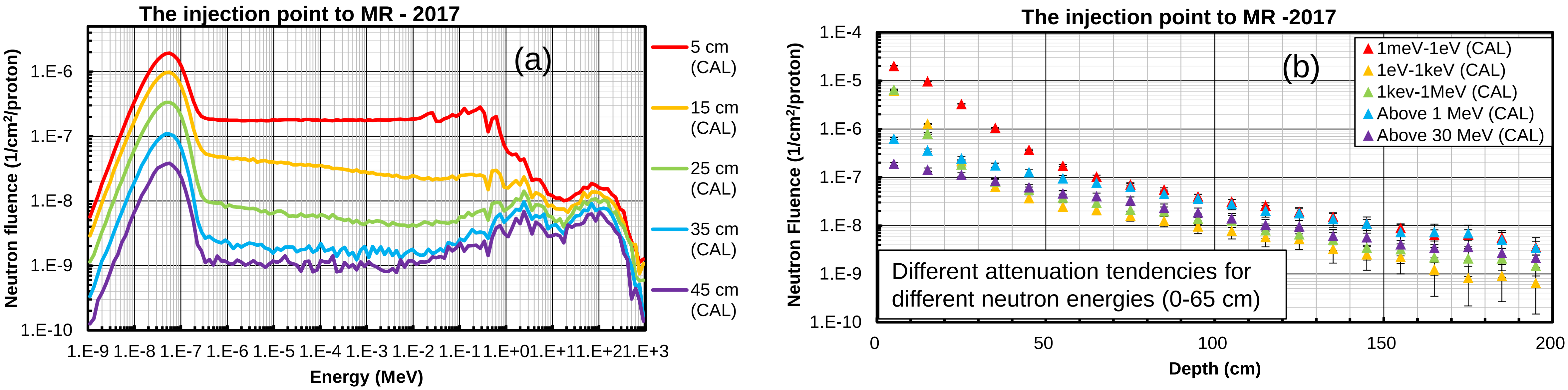
Neutron spectra (a) and depth profile of neutron fluence (b) in the concrete core at the injection point to MR by PHITS calculation (2017)



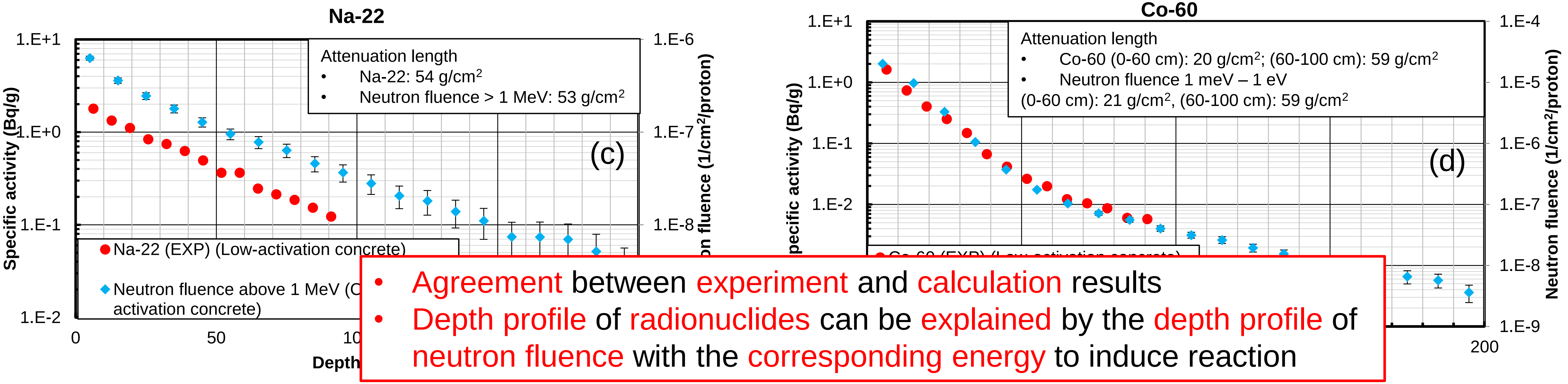


Comparison of depth profile of ^{22}Na (c) and ^{60}Co (d) specific activity (experiment) and neutron fluence (calculation) in ordinary and low-activation concrete core at the injection point to MR (2017)

Neutron spectra and depth profile of neutron fluence at the injection point to MR



Neutron spectra (a) and depth profile of neutron fluence (b) in the concrete core at the injection point to MR by PHITS calculation (2017)



- Agreement between experiment and calculation results
- Depth profile of radionuclides can be explained by the depth profile of neutron fluence with the corresponding energy to induce reaction

Comparison of depth profile of ^{22}Na (c) and ^{60}Co (d) specific activity (experiment) and neutron fluence (calculation) in ordinary and low-activation concrete core at the injection point to MR (2017)

2-steps dump calculation for studying transportation of various-energy neutrons

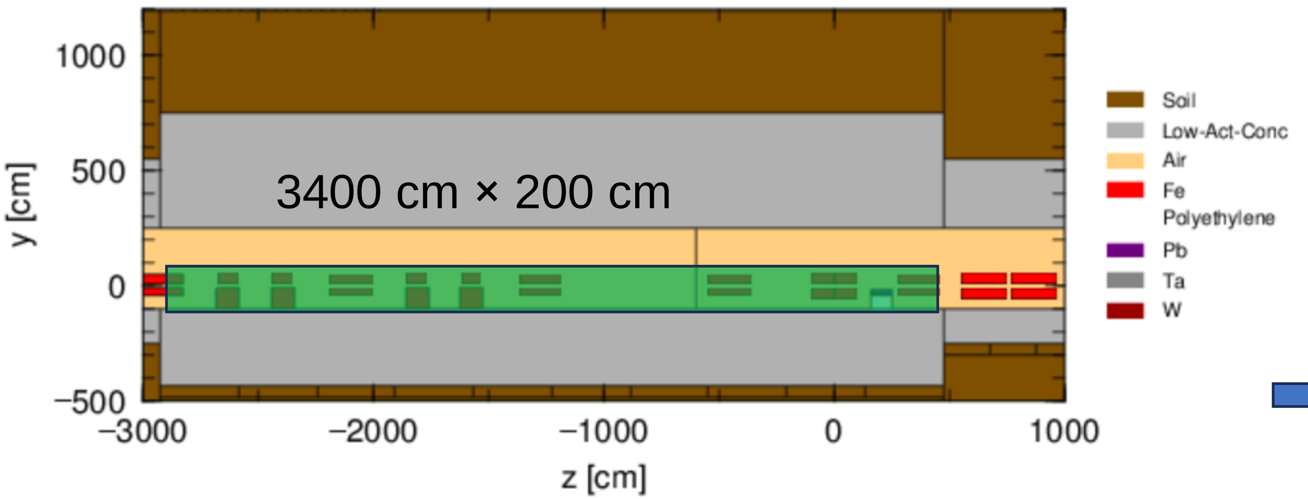
From previous results:

- The depth profile of radionuclides in concrete can be explained by the attenuation tendency of neutrons with the corresponding energy to induce the reaction
- The attenuation tendency of neutrons in concrete depends on incident neutron energies

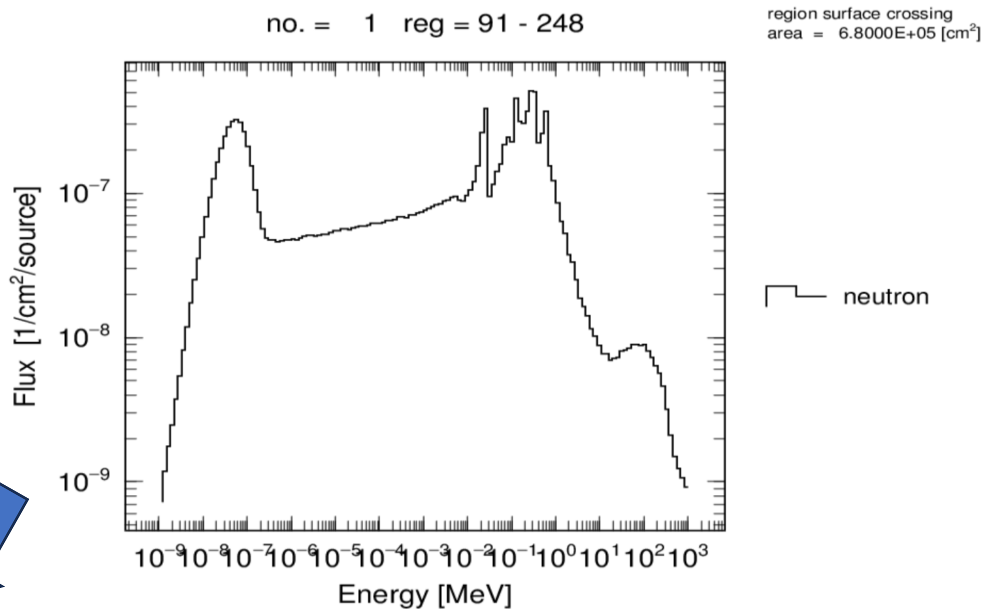
The effects of incident neutron energy on the transportation of neutrons in concrete need to be evaluated

→ 2-steps dump calculation method was used to evaluate the effect of incident neutron energies on the neutron fluence and spectra in the concrete

2-steps dump calculation for studying transportation of various-energy neutrons



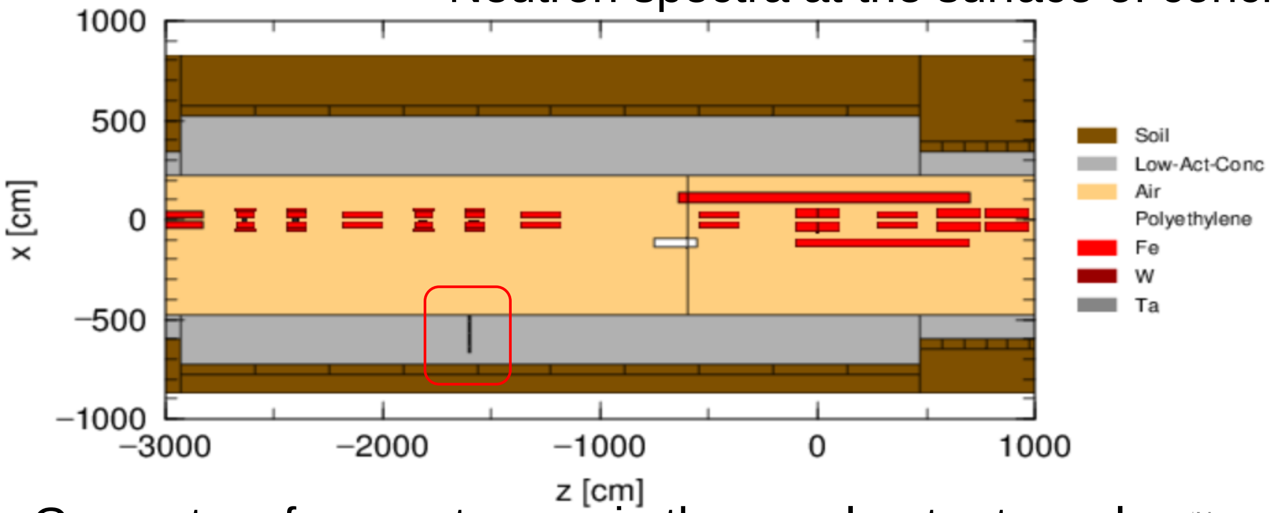
Geometry and calculation area for
neutron spectra at the surface of concrete



Neutron spectra at the surface of concrete

<u>2-steps dump calculation</u>

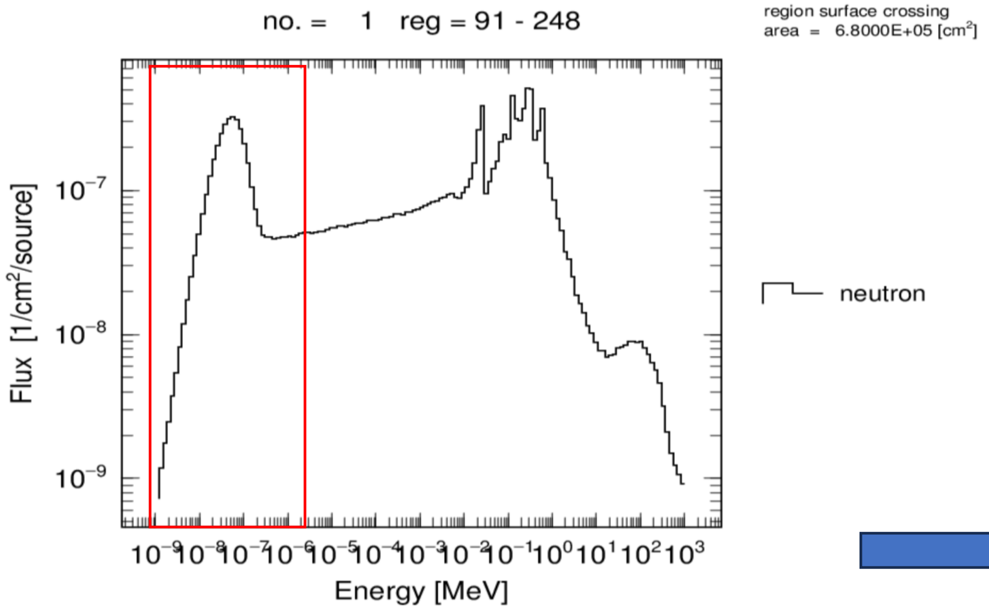
- 1[st] step: <u>calculate the neutron energy, direction, velocity, position for each neutron</u> at the surface of the concrete wall
- 2[nd] step: use the information of neutron source at the surface from 1[st] step as input to calculate the neutron fluences and the spectra at different depths at the concrete core location.



