# 100 MeV Proton-Induced Activation from High-Z Elements

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# Pohang Light Source II + PAL X-ray Free Electron Laser

# Outline

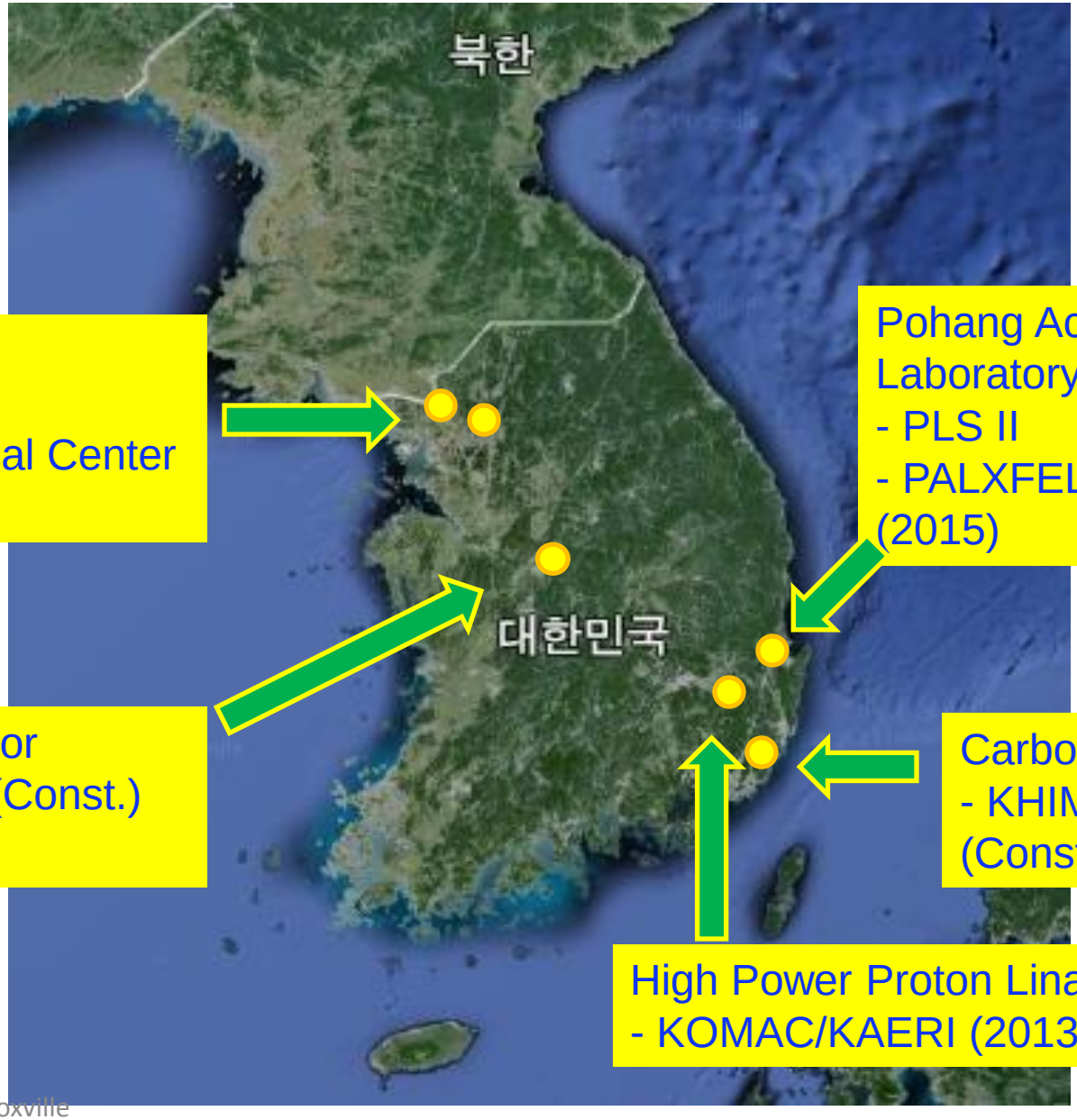
- **Introduction**
  - **Motivations and Status of PAL RP Research**
- **100 MeV Proton Irradiation Experiments at KOMAC**
- **Beam Intensity Monitoring using Au activation**
- **Radionuclide Productions in Pb foils**
- **Summary**

# Motivations

- Current Status of Large Accelerator Projects in Korea
- Three-Year Project : "Development of Core Safety Technology for Large Accelerator Facility"

  - Setup Safety Standard for Large Accelerator
- Shielding Analysis Project of RISP Accelerator, RAON
- Accelerator Driven System as Next Accelerator in Korea

# Large Accelerator Facilities in Korea




Proton Therapy
- KNCC (2006)
- Samsung Medical Center (2014)

Pohang Accelerator Laboratory (PAL)
- PLS II
- PALXFEL (Const.) (2015)

RI Accelerator
- RISP/IBS (Const.) (2021)

Carbon Therapy
- KHIMA/KIRAMS (Const.) (2017)

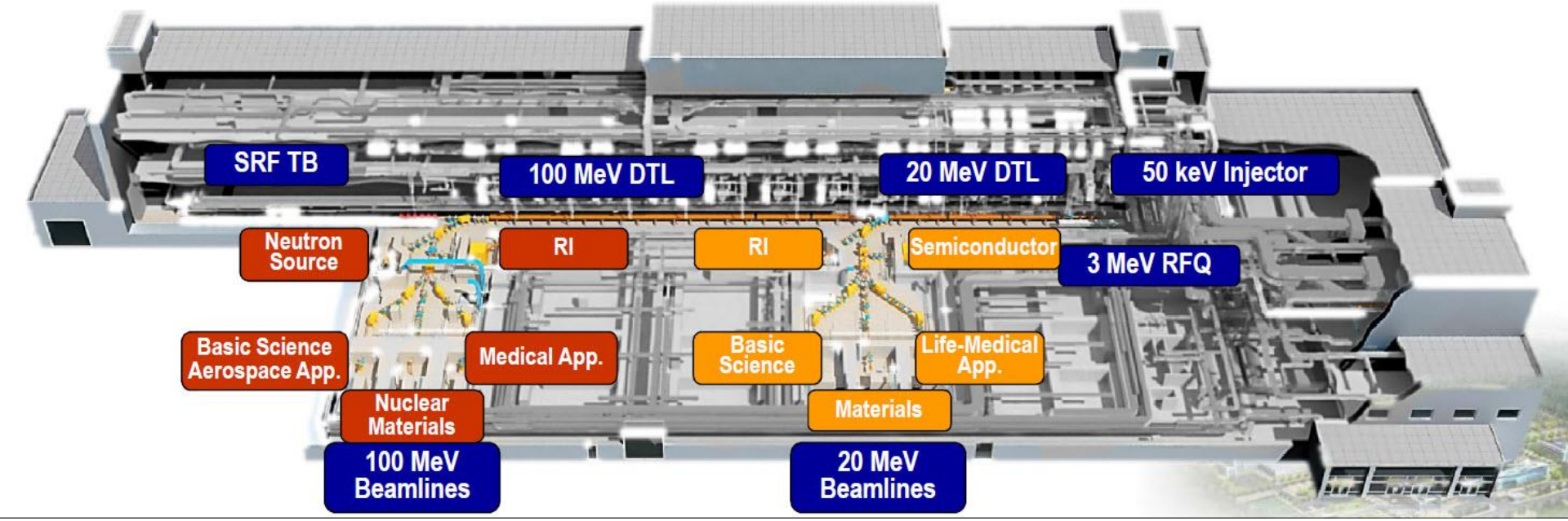
High Power Proton Linac
- KOMAC/KAERI (2013)

# KOMAC of PEFP

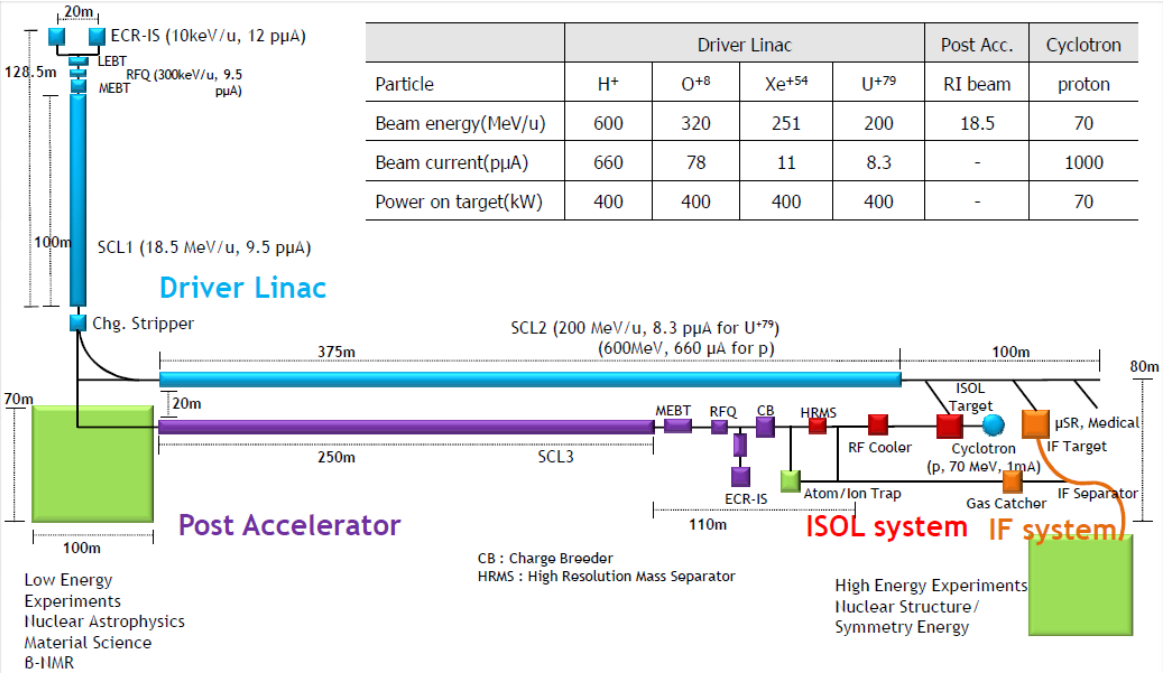
**Features of the PEFP 100 MeV linac**

- 50 keV Injector (Ion source + LEBT)
- 3 MeV RFQ (4-vane type)
- 20 & 100 MeV DTL
- RF Frequency: 350 MHz
- Beam Extractions at 20 or 100 MeV
- 5 Beamlines for 20 MeV & 100 MeV

| Energy (MeV) | 20 | 100 |
|---|---|---|
| Peak Current (mA) | 0.1 ~ 20 | 0.1 ~ 20 |
| Max. Duty (%) | 24* | 8 |
| Max. Ave. Current (mA) | 4.8 | 1.6 |
| Pulse Width (ms) | 0.05 ~ 2 | 0.05 ~ 1.33 |
| Max. Repetition Rate (Hz) | 120 | 60 |
| Max. Beam Power (kW) | 96 | 160 |
| Emmitance (mm-mrad) | 0.22(x), 0.25(y) | 0.3 / 0.3 |

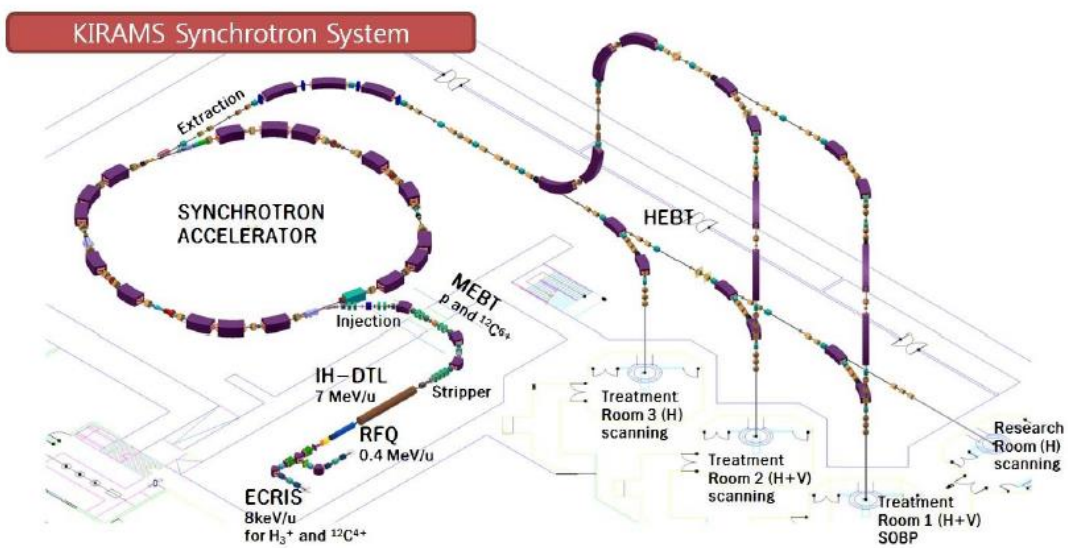


# RISP Accelerator - Raon




| | Driver Linac | | | | Post Acc. | Cyclotron |
|---|---|---|---|---|---|---|
| Particle | $H^{+}$ | $O^{+8}$ | $Xe^{+54}$ | $U^{+79}$ | RI beam | proton |
| Beam energy(MeV/u) | 600 | 320 | 251 | 200 | 18.5 | 70 |
| Beam current(pμA) | 660 | 78 | 11 | 8.3 | - | 1000 |
| Power on target(kW) | 400 | 400 | 400 | 400 | - | 70 |

# KHIMA - 430MeV/n C



# Introduction – Project 1

## Standard Technology for Safety Inspection of Large Accelerator Facility

- What is optimum method for shielding design?
- What is acceptance level in shielding analysis?
- How serious is the activation issues? (hadron facility)
- How important is the accident analysis and What is it?
- What should be included in Radiation Safety Analysis Report? (Decommissioning?)