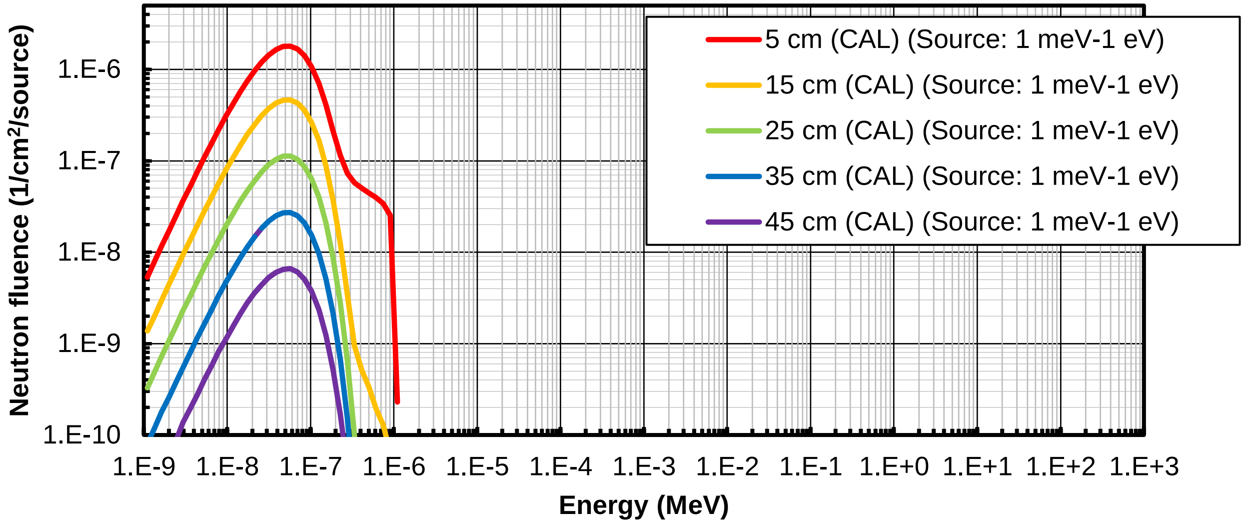
Geometry of concrete core in the accelerator tunnel

➡ <u>Evaluate the effect of incident neutron energies on the neutron fluence and spectra in the concrete</u>

Effect of 1 meV – 1 eV incident neutron on neutron fluence in concrete



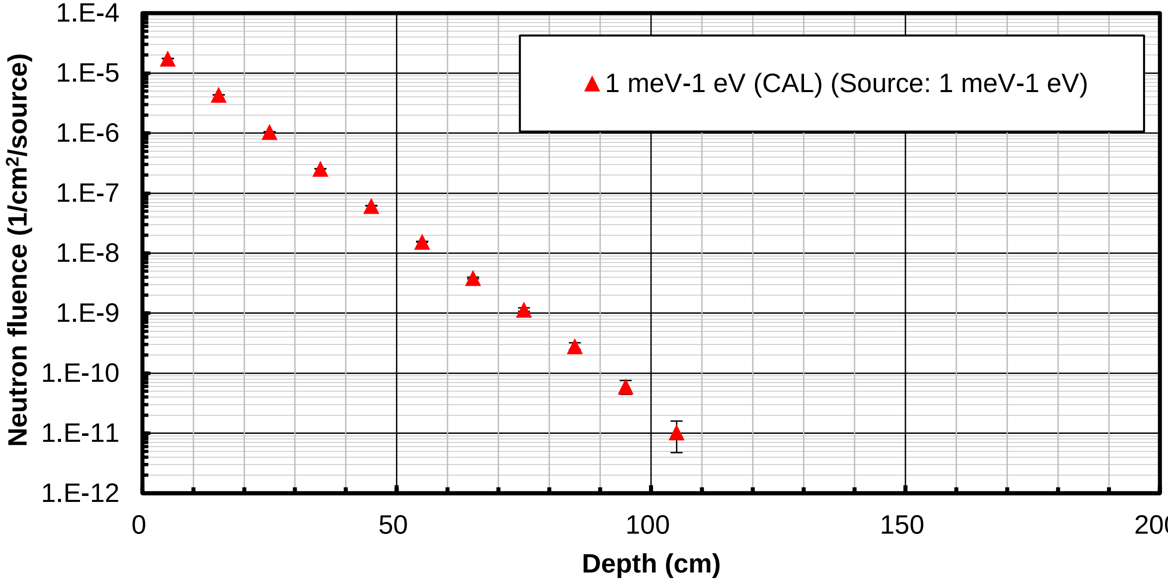
Input neutron source with energy range from 1 meV to 1 eV



Output neutron spectra in the concrete core

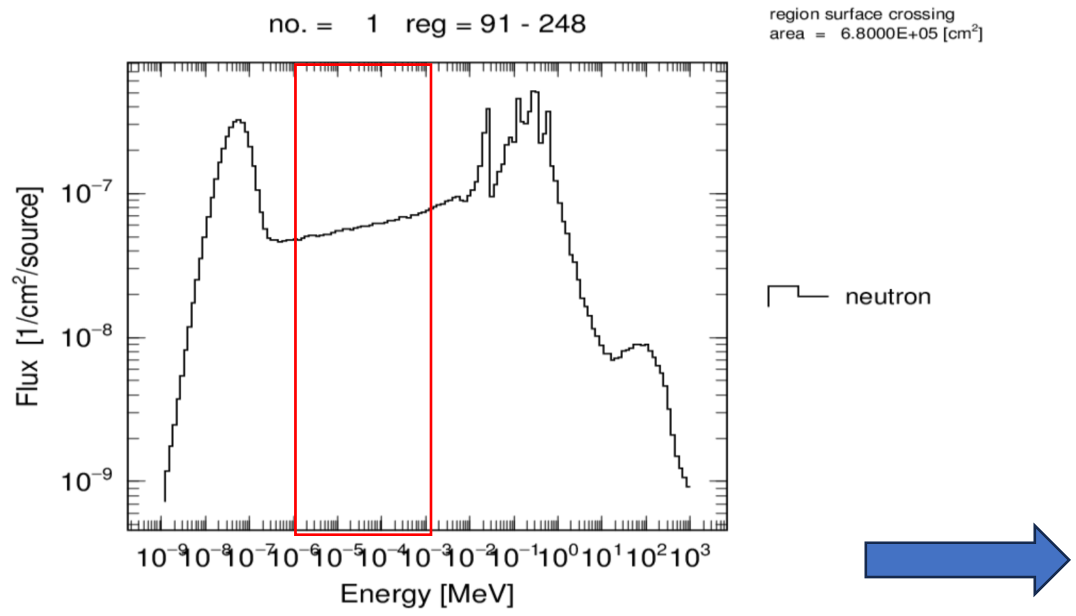
Neutron fluence (1 meV-1 eV):

- Follow single exponential function

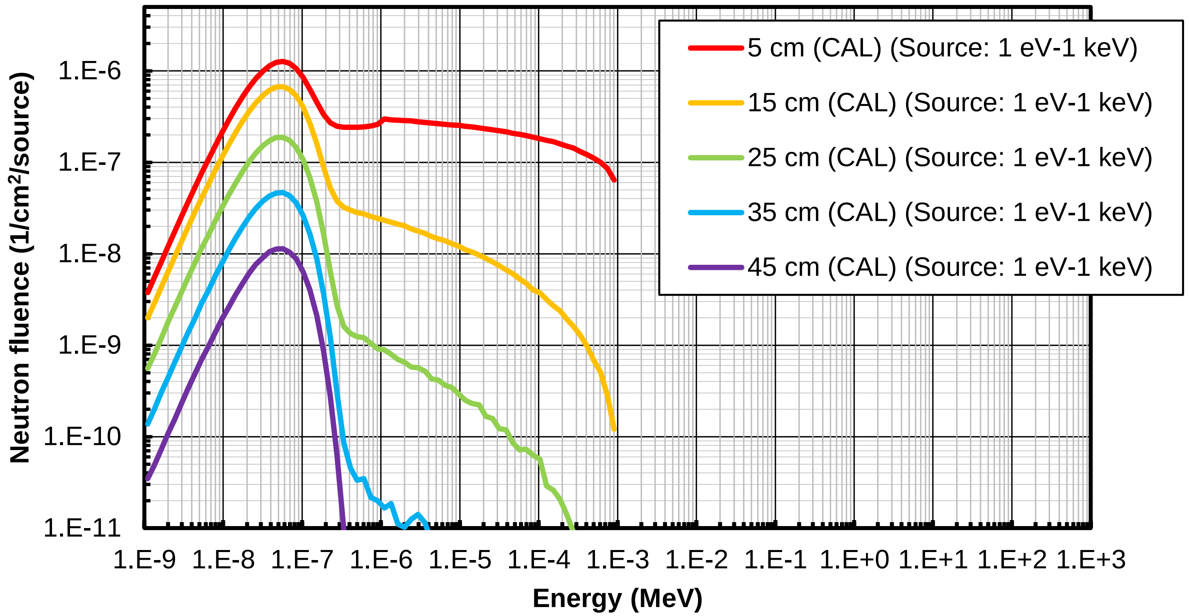


Output depth profile of neutron fluence in the concrete core

Effect of 1 eV – 1 keV incident neutron on neutron fluence in concrete



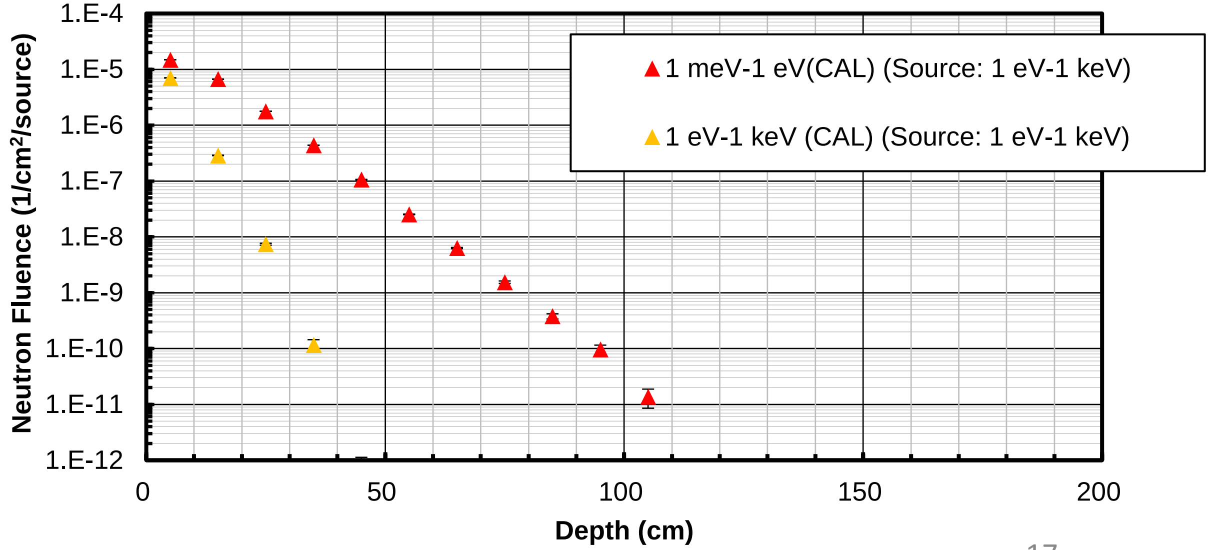
Input neutron source with energy range from 1 eV to 1 keV



Output neutron spectra in the concrete core

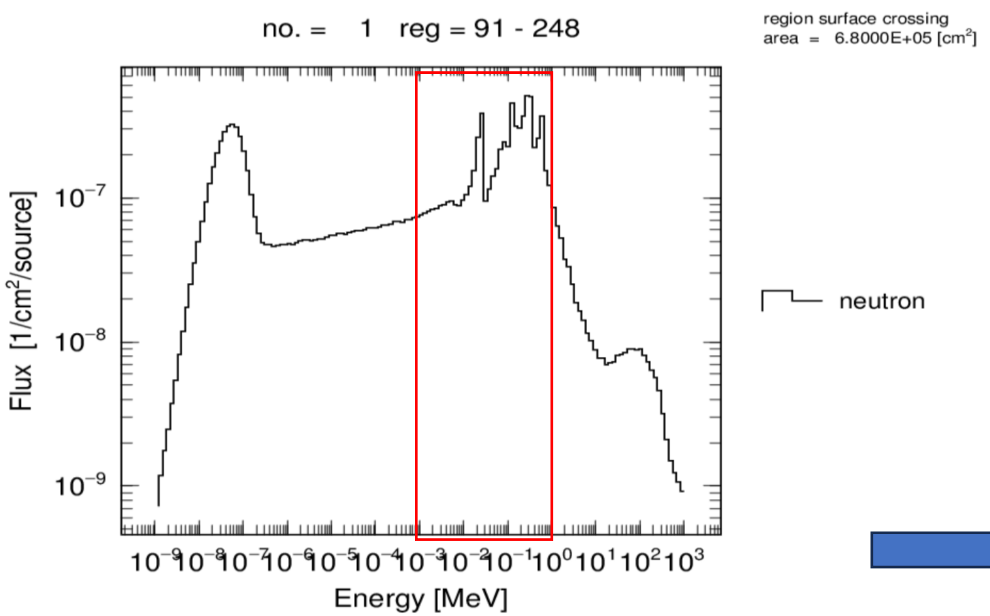
Unexpected results of neutron fluence (1 meV-1 eV):

- Higher and penetrate deeper than neutron fluence (1 eV - 1 keV)
- Shallow region (0~20 cm): neutrons (1 eV – 1 keV) decelerated into neutron (1 meV – 1 eV)
- Deep region (20~200 cm): neutron (1 meV – 1 eV) might not come from neutron (1 eV – 1 keV)

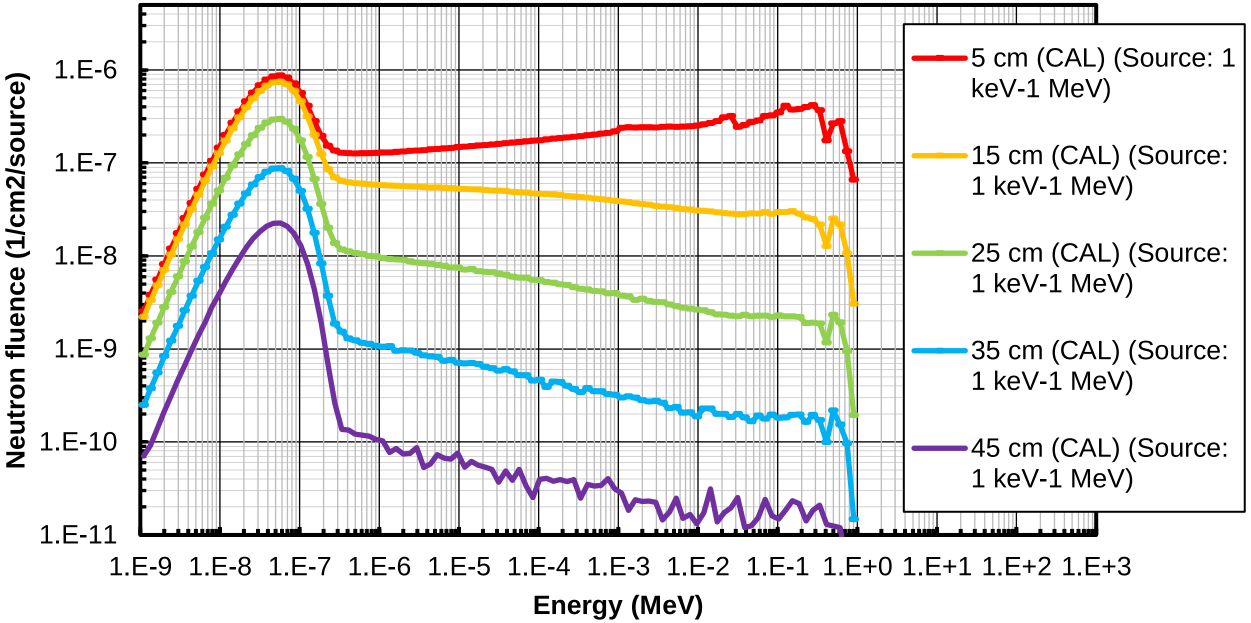


Output depth profile of neutron fluence in the concrete core

Effect of 1 keV – 1 MeV incident neutron on neutron fluence in concrete



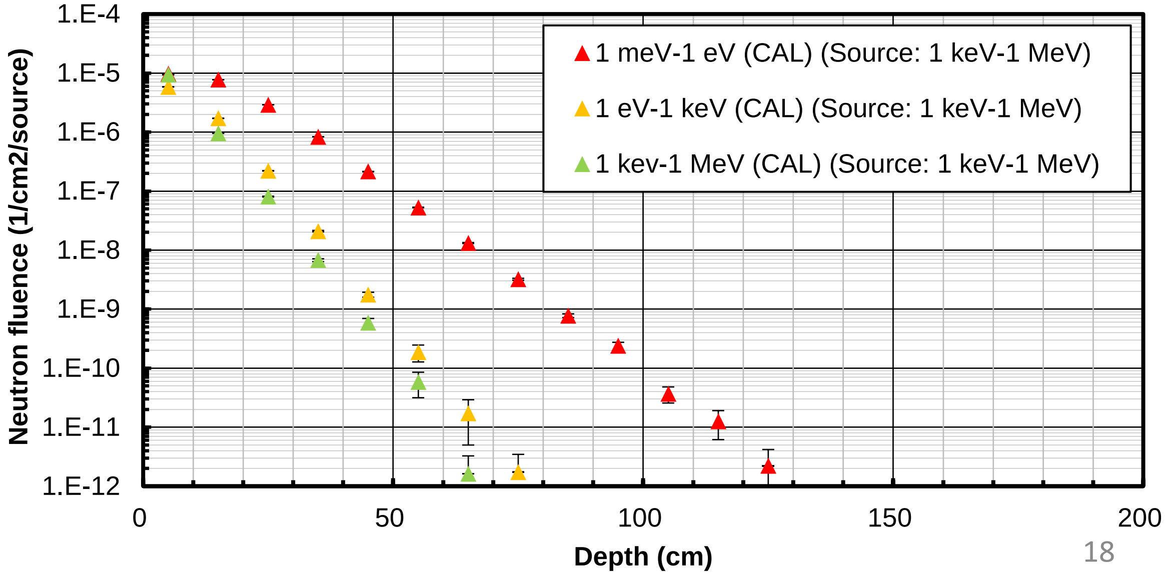
Input neutron source with energy range from 1 keV to 1 MeV



Output neutron spectra in the concrete core

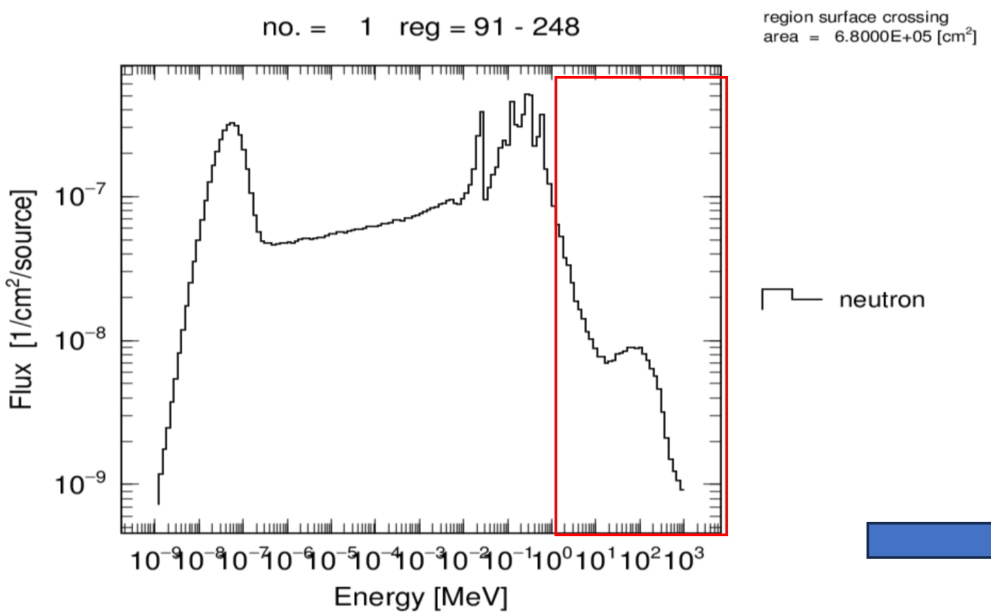
Unexpected results of neutron fluence (1 meV-1 eV):

- Higher and penetrate deeper than neutron fluence (1 eV-1 keV) (1 keV – 1 MeV)
- Shallow region (0~30 cm): neutrons (1 eV – 1 keV) (1 keV – 1 MeV) decelerated into neutron (1 meV – 1 eV)
- Deep region (30~200 cm): neutron (1 meV – 1 eV) might not come from neutron (1 eV – 1 keV) (1 keV – 1 MeV)

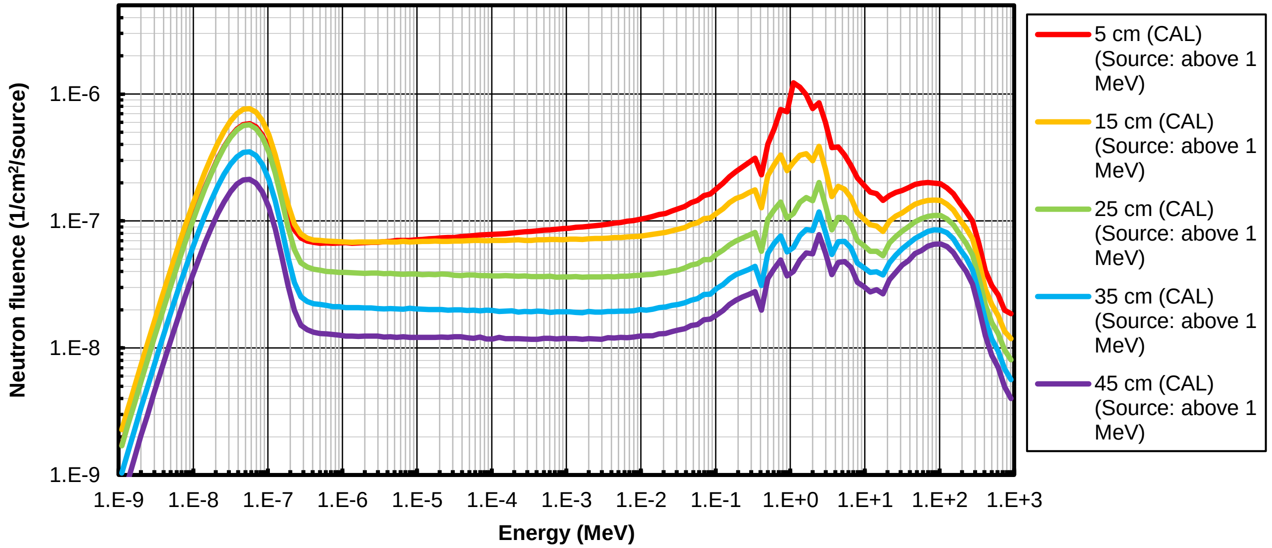


Output depth profile of neutron fluence in the concrete core

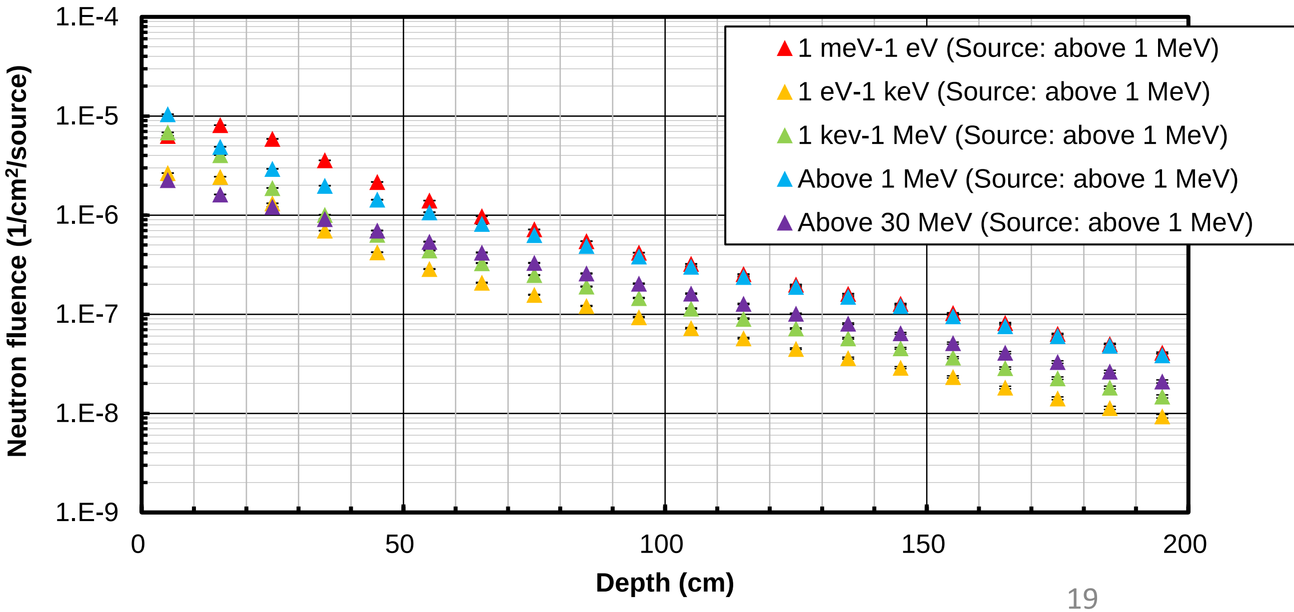
Effect of above 1 MeV incident neutron on neutron fluence in concrete