# Benchmarking Studies

- **Shielding analysis including activity estimation is an important process in designing large particle accelerator facility .....**

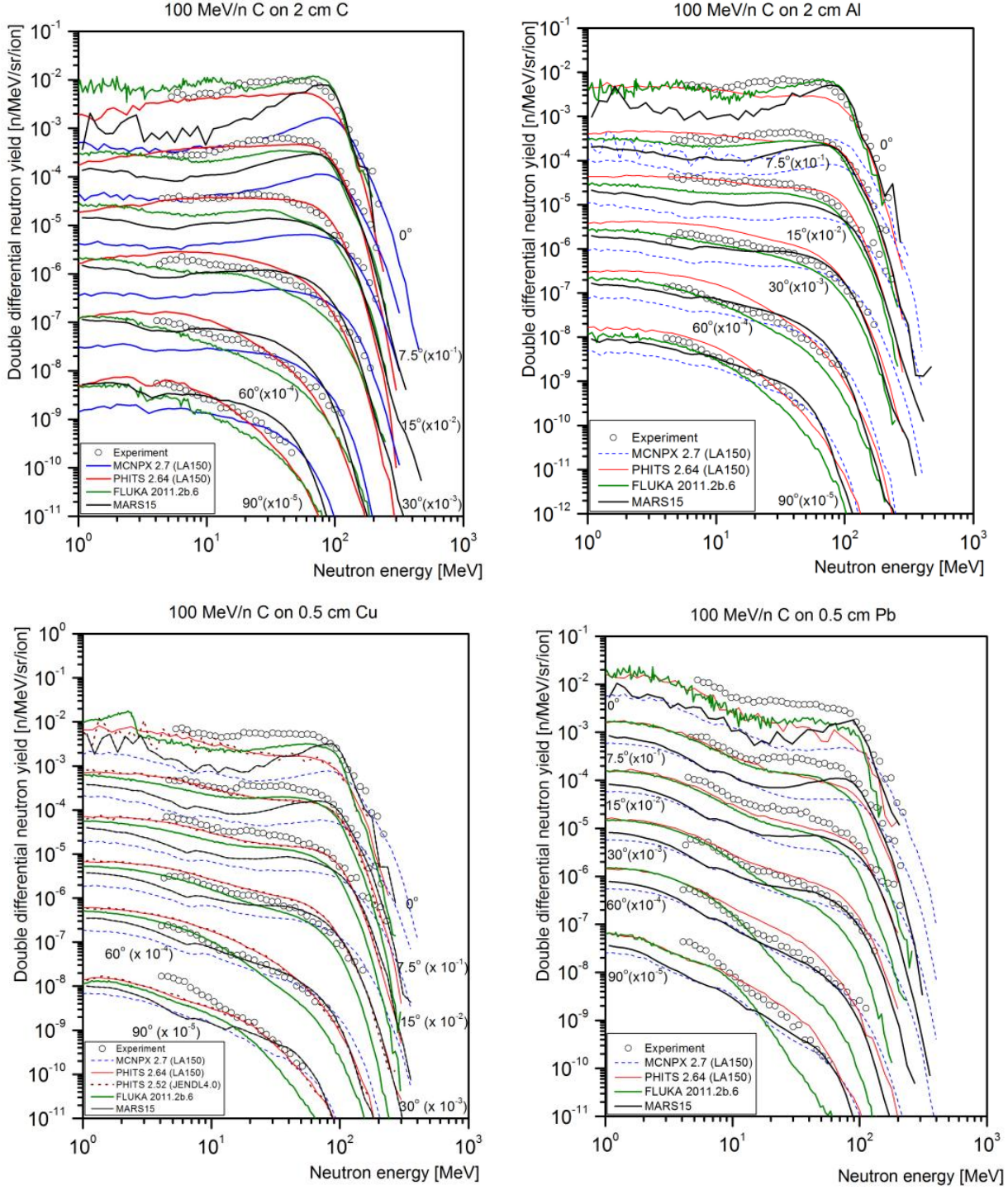
  **PALXFEL, KOMAC, KHIMA, RISP....**

- **Large accelerator operate high-energy, high-power particles including heavy ion**

- **Analysis tools are improved very much in Monte Carlo codes**

- **Eventually can the existing Monte Carlo codes give credible results ? for the specific accelerator. How much accurate?**

- **Performing the code comparison using benchmarking studies**




# Benchmarking Studies using MC codes

- FLUKA
- PHITS
- MCNPX
- MARS

# Introduction – Project 2

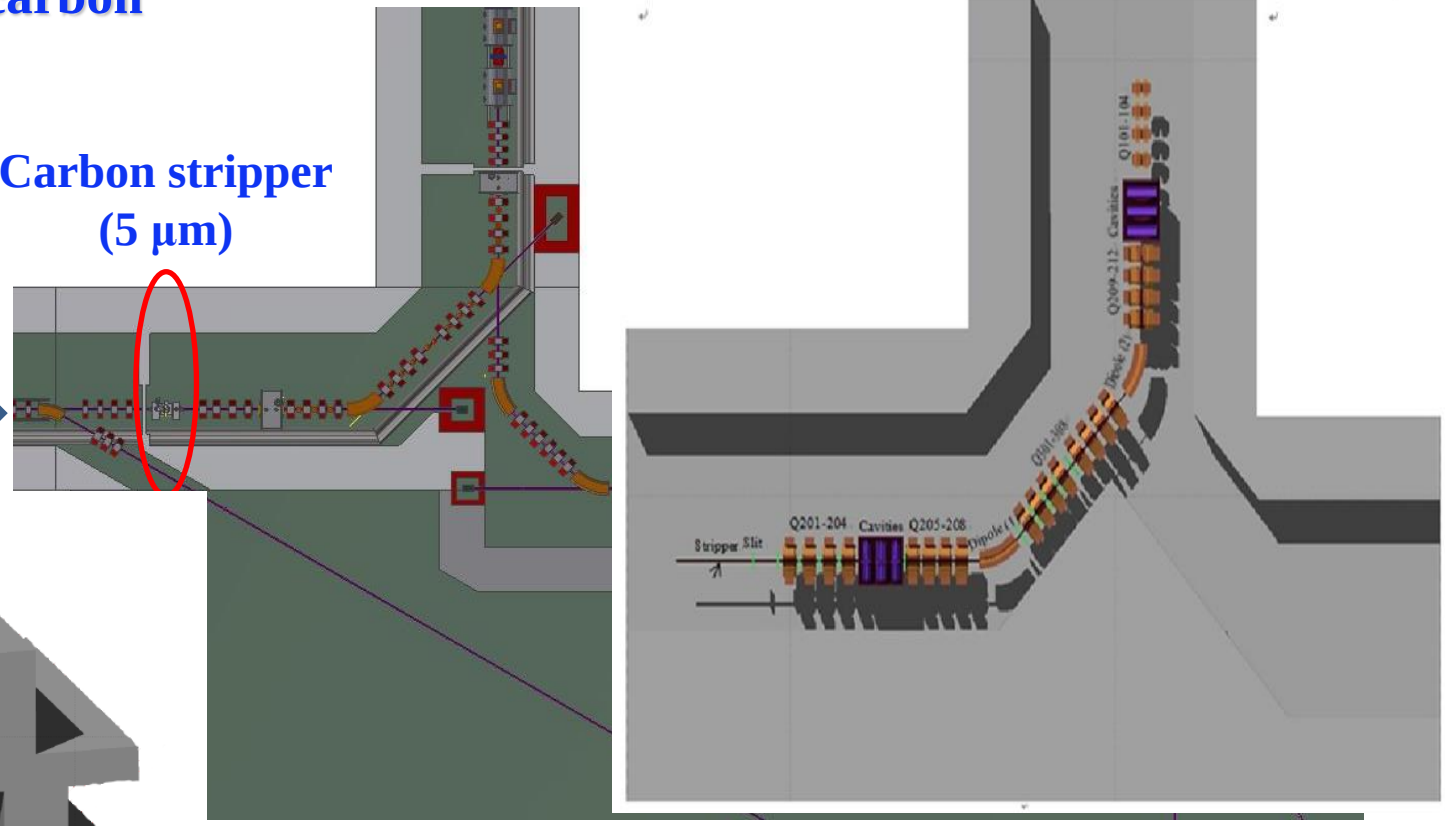
✓ **In the case of major $^{238}U$ ion beam**

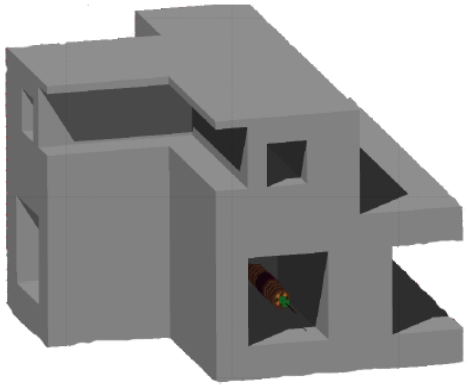
✓ **Multi-charged ions beam from carbon stripper**