Input neutron source with energy range above 1 MeV



Output neutron spectra in the concrete core

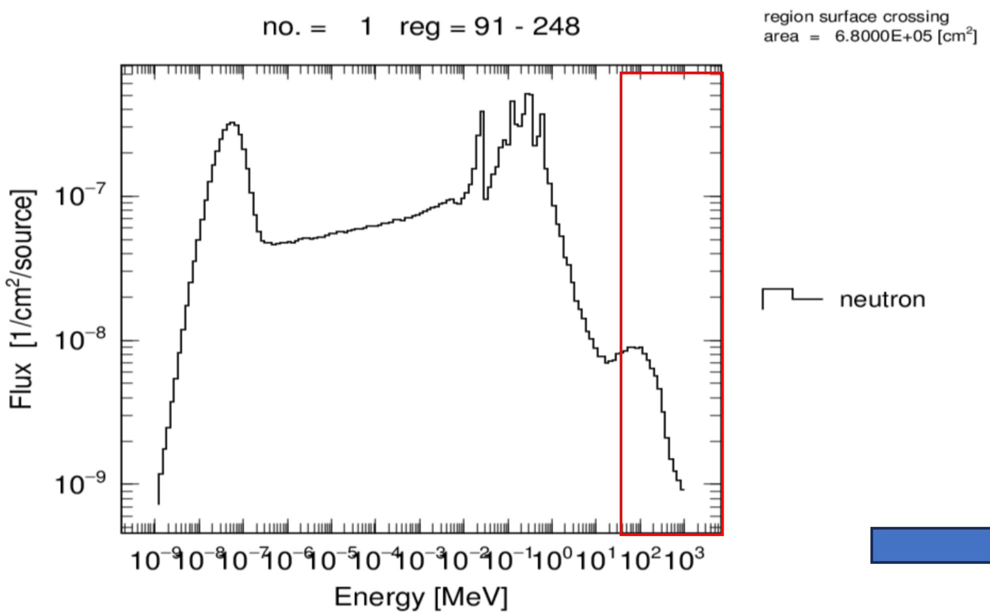


Output depth profile of neutron fluence in the concrete core

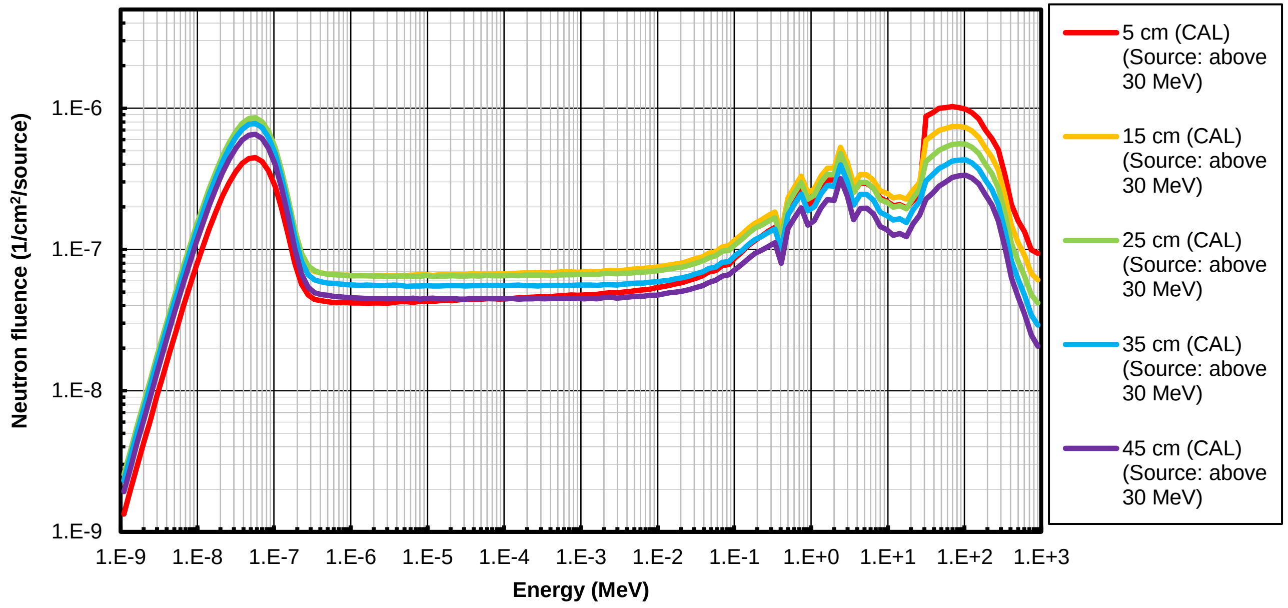
- Build-up effects observed in neutrons (1 meV – 1 eV)
- Different slopes compared to lower incident neutron energies
- Much higher penetration tendency compared with lower input energies, and show similar attenuation tendency for all neutron energies from 90 cm

⇒ High-energy neutrons were decelerated into low-energy neutrons and kept equilibrium at deep region of the concrete core (~ 90 cm)

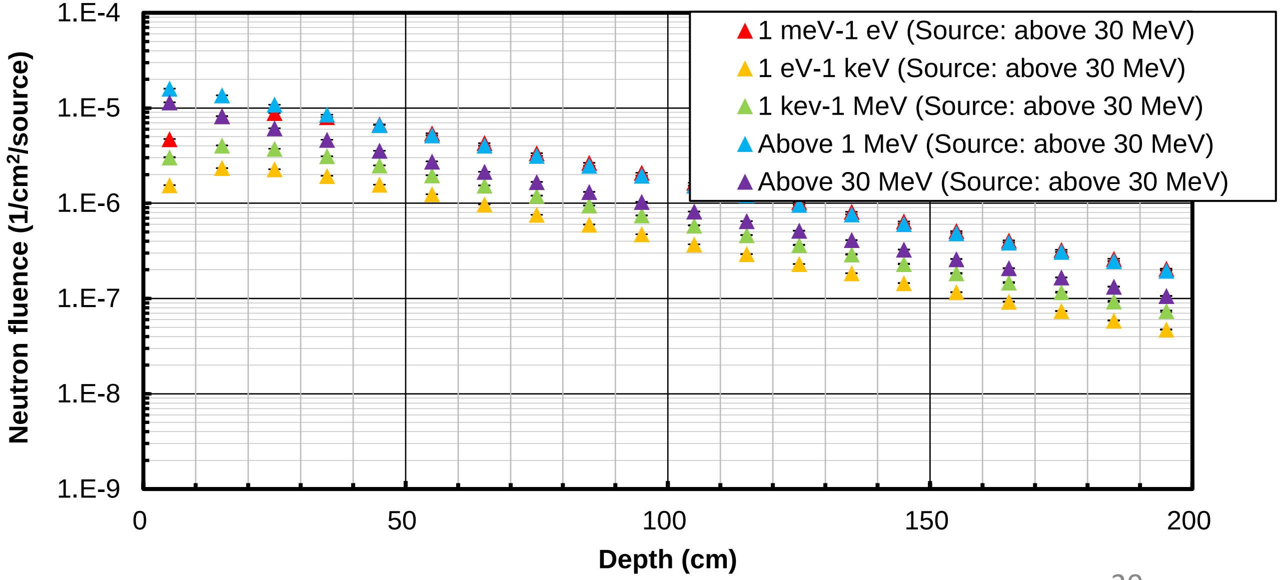
Effect of above 30 MeV incident neutron on neutron fluence in concrete



Input neutron source with energy range above 30 MeV



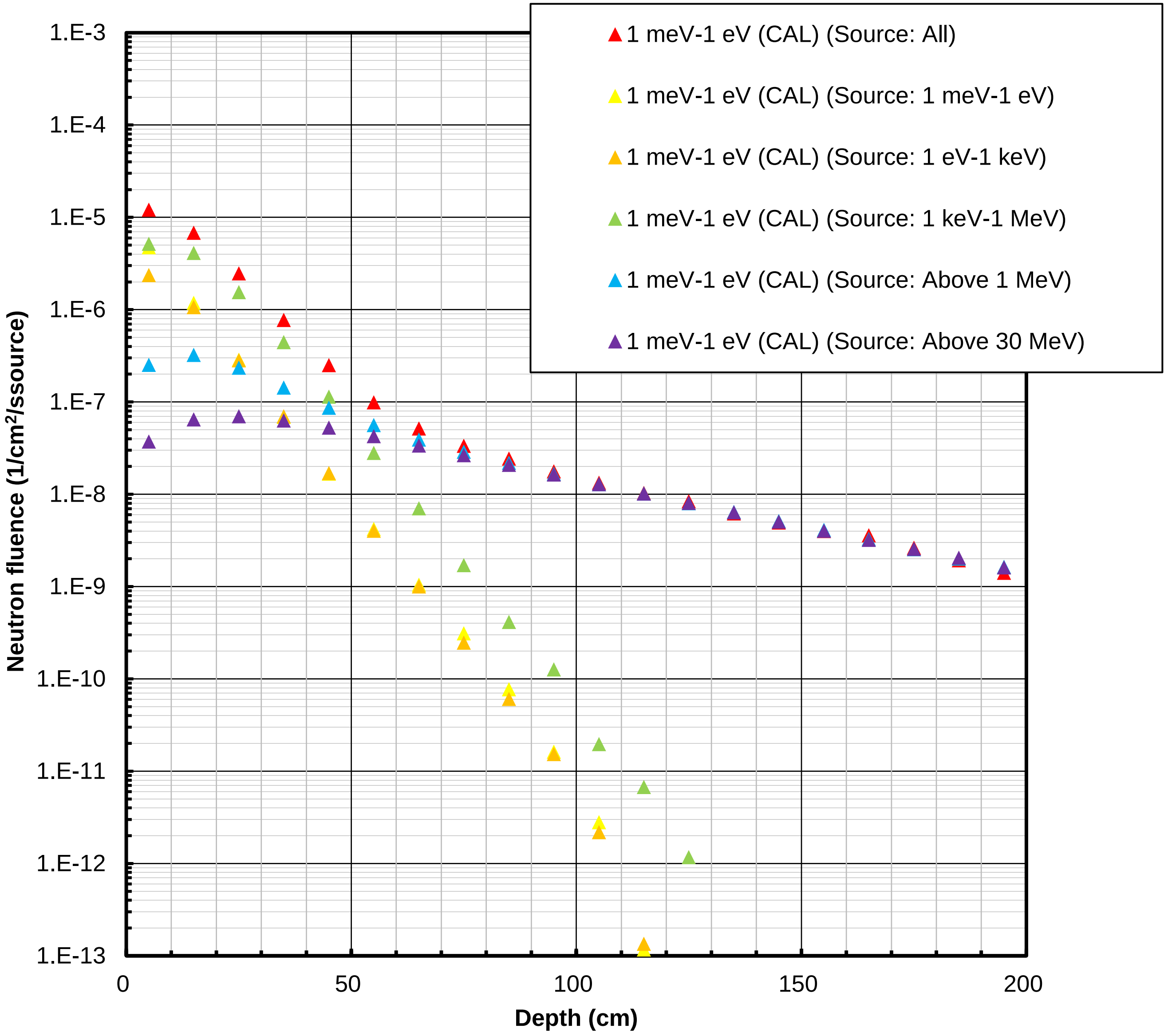
Output neutron spectra in the concrete core



Output depth profile of neutron fluence in the concrete core

- Build-up effects observed in neutrons (1 meV – 1 MeV)
- Similar slopes with the incident neutron energy of above 1 MeV.
- High-energy neutrons were decelerated into low-energy neutrons and kept equilibrium at deep region of the concrete core (~ 60 cm)

Dependence of 1 meV - 1 eV neutron attenuation on incident neutron energy



Depth profile of neutron fluence in the energy range 1 meV - 1 eV in the concrete from different input energy range sources

Dependence of 1 meV – 1 eV neutron attenuation on different incident neutron energies:

❖ Incident neutron energies 1 meV ~ 1 MeV :

- Rapidly attenuate along the depth of the concrete core
- Similar attenuation tendency
- Incident neutron 1 keV – 1 MeV is the main contribution to the total neutron fluence 0 - 60 cm
- Build-up effects observed from 1 keV

❖ Incident neutron energy > 1 MeV:

- Gradually attenuate along the depth of the concrete
- Similar attenuation tendency (70~200 cm)
- Incident neutron above 1 MeV is the main contribution to the total neutron fluence 60 – 200 cm

Summary

To clarify the activation mechanism and neutron transportation in the concrete at J-PARC, experiments and calculations were carried out:

- γ-ray spectrometry of radionuclides in concrete
- Monte-Carlo simulation of neutron transportation in concrete

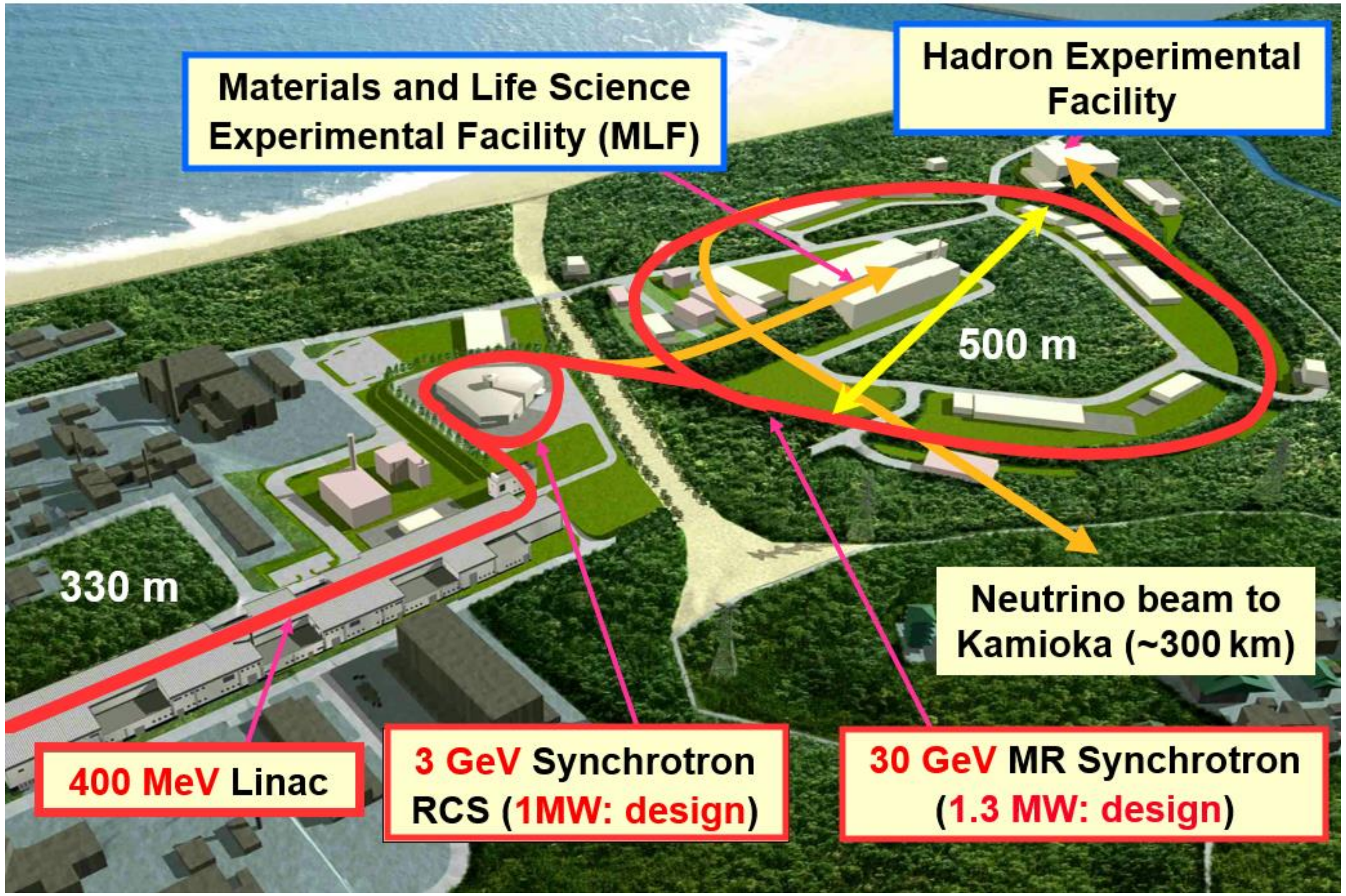
The results indicate:

- ➢ Agreement between experiment and calculation results
- ➢ The depth profile of radionuclides can be explained by the attenuation tendency of neutron flux
- ➢ Neutron penetration and attenuation tendency inside concrete largely differ depending on the incident neutron energies
- ➢ Build-up effects can be observed from incident neutron energy above 1 keV
- ➢ Incident neutron 1 keV – 1 MeV is the main contribution to the total neutron fluence 0 - 60 cm
- ➢ Incident neutron above 1 MeV is the main contribution to the total neutron fluence 60 – 200 cm

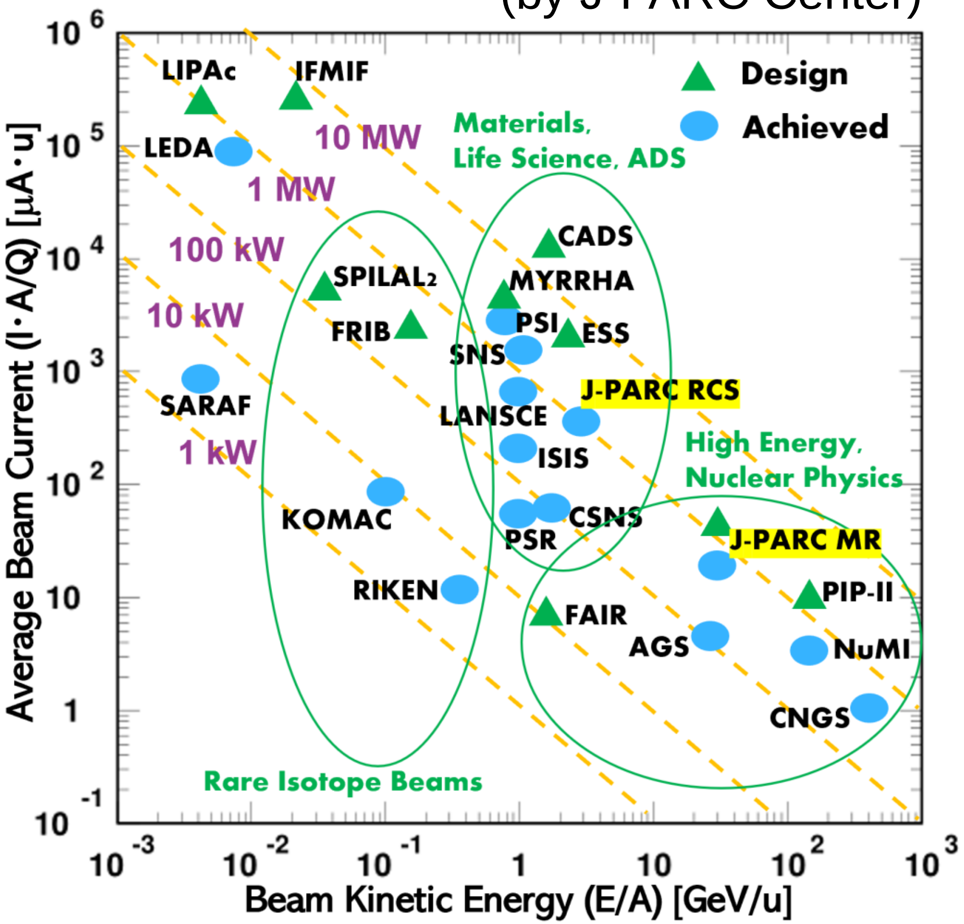
THANK YOU FOR LISTENING

J-PARC (Japan Proton Accelerator Research Complex)

(by J-PARC Center)



Outline of J-PARC facilities (by J-PARC Center)

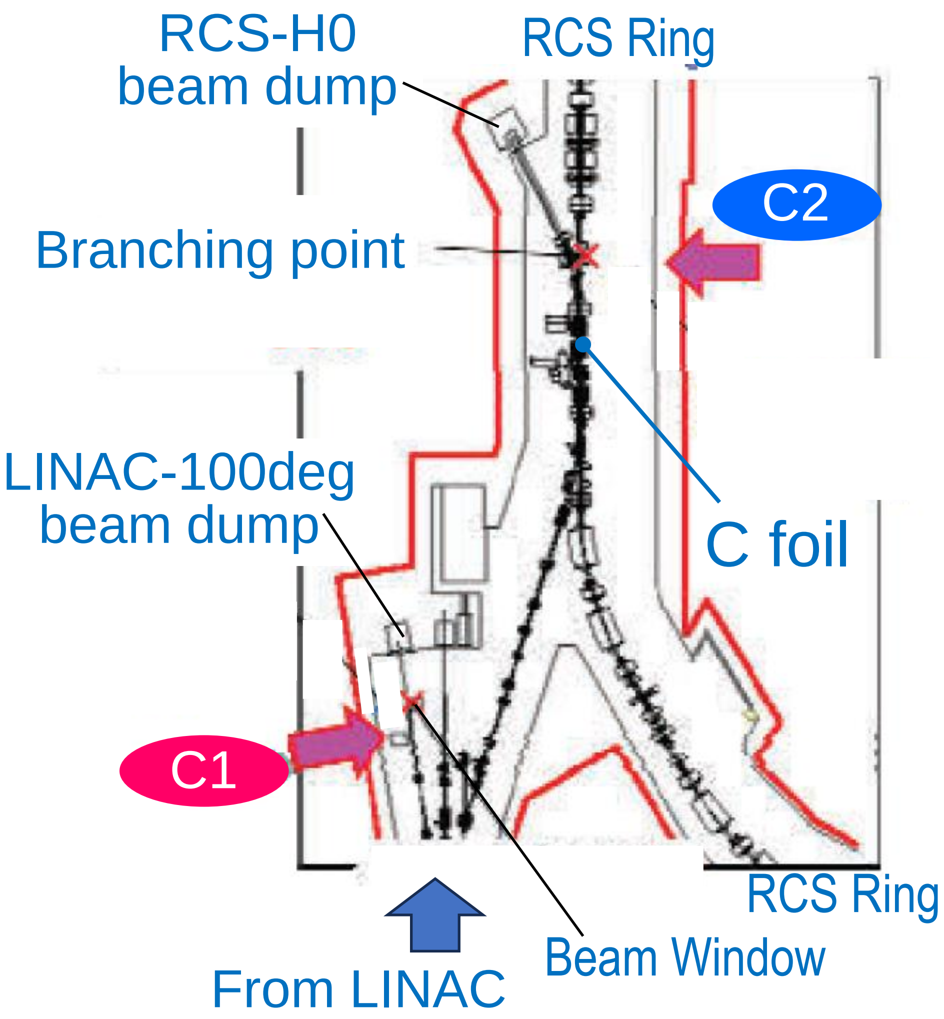


Beam kinetic energy and beam current for proton accelerator facilities in the world

Unique characteristic of J-PARC: High-power and high-energy proton beam

⇨ High-level activation with various radionuclides

⇨ Typical case for activation of concrete at high-energy accelerator facilities

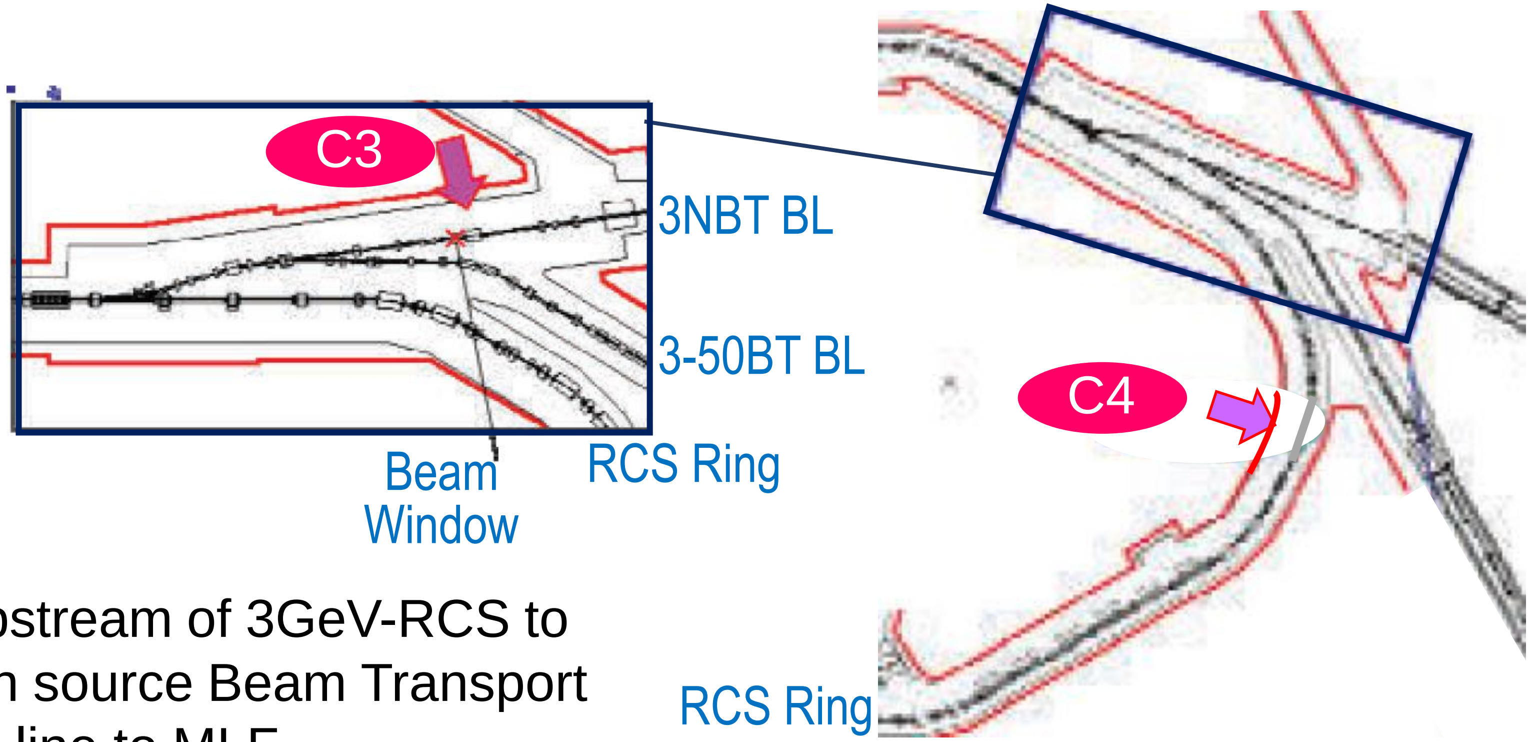


C1 : Linac-to-3-GeV beam transport line (L-3BT)

C2 : RCS injection section (Low activation concrete)

Location of the concrete cores C1 and C2 for radioactivity measurements.

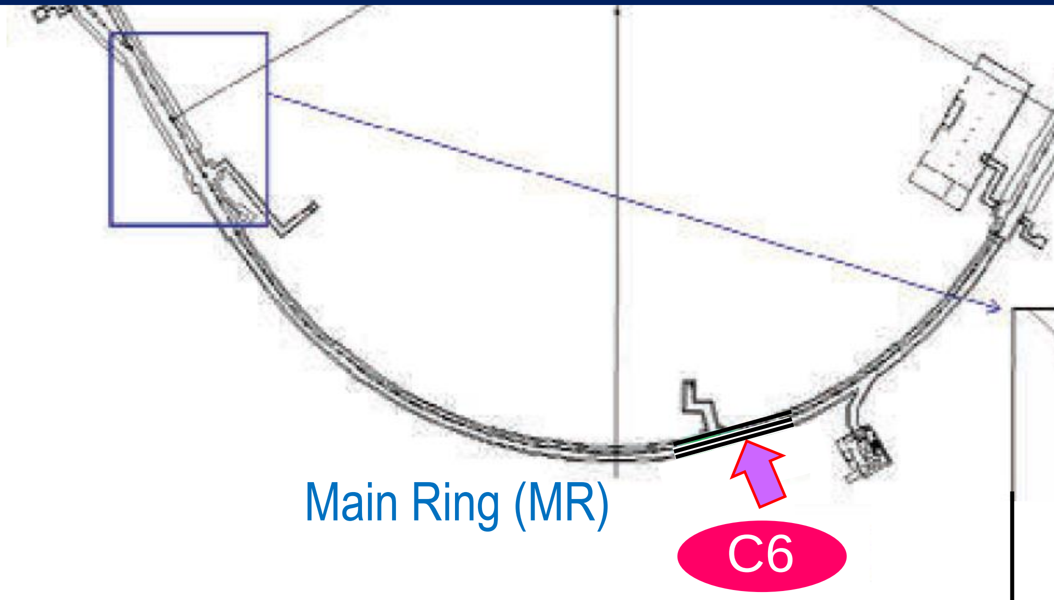
SUPPLEMENT

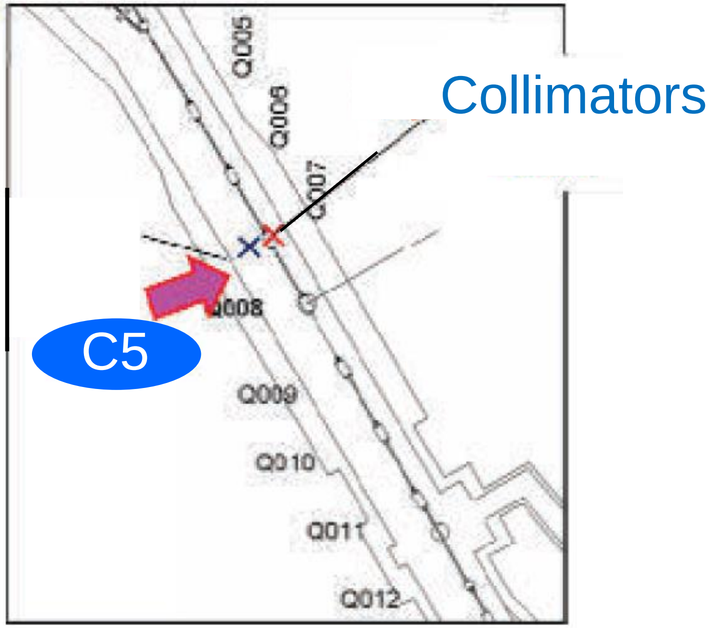


C3 : Upstream of 3GeV-RCS to Neutron source Beam Transport (3NBT) line to MLF

C4 : RCS 2nd arc section

Location of the concrete cores C3 and C4 for radioactivity measurements.