**Carbon stripper (5 μm)**

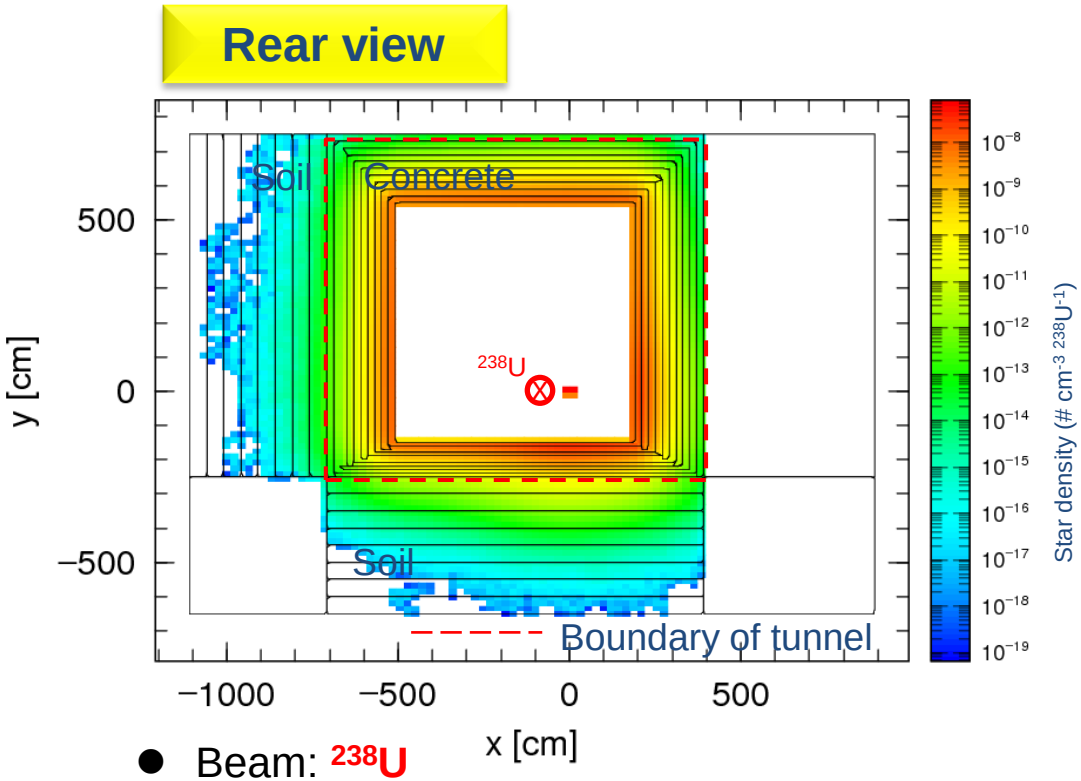
**$^{238}U$ 33+, 34+**

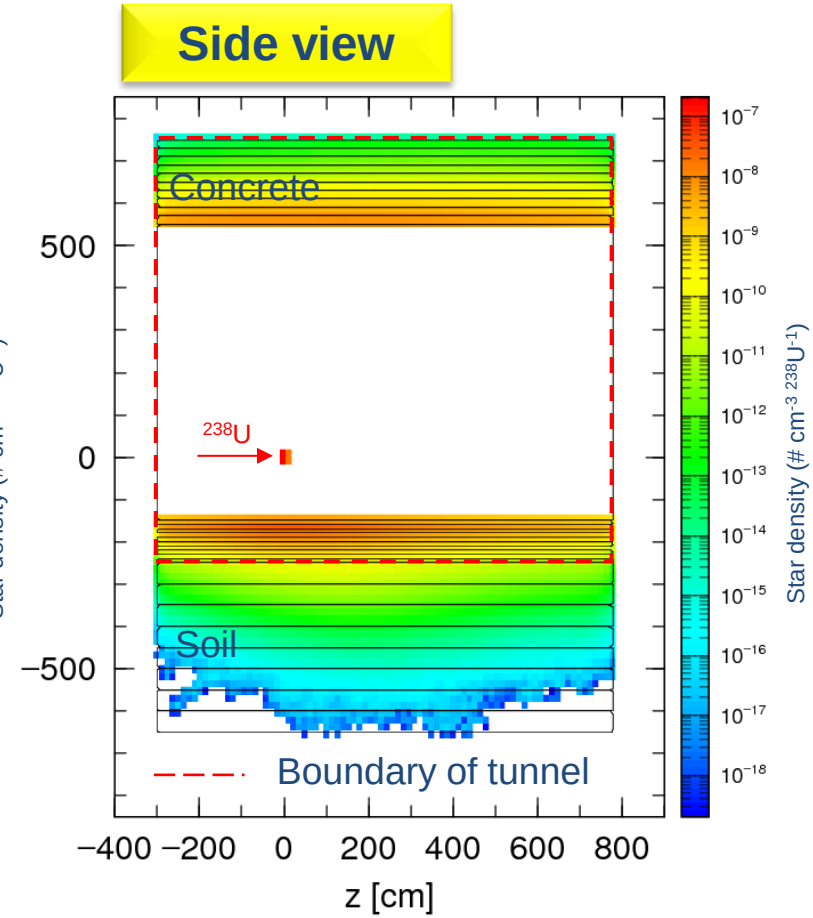
**17.5 MeV/u, 9.5 pμA**



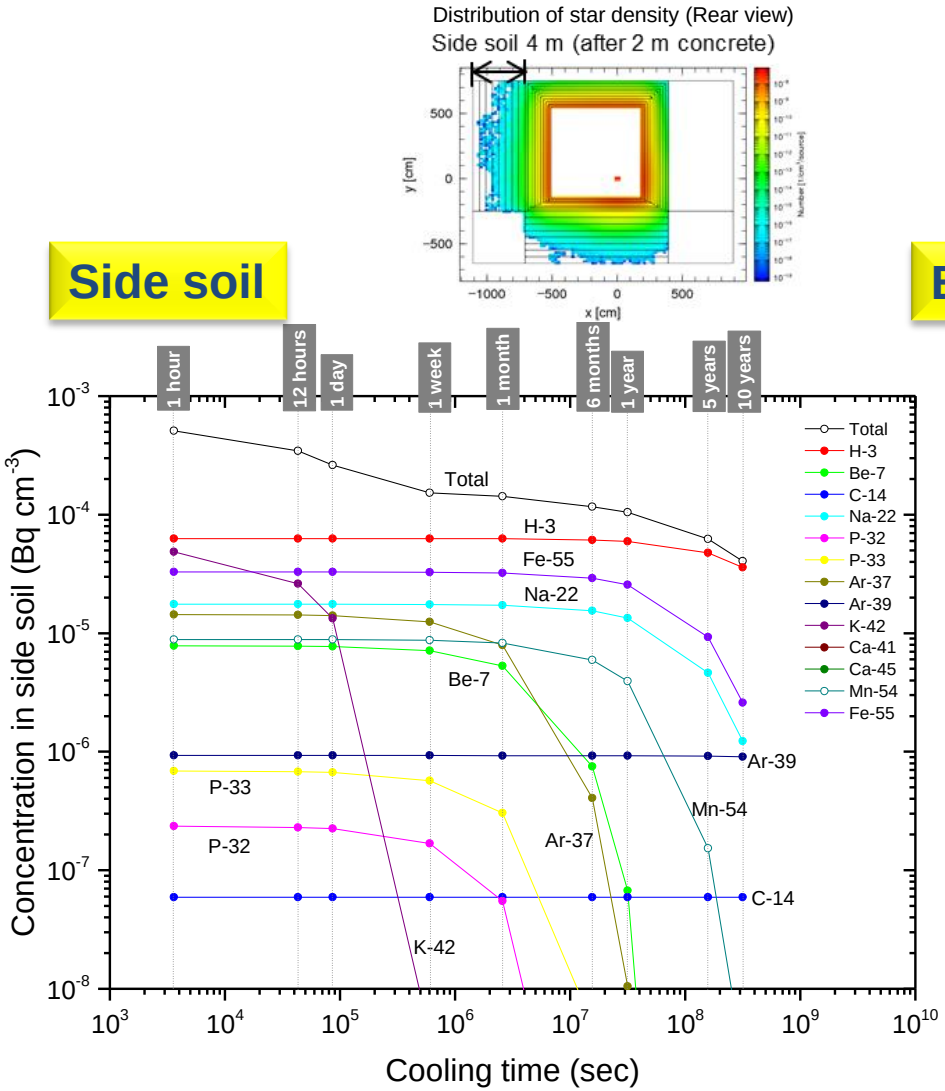
# Estimation of Soil activation - Star density (PHITS results)

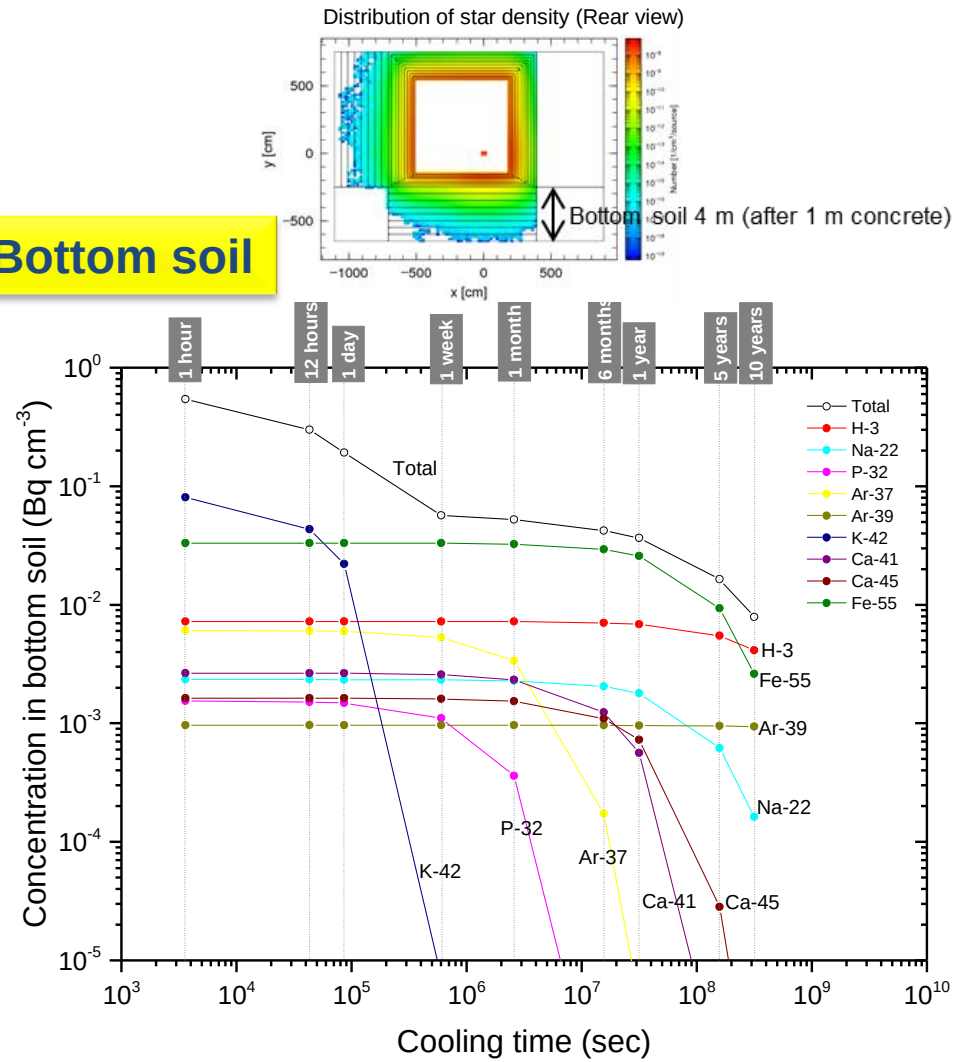



- Beam: $^{238}$U (17.841 MeV/u, 7.34x10$^{13}$pps)
- Thick Iron target (Φ 10 cm, t = 10 cm, 7.86 g/cm$^3$)
- PHITS 2.64 using T-star tally.

# Isotope Concentration in Soil
## (Irradiation time = 20 years)

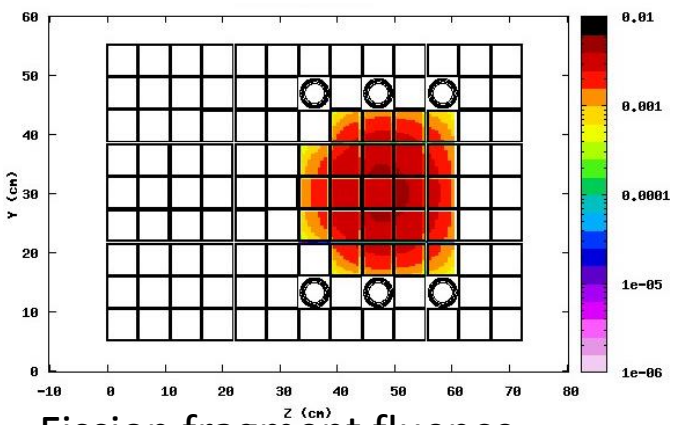


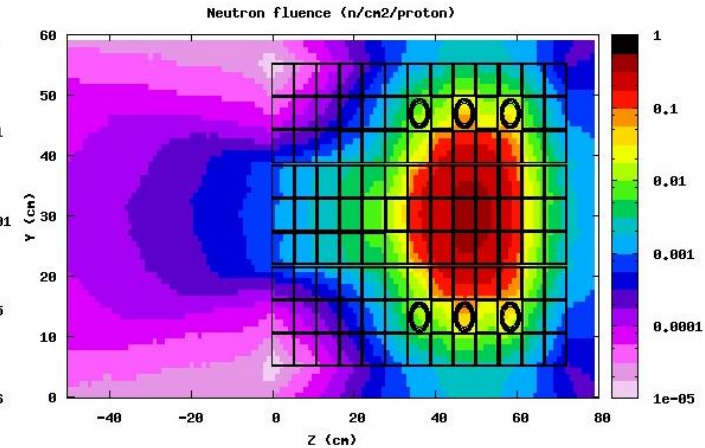
# ADS Study at Critical Assembly (KUCA)

**When W target is at the middle of U (90%) fuel assembly,**

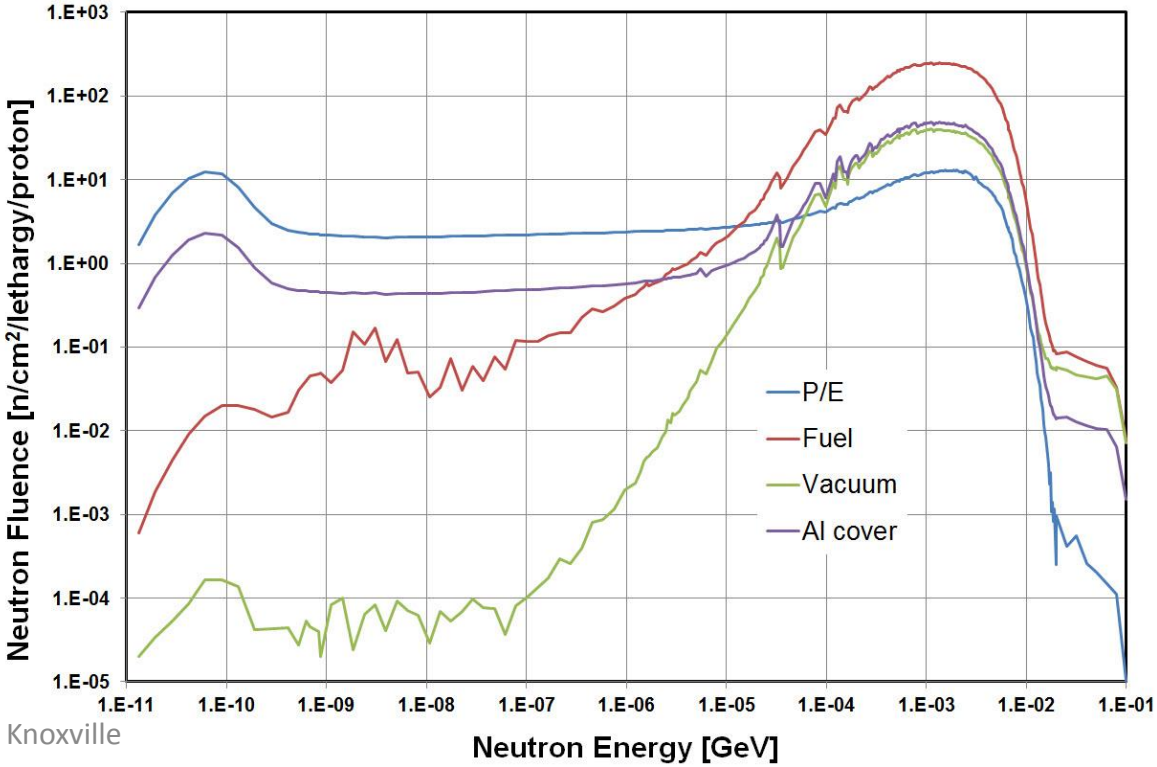
**Particle Distributions**




Fission fragment fluence

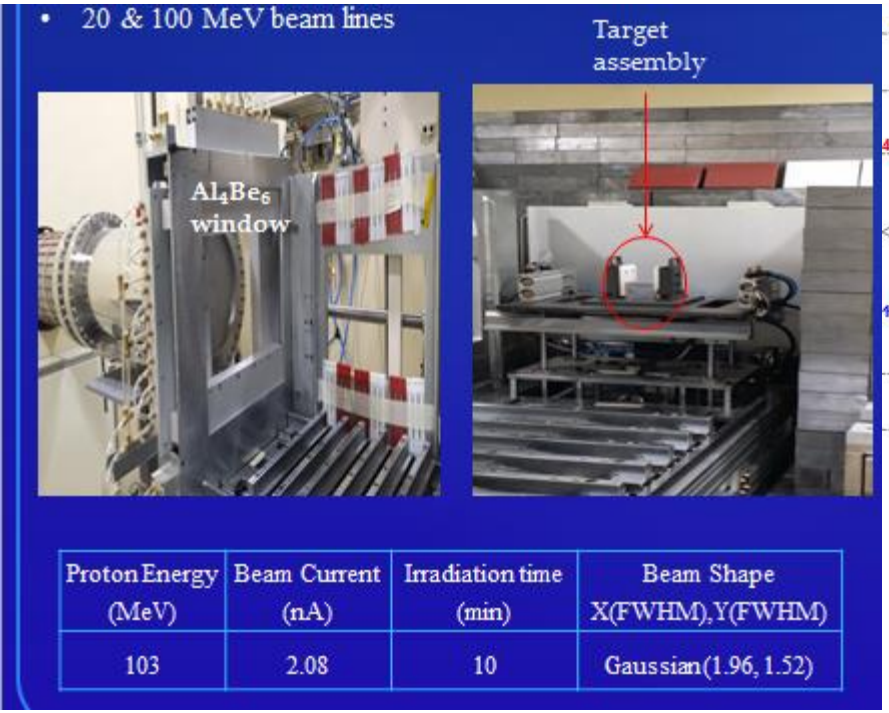



Neutron fluence

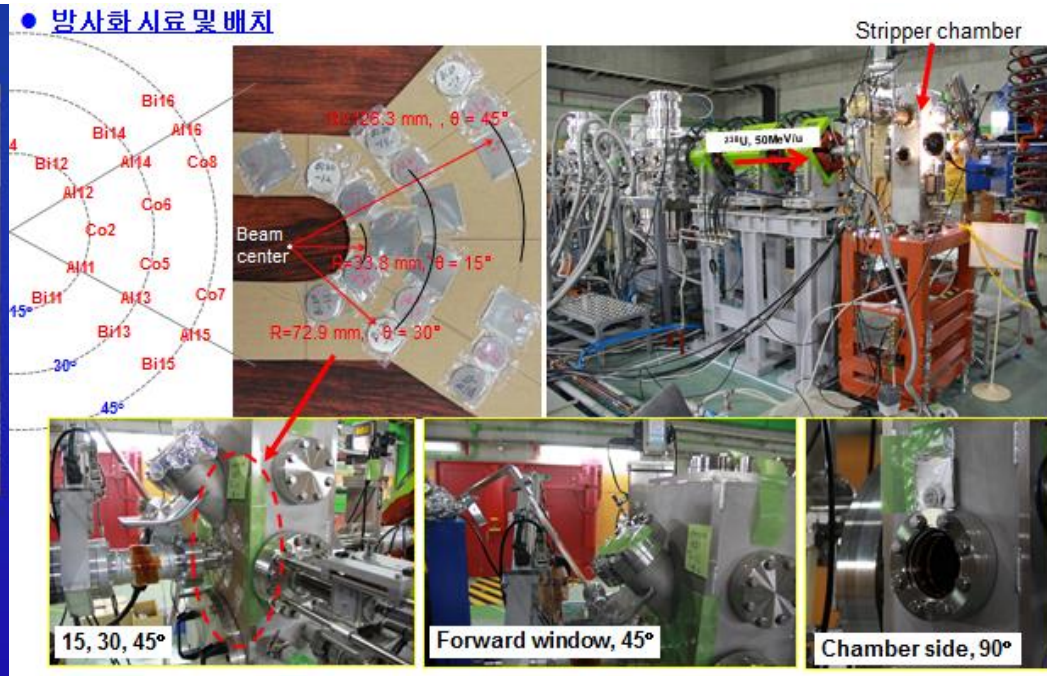


# Developing Data in Unknown Range

- Radioisotope Production from High Z elements by 100 MeV Protons with Pb target (KOMAC)
- Neutron measurements using Activation Analysis for 50 MeV/u Uranium ion - induced Reaction at thin Be stripper (RIBF at RIKEN)




| Proton Energy (MeV) | Beam Current (nA) | Irradiation time (min) | Beam Shape X(FWHM),Y(FWHM) |
|---|---|---|---|
| 103 | 2.08 | 10 | Gaussian(1.96, 1.52) |



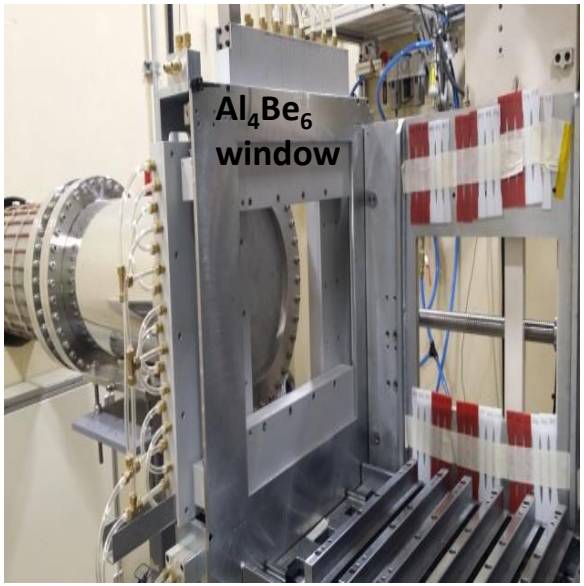

Bi(Φ 20 mm x 2 mm), (0.127 x 50 x 50 mm³), 99.997% pure
Co(0.5 x 25 x 25 mm³), (0.5 x 50 x50 mm³), 99.997% pure
Al(Φ 20 mm x 2 mm), 99.5% pure

# Irradiation Experiments at KOMAC

# Experiment at KOMAC-100 MeV Proton on Pb & Au

- **KOMAC facility:**
- 100 MeV proton linac
- 20 & 100 MeV beam lines

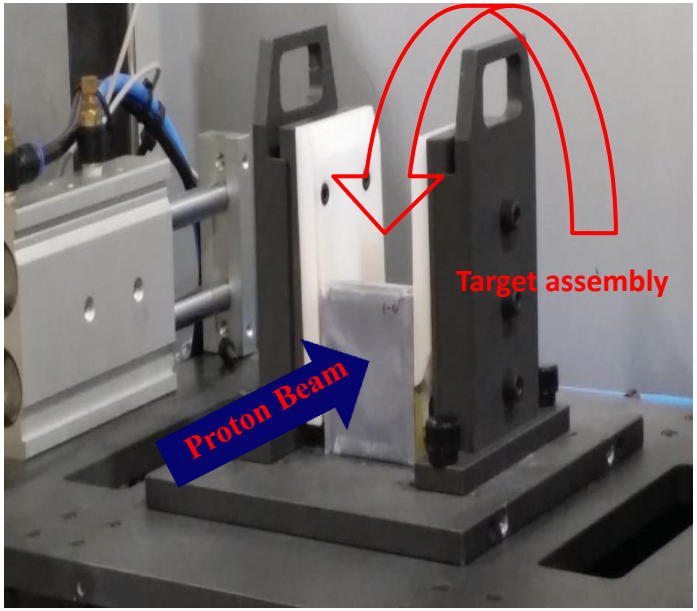
Target Assembly



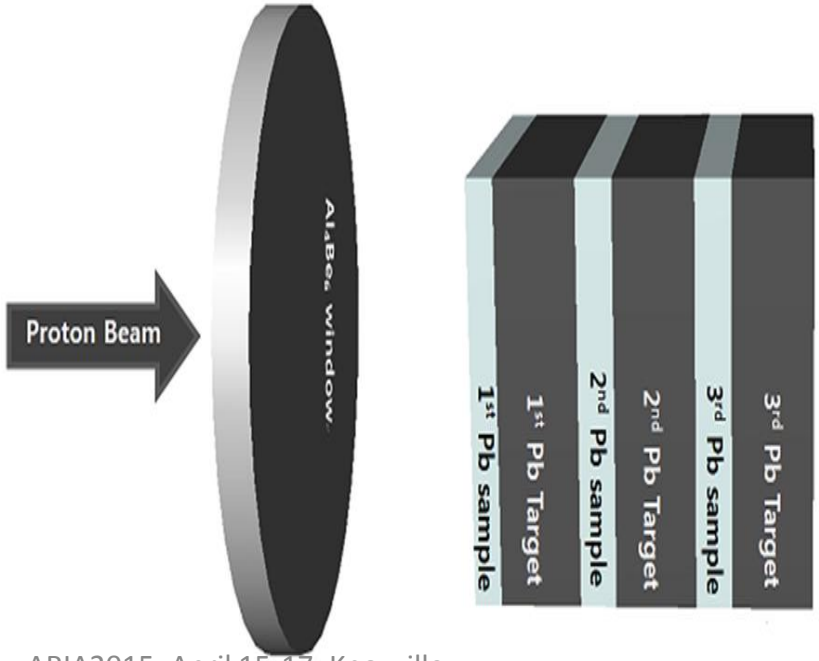
# 100 MeV Proton on Pb target assemply

- Beam Conditions

| Proton Energy (MeV) | Beam Current (nA) | Irradiation time (min) | Beam Shape X(FWHM),Y(FWHM) |
|---|---|---|---|
| 103 | 2.08 | 10 | Gaussian (1.96, 1.52) |