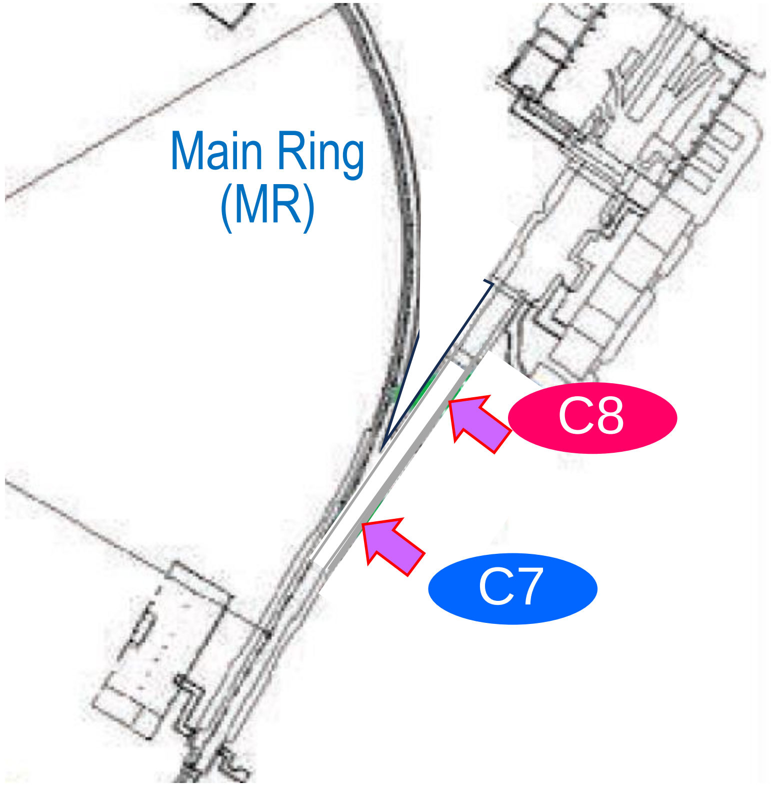


C5 : Injection point from RCS to MR through the 3-50BT beamline (Low activation concrete)

C6 : MR arc section

Location of the concrete cores C5 and C6 for radioactivity measurements.

SUPPLEMENT

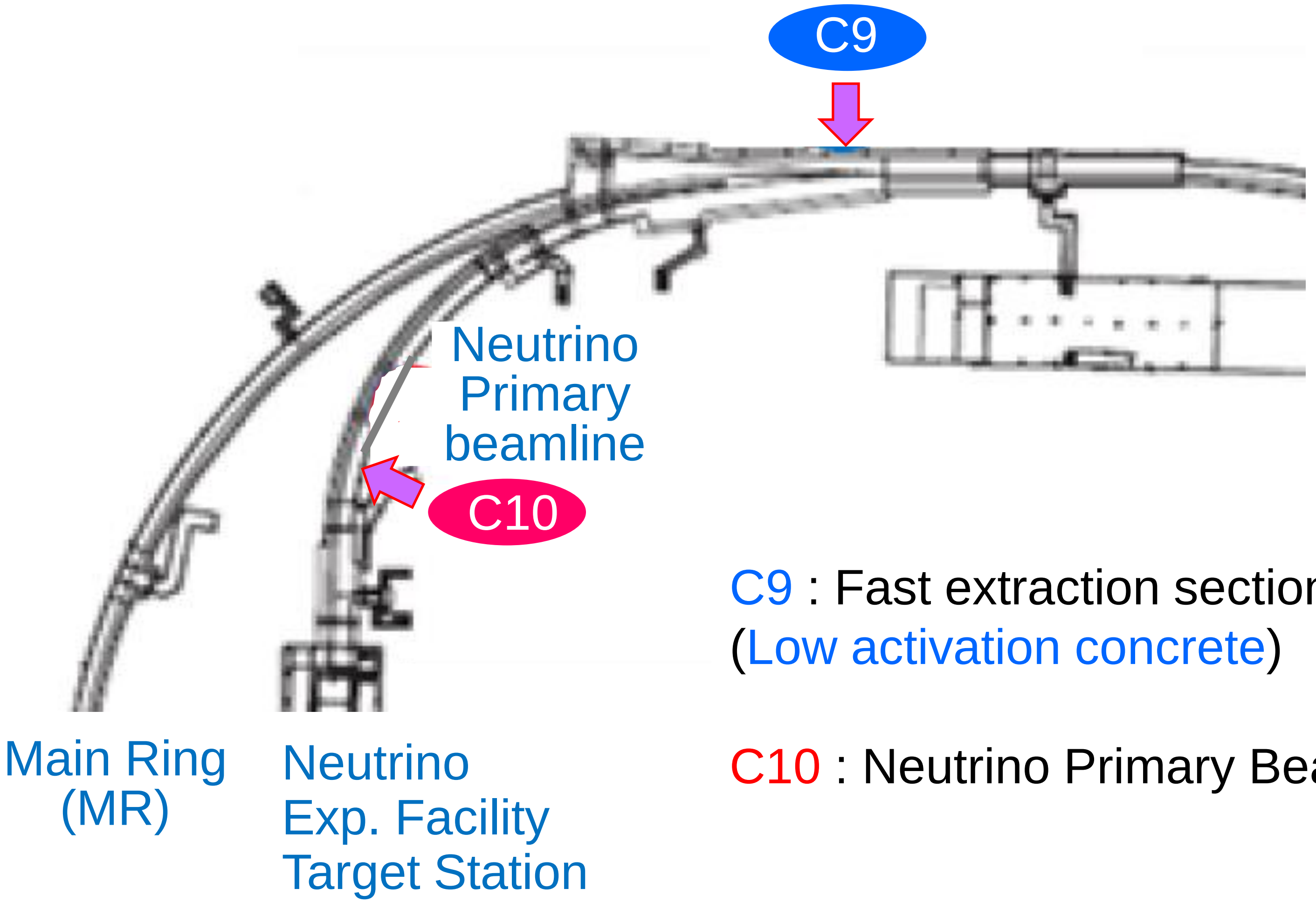


C7 : Branching point to the Hadron Experimental Facility (HD)
(Low activation concrete)

C8 : Beam switching yard at the HD facility

Location of the concrete cores C7 and C8 for radioactivity measurements.

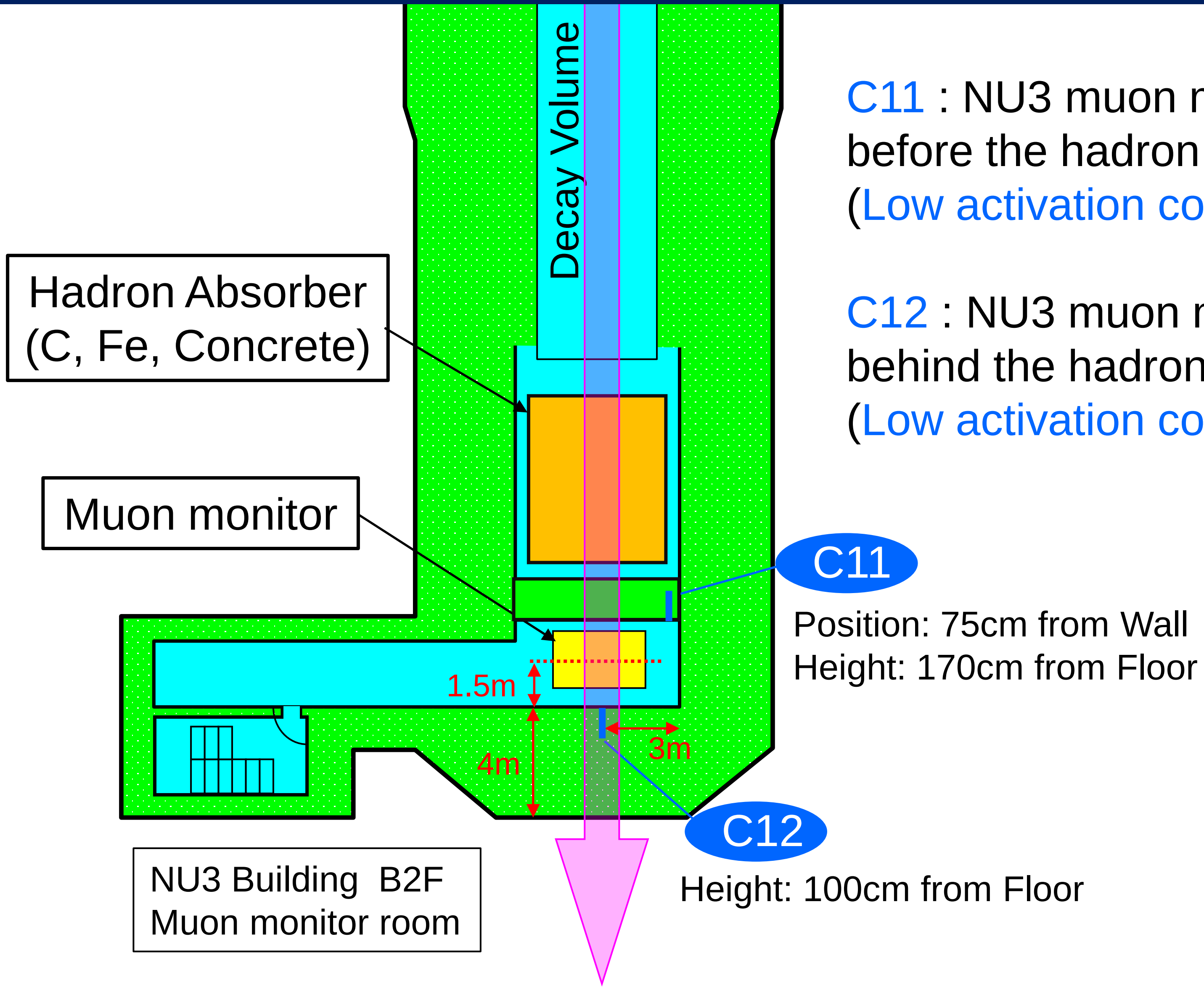
SUPPLEMENT



C9 : Fast extraction section on the MR
(Low activation concrete)

C10 : Neutrino Primary Beamline

Location of the concrete cores C9 and C10 for radioactivity measurements.

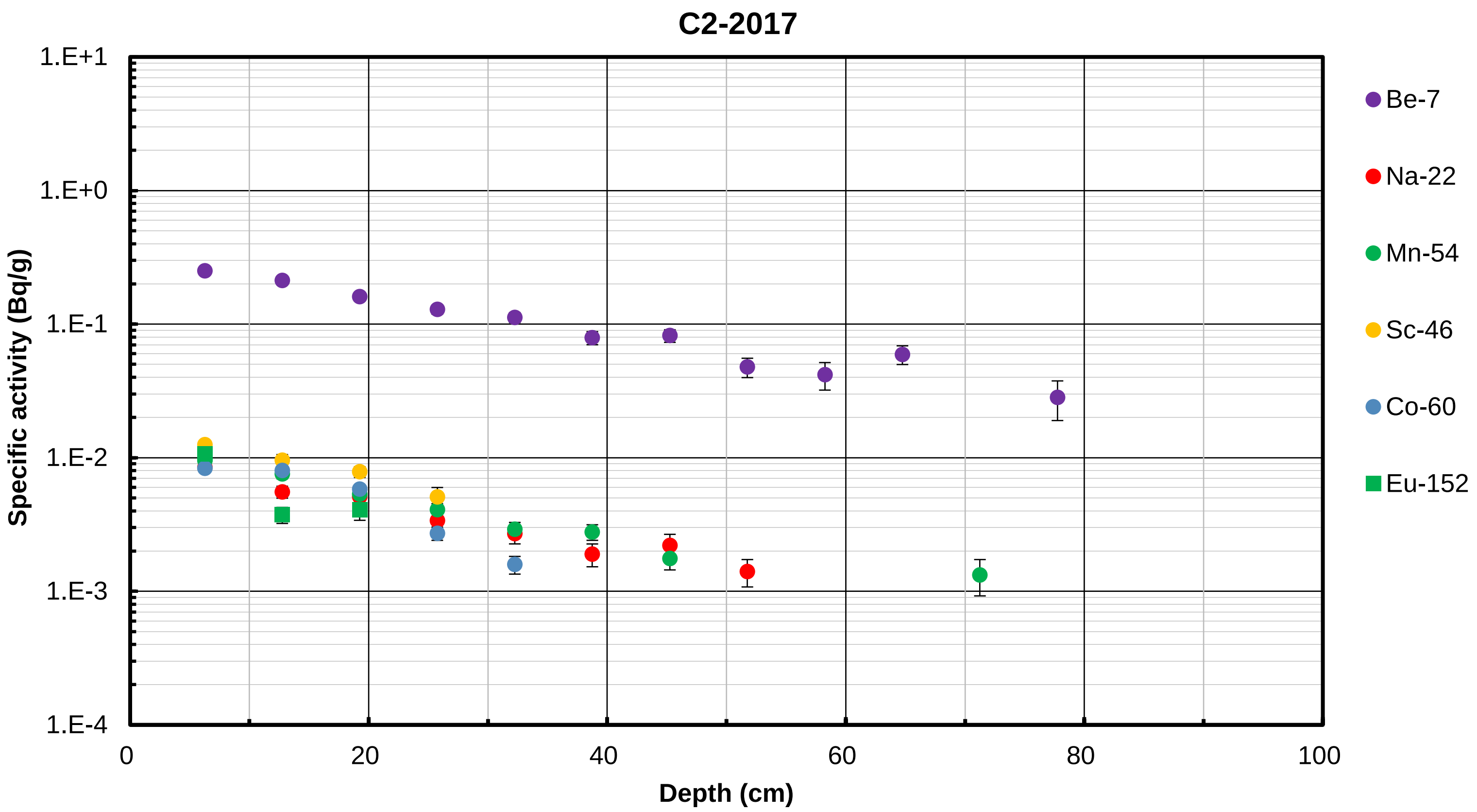


C11 : NU3 muon monitor room, before the hadron absorber (Low activation concrete)