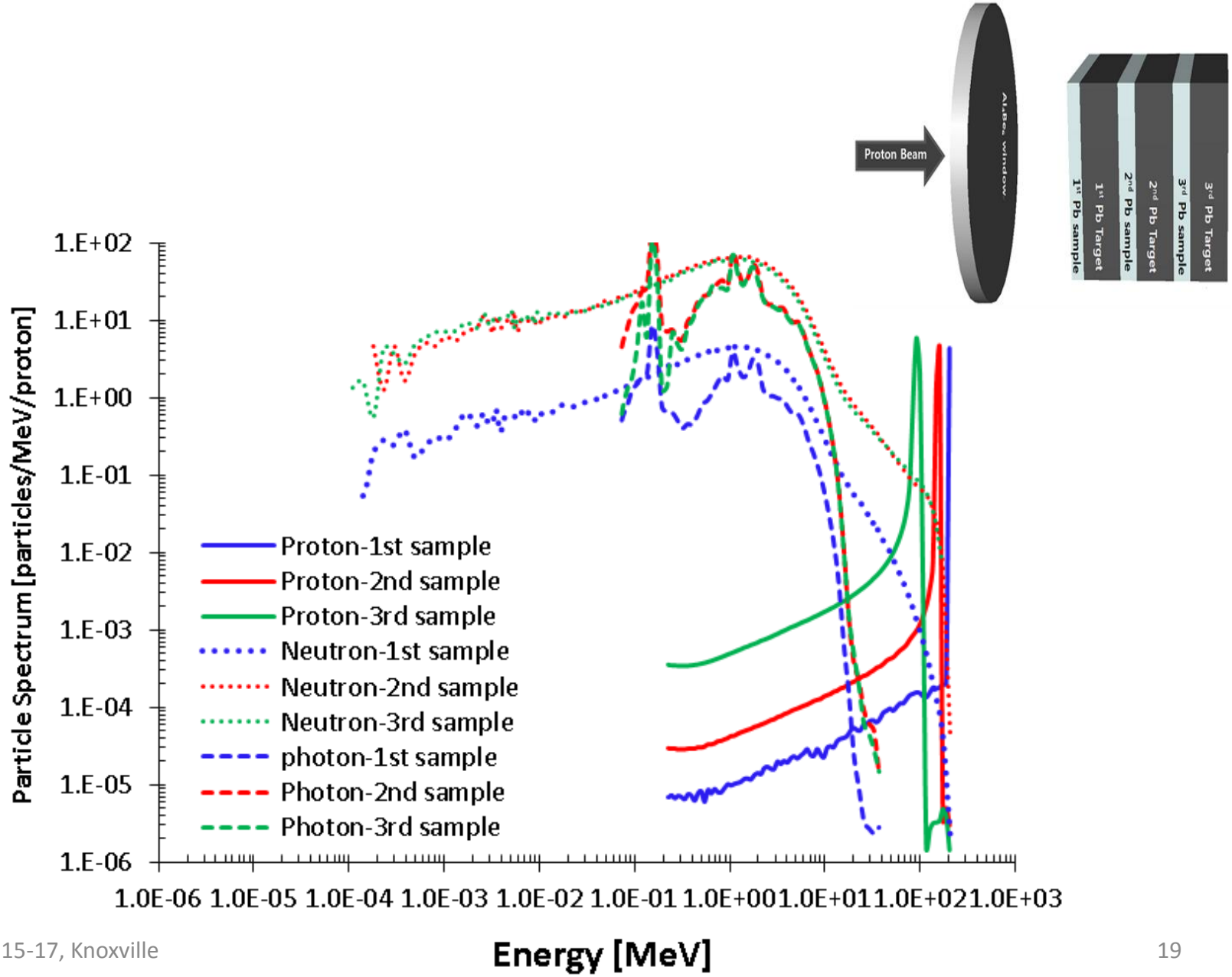

- Schematic view of the experimental setup



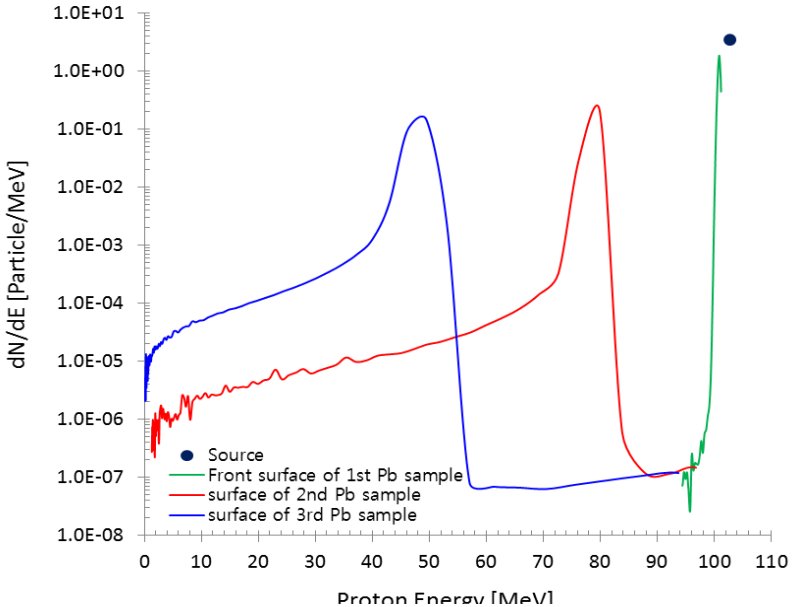

- Parameters of irradiated structures

| Components | Material | Number | H × W (mm) | Thickness(mm) |
|---|---|---|---|---|
| Target | Lead | 3 | 50 × 50 | 5 |
| Sample | Lead | 1 | 50 × 50 | 0.05 |
| | | 2 | 50 × 50 | 0. 5 |
| window | $Al_4Be_6$ | 1 | R=150 | 0. 5 |

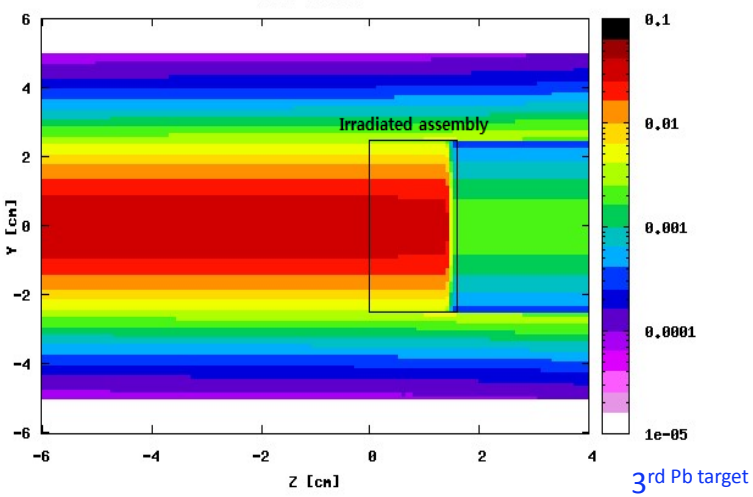
# Particle Spectra at Sample Positions



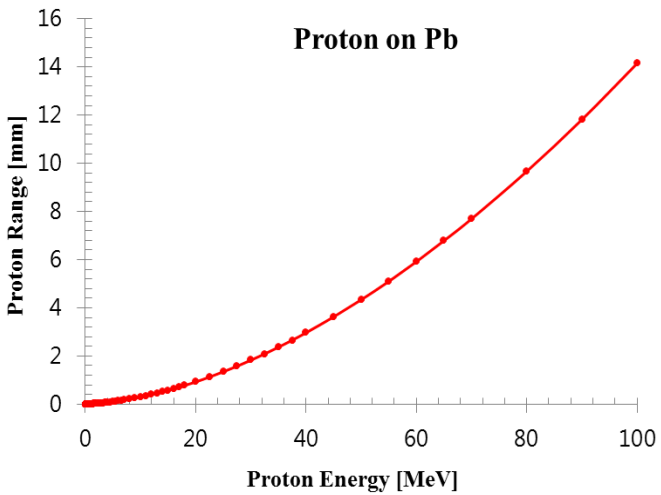
# Proton energy distribution at the various sample surfaces



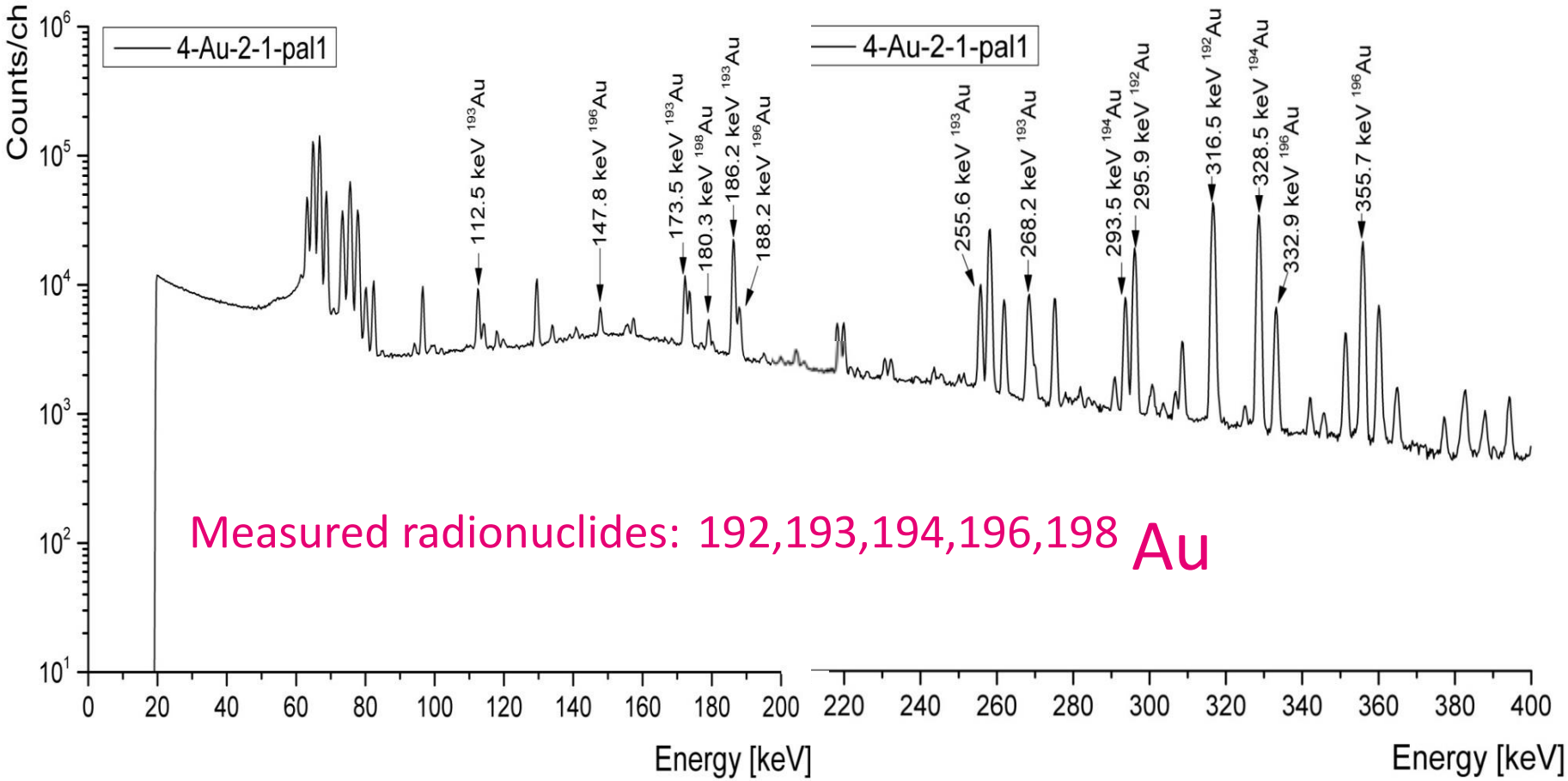

- **Proton range in the irradiated assembly**




- **FLUKA can not identify proton spectrum in the $Al_4Be_6$ window. Range of proton beam is defined By SRIM code in this region.**
- **Incident Proton Energy in the 1st sample is 101.45 MeV.**
- **Incident proton beam in the 2nd sample has a maximum energy of 79.9 MeV.**
- **Incident proton beam in the 3rd sample has a maximum energy of 49.5 MeV**
- **Proton beam stop in the 3rd Pb target**



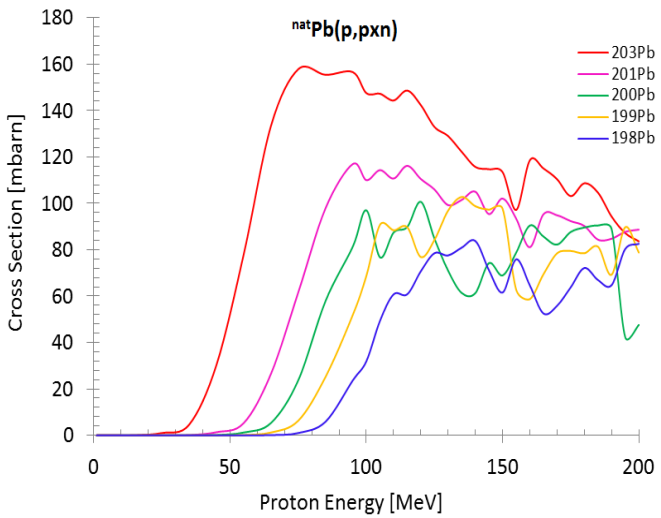
# Gamma Spectrum Analysis by HPGe and Hypergam

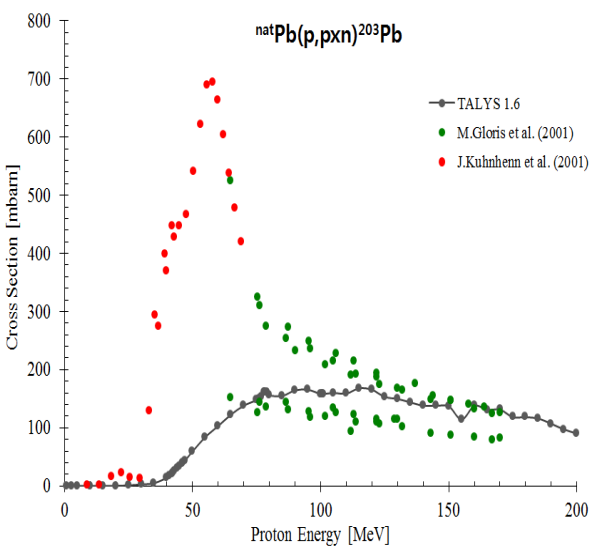


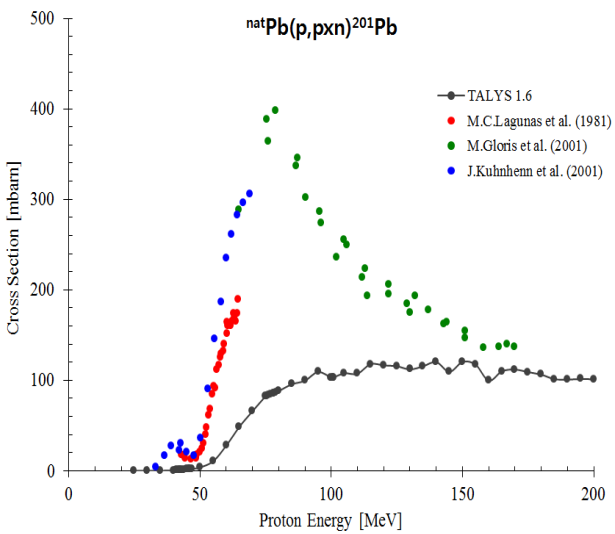

Measured radionuclides: 192,193,194,196,198 Au

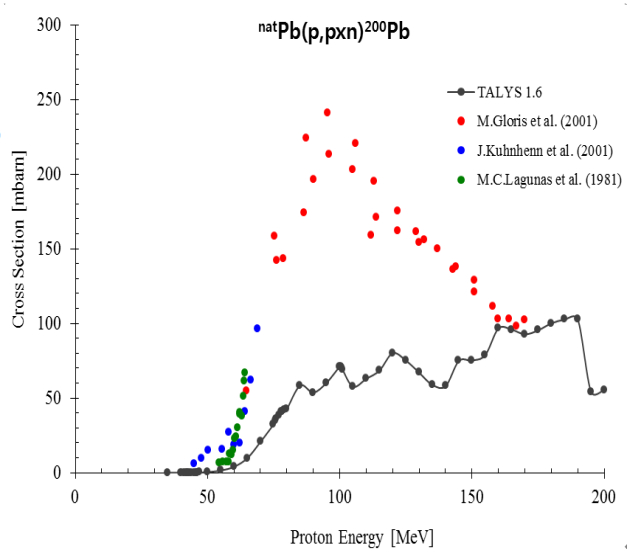
# Reviews of Cross-section Data: $^{nat}$Pb(p, pxn) Reactions

- In (p, pxn) reactions, TALYS-1.6 calculations based on the defaults mode underestimate the experimental data.



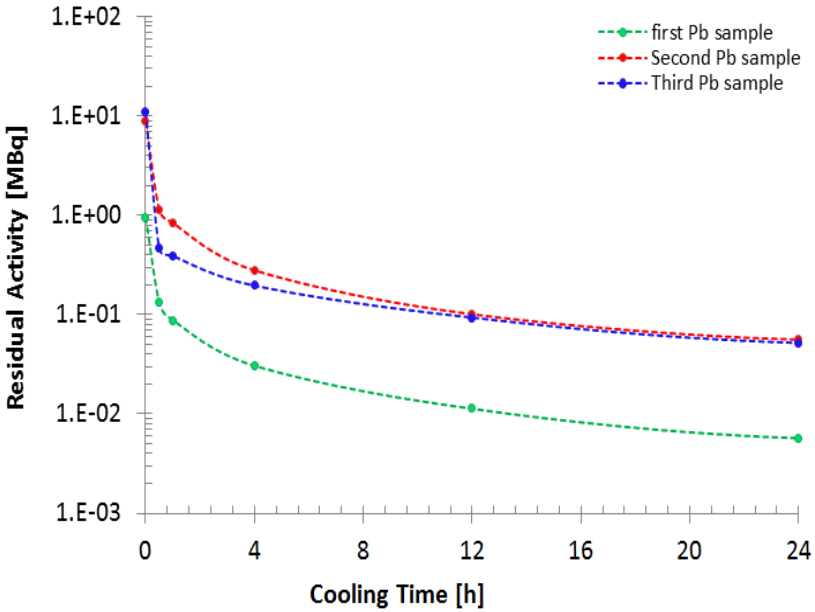



# Production Yields of Major Isotopes in Pb Samples Calculated by FLUKA

- Residual activity of Pb samples during 24 hours cooling time

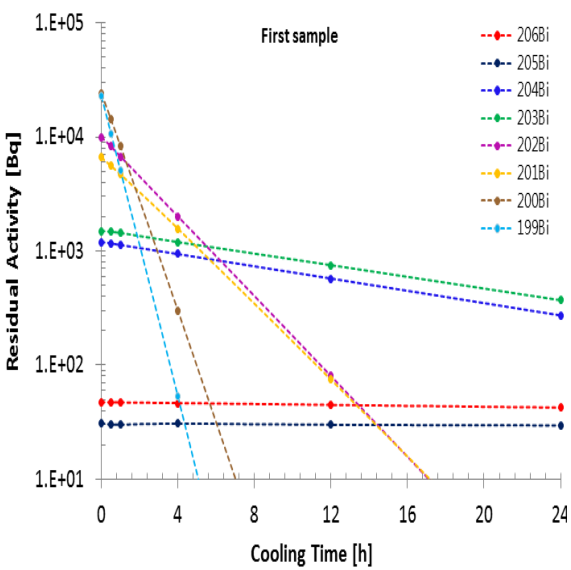


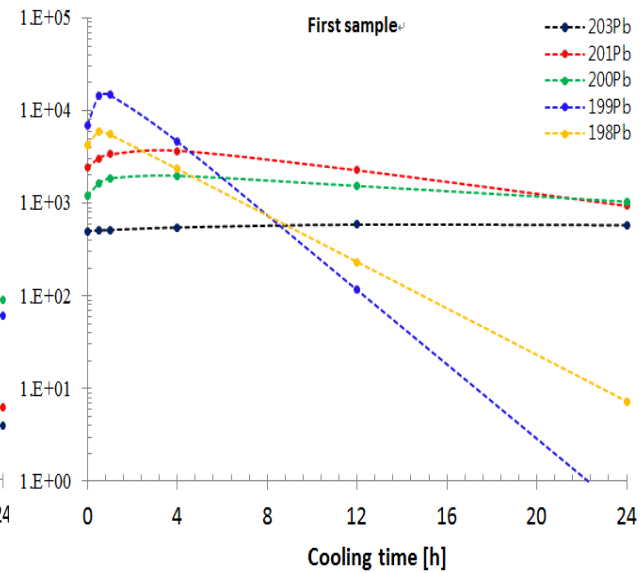

- Production Yield of third Pb sample at the end of irradiation is higher than other samples (31.7 MBq/nA·h) which reduce after 30 minutes considerably (1.33 MBq).

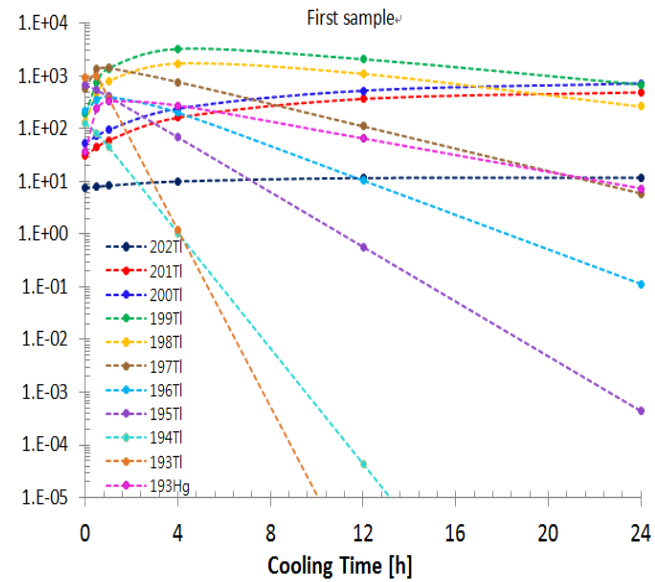
- Production yield of Pb samples after end of the irradiation

| Sample | Yield at EOB [MBq/nA·h] | Uncertainty [%] |
|---|---|---|
| first sample | 2.76 | 0.7 |
| second sample | 25.58 | 0.2 |
| Third sample | 31.70 | 0.2 |

# Residual Activity of Bi, Pb, Tl and Hg Radioisotopes in the 1st Pb Sample




$^{199}$Bi(27min) $\xrightarrow{EC}$ $^{199}$Pb (90 min) $\xrightarrow{EC}$ $^{199}$Tl(7.4 h) $\xrightarrow{EC}$ $^{199}$Hg(stable)