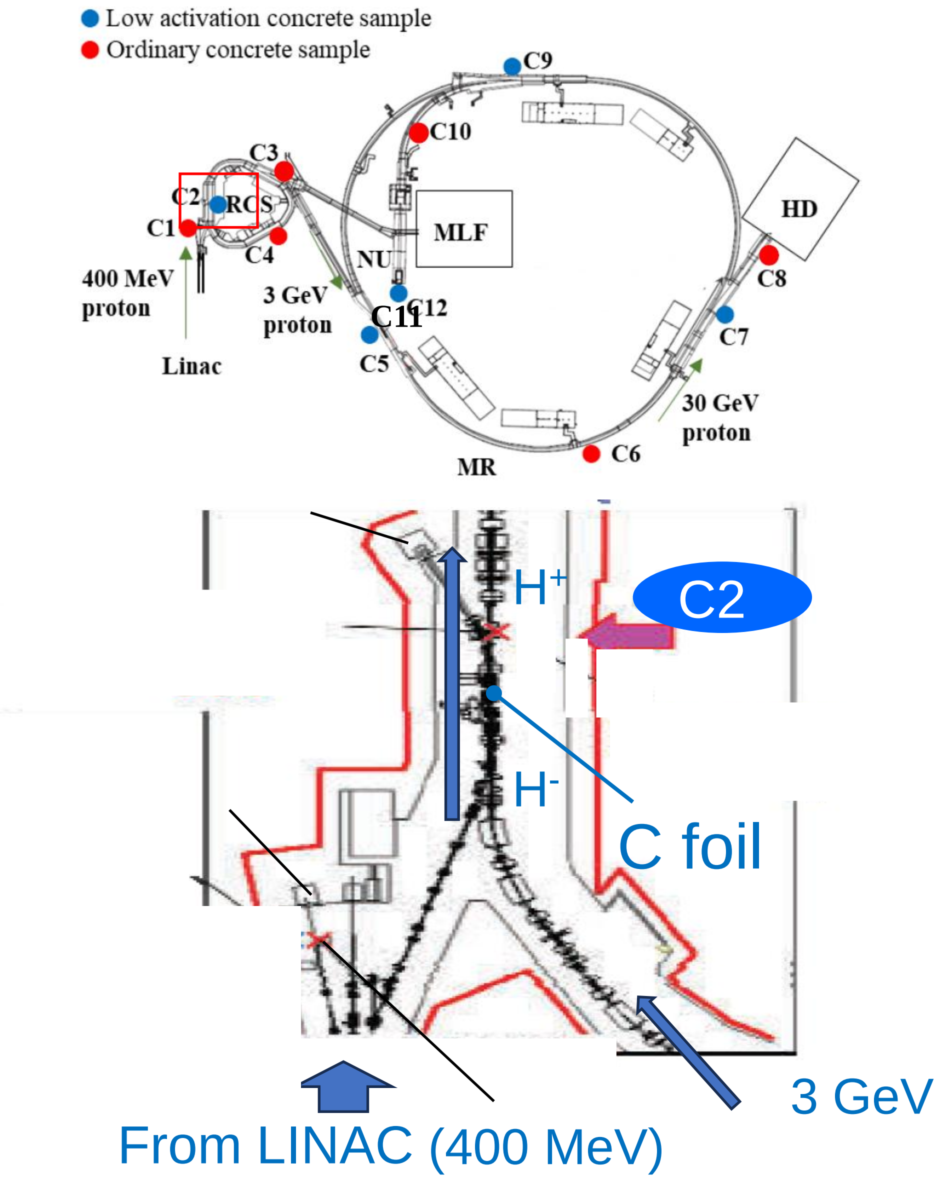
C12 : NU3 muon monitor room, behind the hadron absorber (Low activation concrete)

Location of the concrete cores C11 and C12 for radioactivity measurements.

SUPPLEMENT



Depth profile of radionuclides induced in concrete at C2 location (2017)

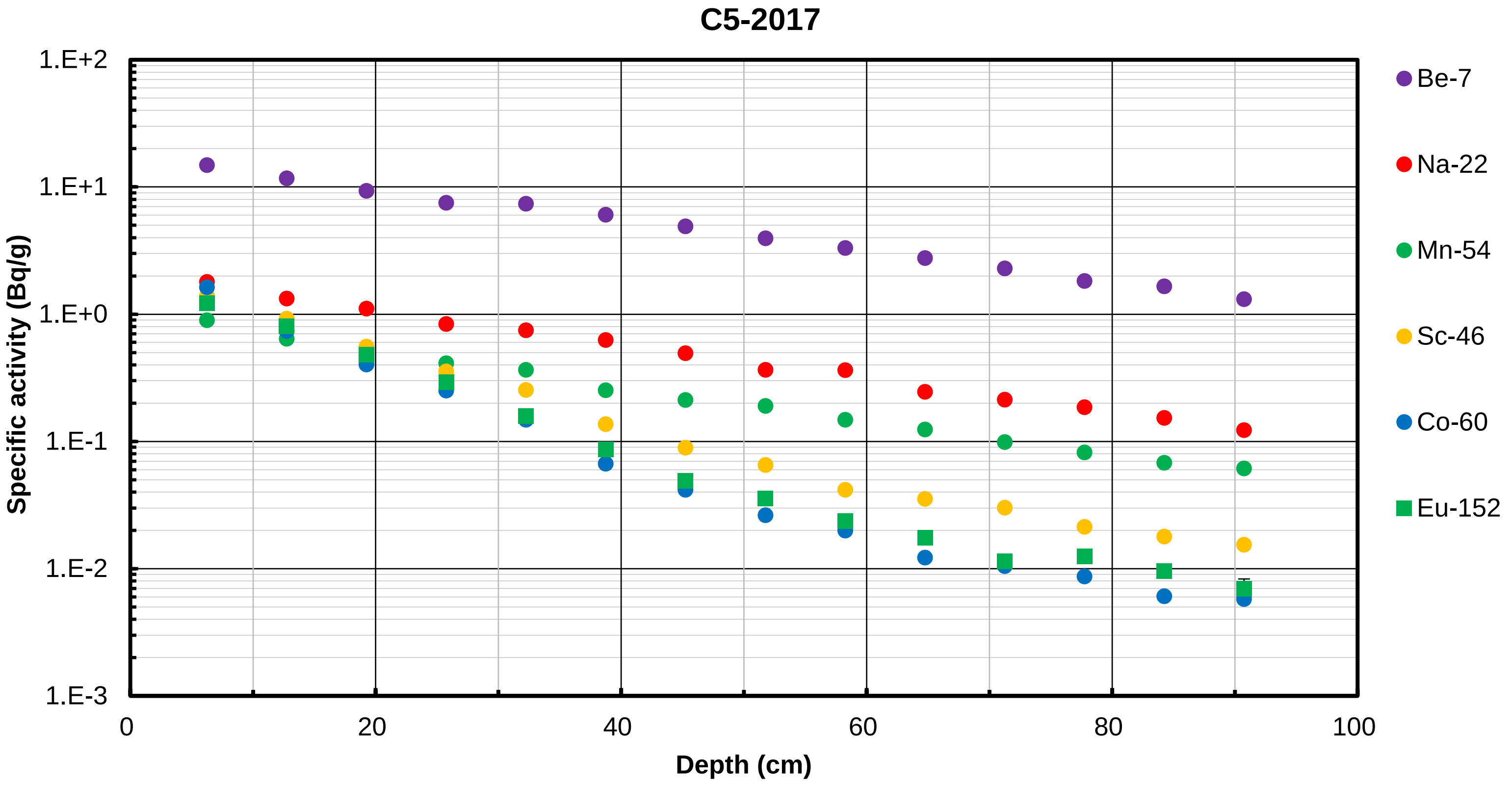


C2: RCS injection section, where it is charge-exchange injected through a carbon stripper foil.

Large beam loss at the carbon stripper foil.

Location of C2 concrete core

SUPPLEMENT

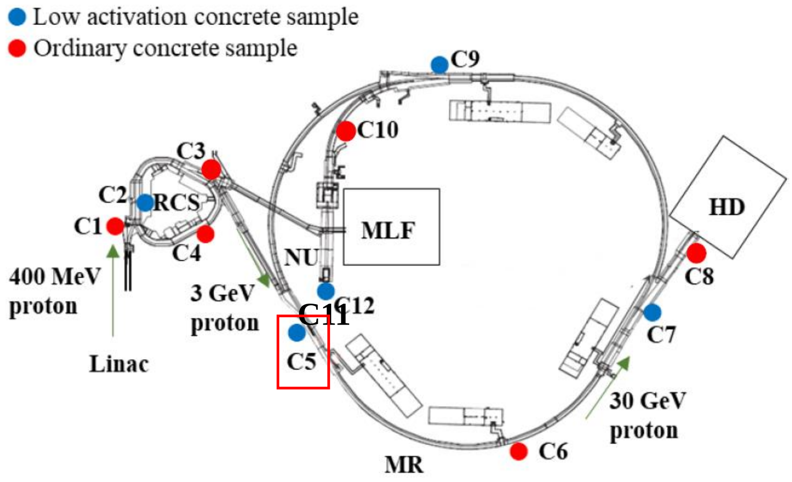


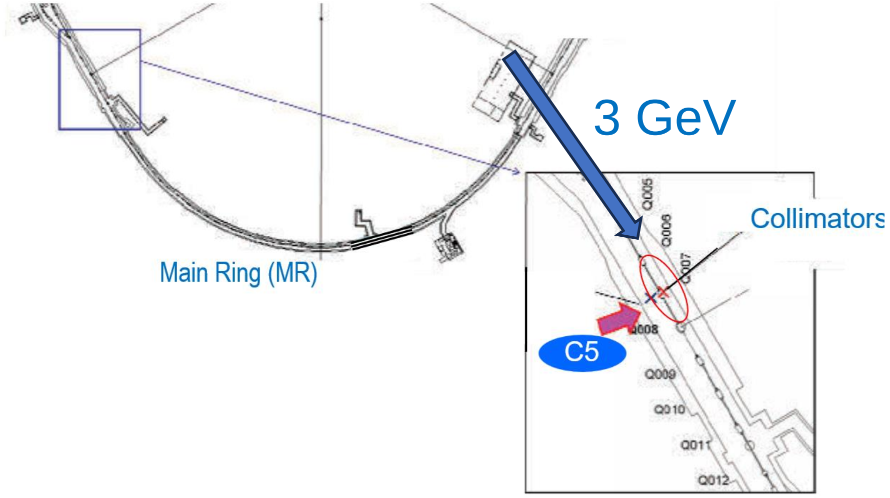
Depth profile of radionuclides induced in concrete at C5 location (2017)

C5: the injection point from RCS to MR through the 3-50 BT beamline.

The halo of 3 GeV proton beam is continuously scraped off by the beam collimators to stabilize beam transport in the MR accelerator.