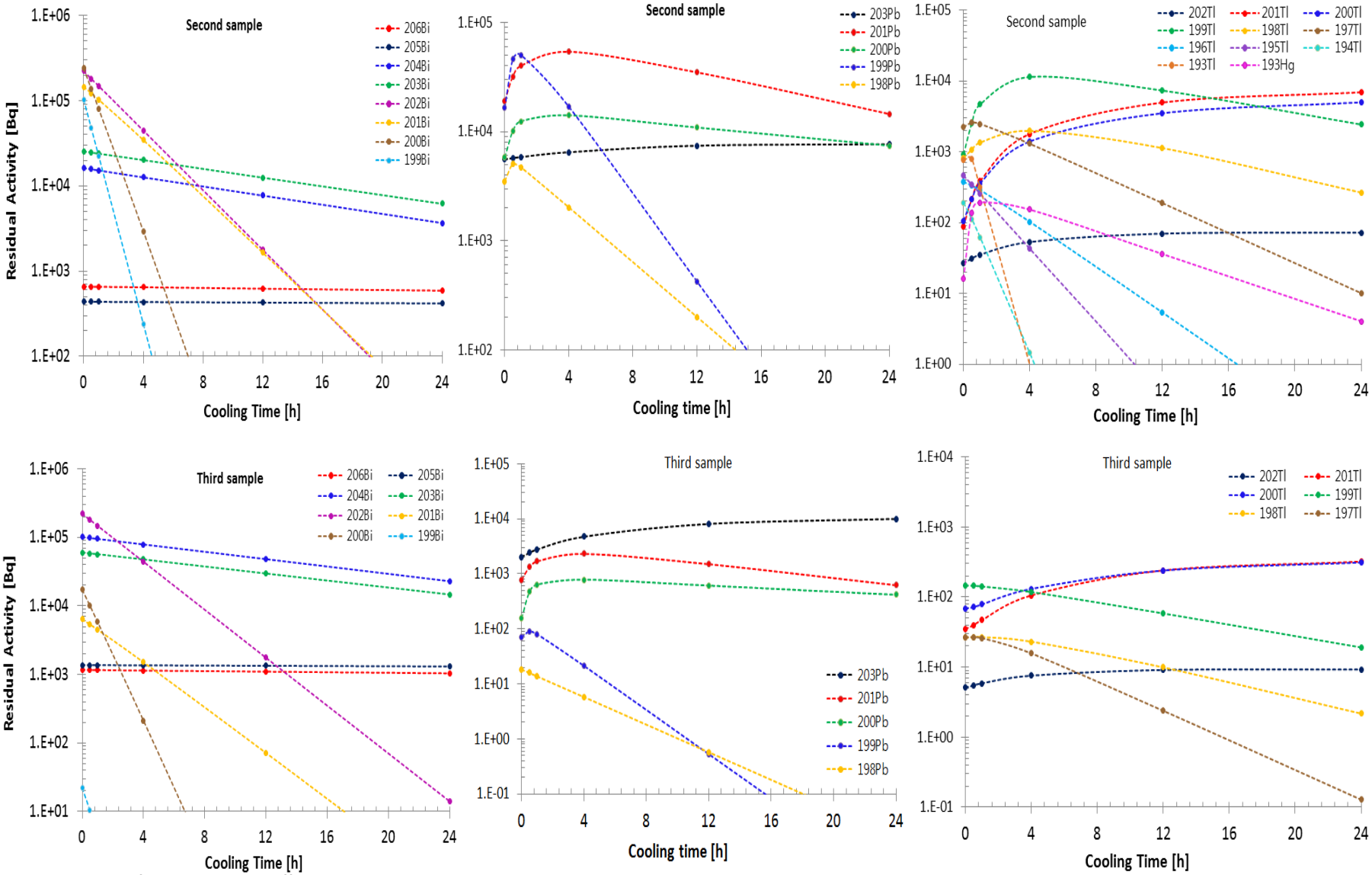
$^{200}$Bi(36min) $\xrightarrow{EC,\beta+}$ $^{200}$Pb (21.5 h) $\xrightarrow{EC,\beta+}$ $^{200}$Tl(26.1 h) $\xrightarrow{EC}$ $^{200}$Hg(stable)

$^{201}$Bi(1.77 h) $\xrightarrow{EC,\beta+}$ $^{201}$Pb (9.4 h) $\xrightarrow{EC,\beta+}$ $^{201}$Tl(73.5 h) $\xrightarrow{EC}$ $^{201}$Hg(stable)

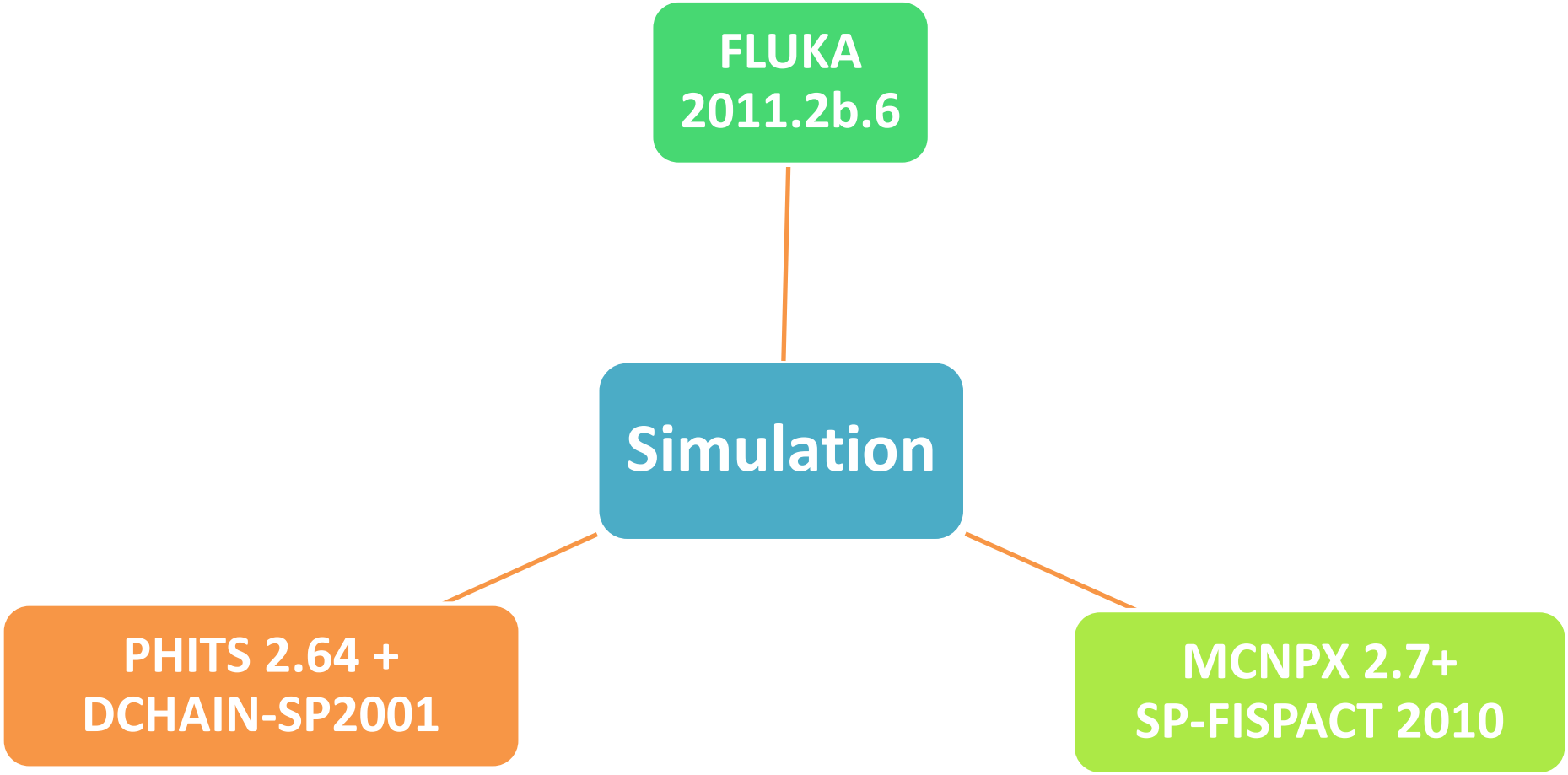
$^{202}$Bi(1.67 h) $\xrightarrow{EC,\beta+}$ $^{202}$Pb (3E+05 y) $\xrightarrow{EC}$ $^{202}$Tl(12.2 d) $\xrightarrow{EC}$ $^{202}$Hg(stable)

$^{203}$Bi(11.8 h) $\xrightarrow{EC,\beta+}$ $^{203}$Pb (52 h) $\xrightarrow{EC}$ $^{203}$Tl(stable)

# Residual Activity of Bi, Pb, Tl and Hg Radioisotopes in the 2nd and 3rd Pb Samples

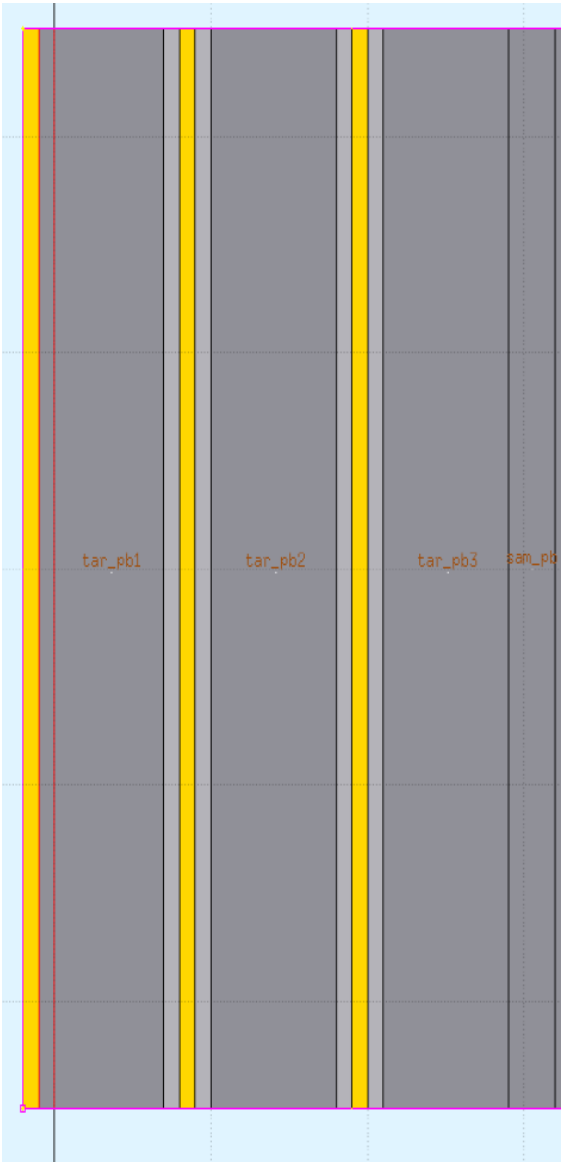


# Monte Carlo Codes used for Estimating Induced Activities



# Beam Intensity Monitoring by Au foil

# Experimental Conditions




| Proton Energy (MeV) | Beam Current pps | Irradiation time (min) | Beam Shape X(FWHM),Y(FWHM) |
|---|---|---|---|
| 103 | 1.3E+10 | 2 | Gaussian (1.96, 1.52) |

- ✓ Proton energy on the surface of 1st sample ~ 100 MeV
- ✓ 89% beam on the target assembly

| Components | Material | Number | H × W (mm) | Thickness(mm) |
|---|---|---|---|---|
| Target | Pb | 3 | 50 × 50 | 5 |
| Sample | Au | 3 | 50 × 50 | 0.05 |
| | Pb | 1 | 50 × 50 | 0.5 |
| Foil | Al | 4 | 50 × 50 | 0.1 |
| Window | $Al_4Be_6$ | 1 | R=150 | 0. 5 |

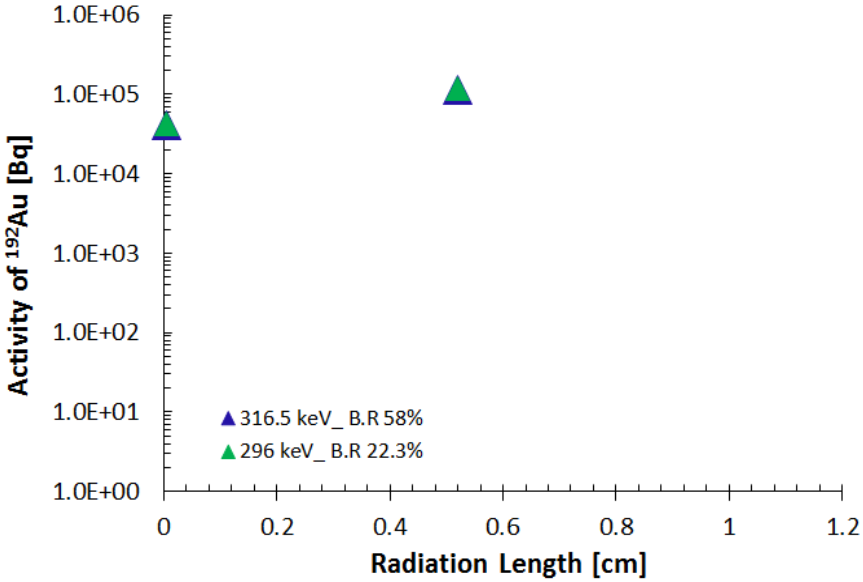
# 100 MeV P on $^{197}$Au-Contributing Reactions