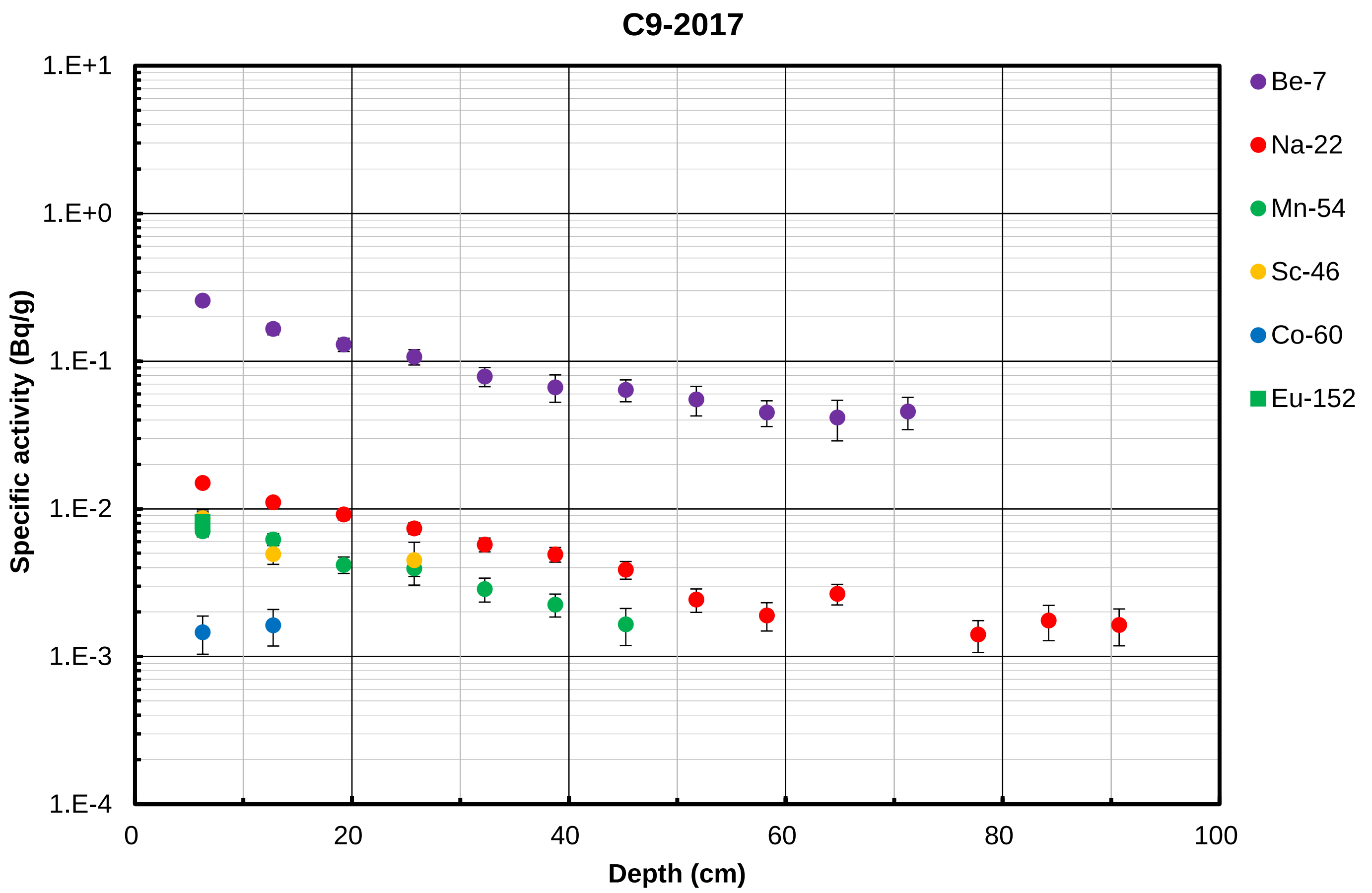
Large beam loss occurs at collimators



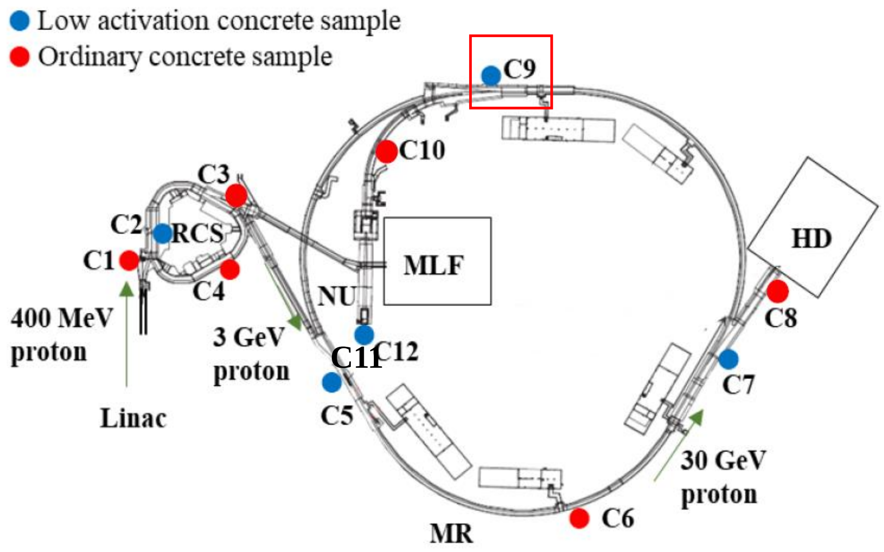


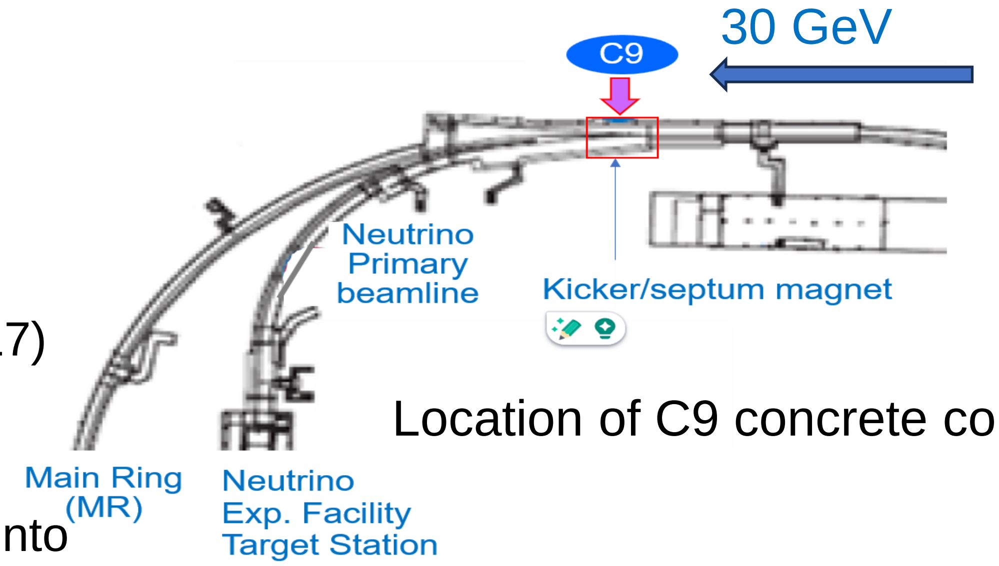
Location of C5 concrete core

SUPPLEMENT



Depth profile of radionuclides induced in concrete at C9 location (2017)



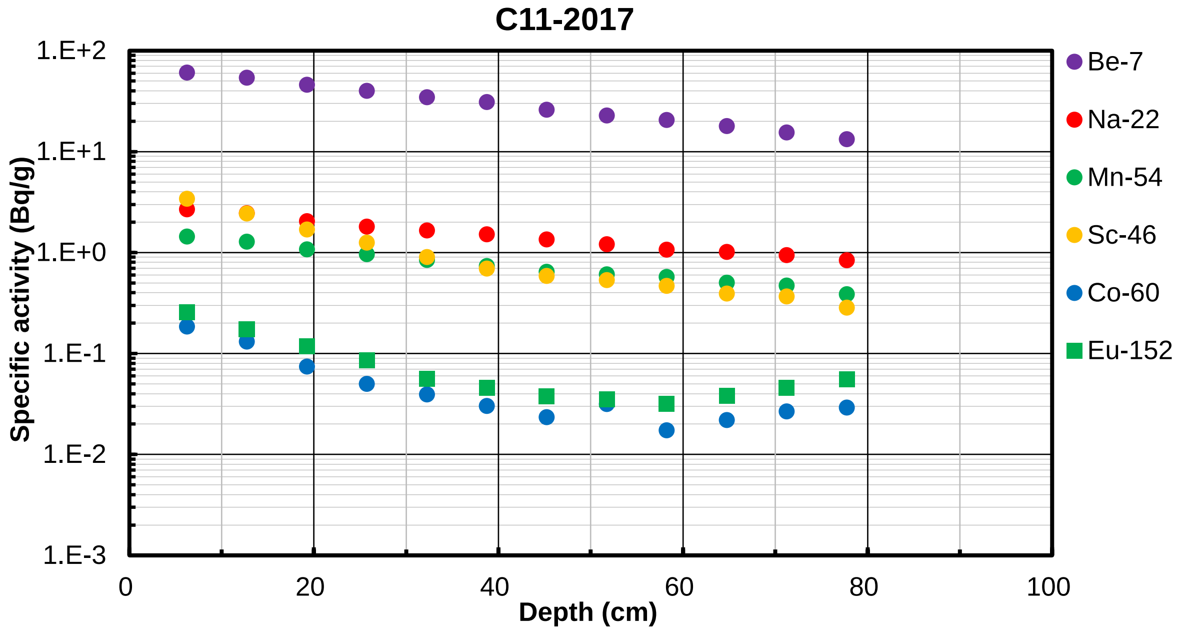


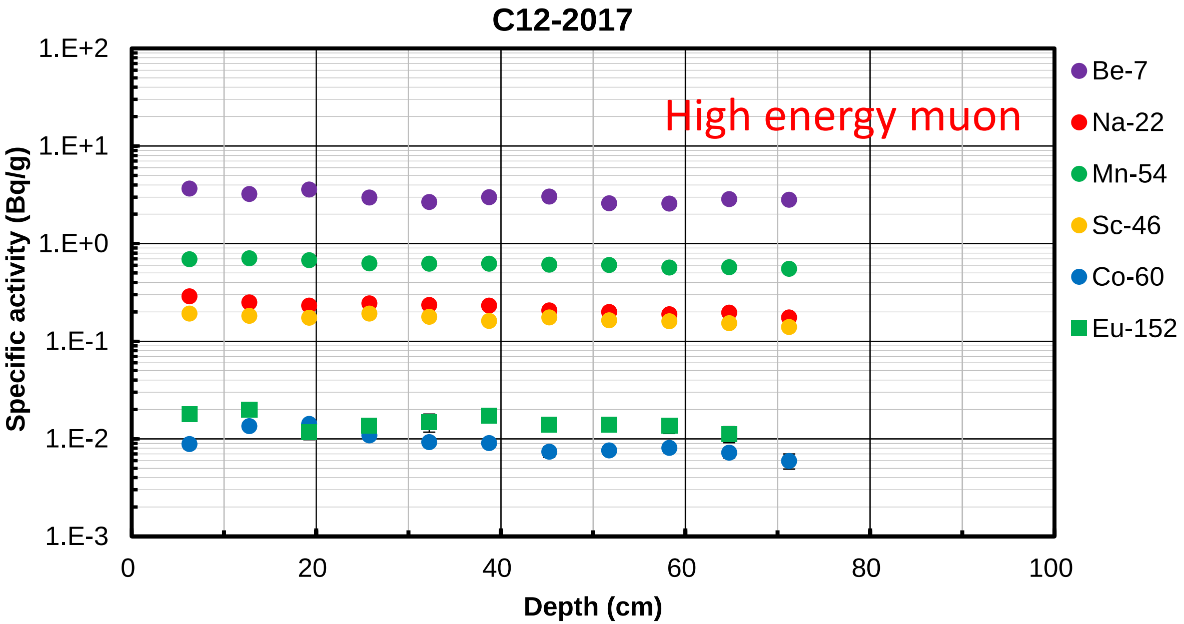
Location of C9 concrete core

C9: the fast extraction section on the MR ring

Circulating proton beam bunches are extracted within a single turn into the Neutrino Primary Beamline by a kicker/septum magnet system.

SUPPLEMENT





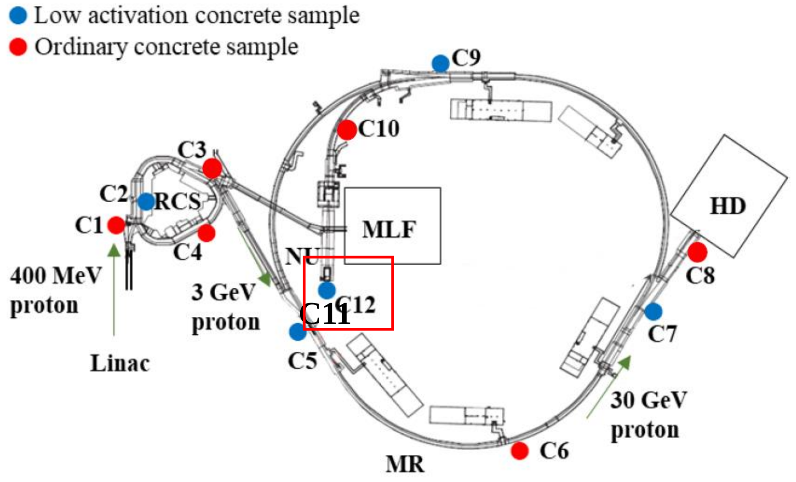
Depth profile of radionuclides induced in concrete at C11 and C12 locations (2017)

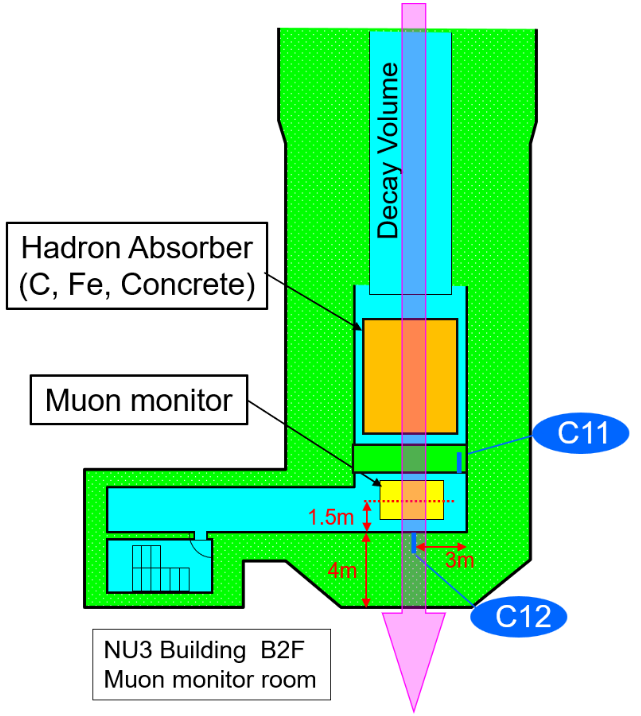
❖ C11:

- NU3 muon monitor room
- Off-beam axis
- Before the muon monitor
- Opposite to the beam direction

❖ C12:

- NU3 muon monitor room
- On-beam axis
- Behind the muon monitor





Locations of C11 and C12 concrete cores