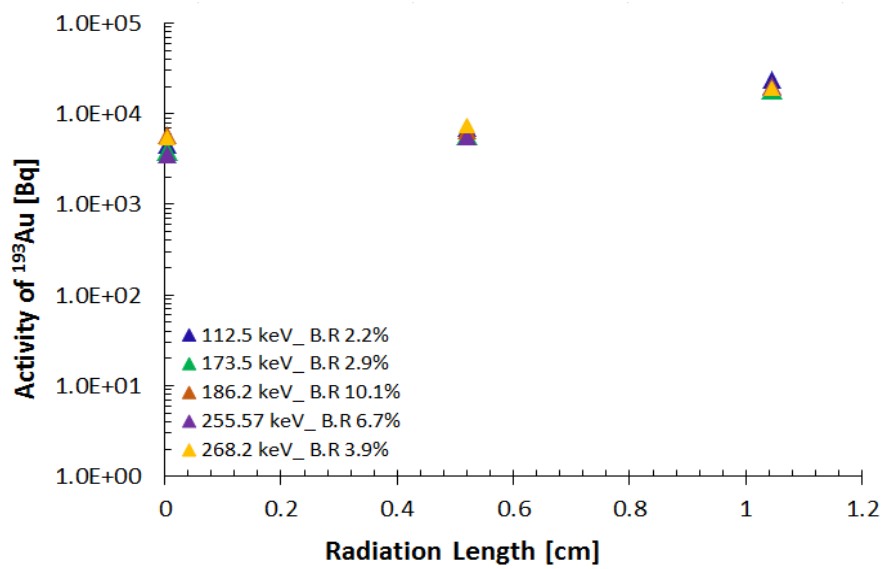
| Contributing Reaction from incident proton | | $^{197}$Au (100%) | Half-life |
|---|---|---|---|
| (p, pxn) | (p,pn) | $^{196}$Au | 6.2 d |
| | (p,p2n) | $^{195}$Au | 186 d |
| | (p,p3n) | $^{194}$Au | 1.58 d |
| | (p,p4n) | $^{193}$Au | 17.65 h |
| | (p,p5n) | $^{192}$Au | 4.9 h |
| | (p,p6n) | $^{191}$Au | 3.18 h |
| | (p,p7n) | $^{190}$Au | 42.8 min |
| | (p,p8n) | $^{189}$Au | 28.7 min |
| | (p,p10n) | $^{187}$Au | 8.4 min |
| | (p,p11n) | $^{186}$Au | 10.7 min |
| (p, xn) & (p, ɣ) | (p, ɣ) | $^{198}$Hg | Stable |
| | (p,n) | $^{197}$Hg | 64.14 h |
| | (p,3n) | $^{195}$Hg | 9.9 h |
| | (p,5n) | $^{193m}$Hg | 11.8 h |
| | (p,6n) | $^{192}$Hg | 4.85 h |
| | (p,7n) | $^{191}$Hg | 50.8 m |
| | (p,8n) | $^{190}$Hg | 20 m |
| (p, pxn) | (p,2p5n) | $^{191}$Pt | 2.9 d |
| | (p,2p7n) | $^{189}$Pt | 10.87 d |
| | (p,2p8n) | $^{188}$Pt | 10.2 d |
| | (p,2p9n) | $^{187}$Pt | 2.35 h |
| | (p,2p10n) | $^{186}$Pt | 2.0 h |
| | (p,2p11n) | $^{185m}$Pt | 33 min |
| | (p,2p12n) | $^{184}$Pt | 17.3 min |

| Contributing Reaction from secondary neutron & ɣ | $^{197}$Au (100%) | Half-life |
|---|---|---|
| (n,ɣ) | $^{198}$Au | 2.7 d |
| (n,p) | $^{197}$Pt | 19.89 h |
| (n,2n) | $^{196}$Au | 6.2 d |
| (n,α) | $^{194}$Ir | 19.28 h |
| (ɣ,n) | $^{196}$Au | 6.2 d |
| (ɣ,2n) | $^{195}$Au | 186 d |
| (ɣ,3n) | $^{194}$Au | 38.02 h |
| (ɣ,4n) | $^{193}$Au | 17.65 h |
| (ɣ, pn) | $^{195}$Pt | stable |

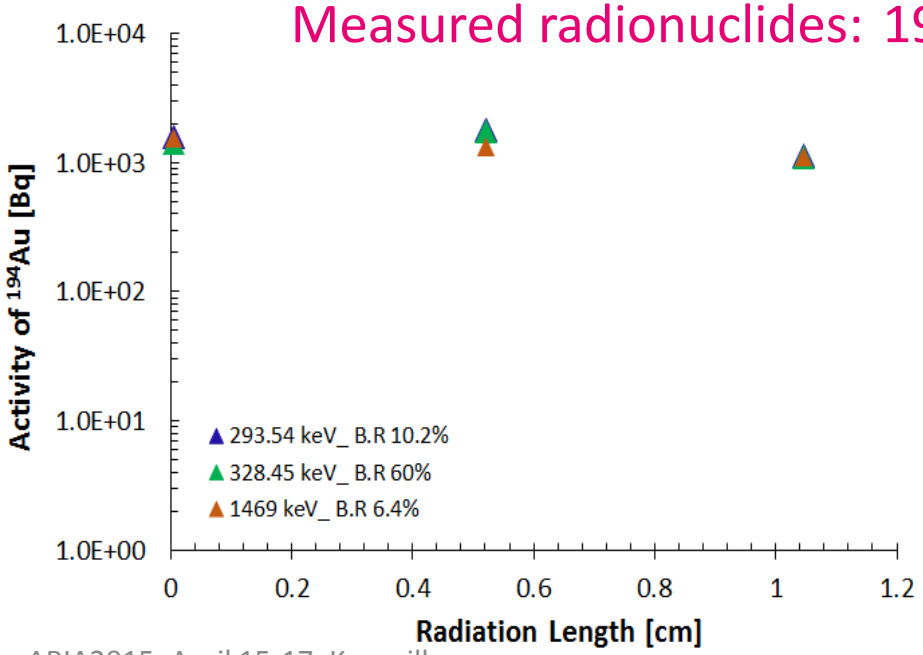
| Element | Atomic Number | Isotope (Abundance %) |
|---|---|---|
| $^{nat}$Au | 79 | $^{197}$Au (100) |

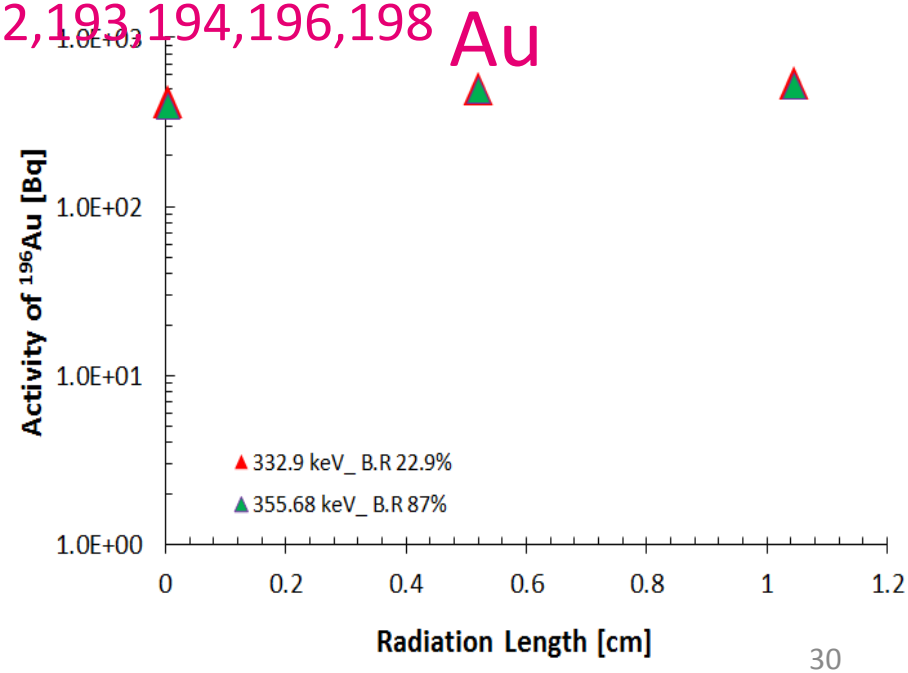
# Measured Radio-nuclides



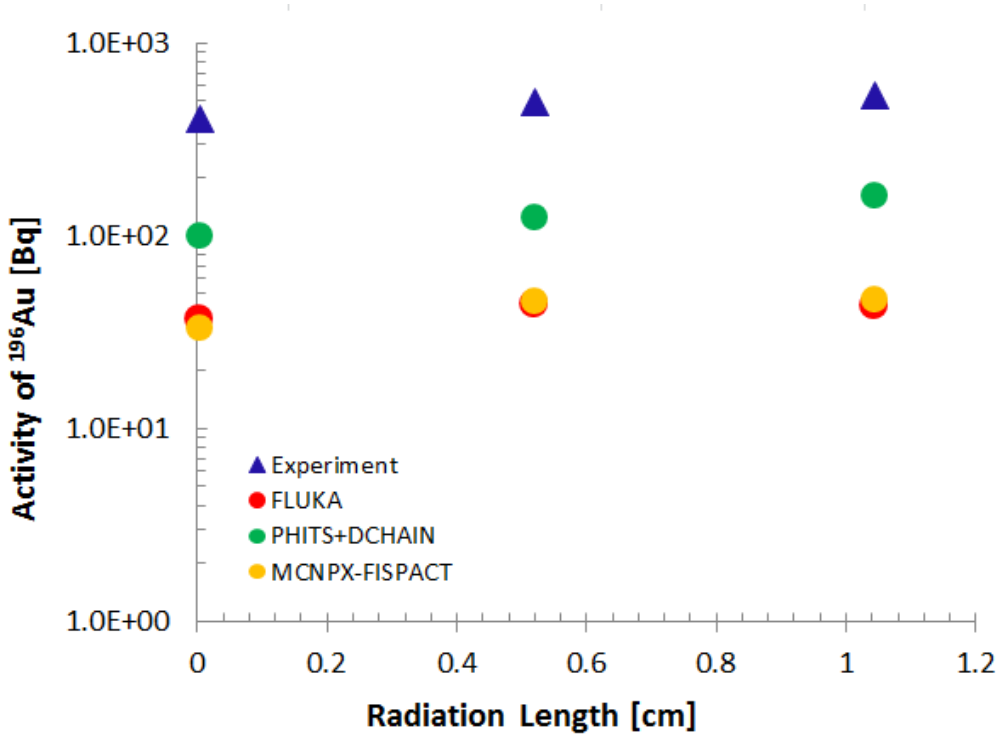




Measured radionuclides: 192,193,194,196,198 Au



# $^{197}Au(p,x)^{196}Au$




(n,2n), (p,pn) , (ɣ,n)

**Half-Life of $^{196}Au$ : 6.2 d**

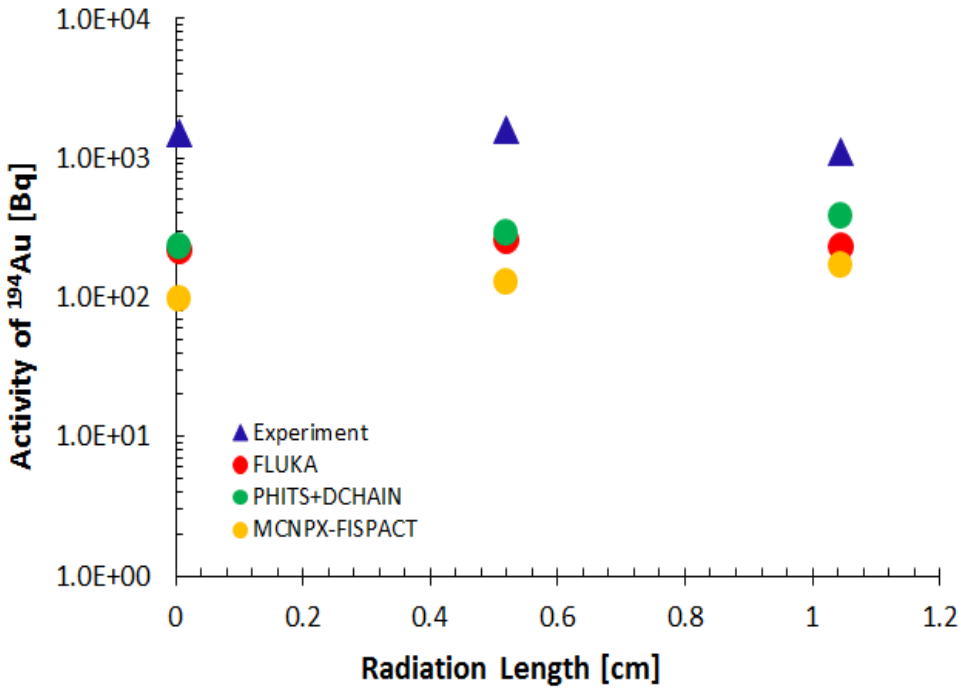
① **Good agreement between results of FLUKA & MCNPX.**

② **Results of PHITS are more close to measured data.**

③ **Production of $^{196}Au$ is underestimated by an order magnitude approximately by FLUKA & MCNPX.**

④ **Results of PHITS code and Measured value have a same order.**

# $^{197}Au(p,x)^{194}Au$




(γ,3n), (p,p3n)

**Half-Life of $^{194}Au$ : 38 h**

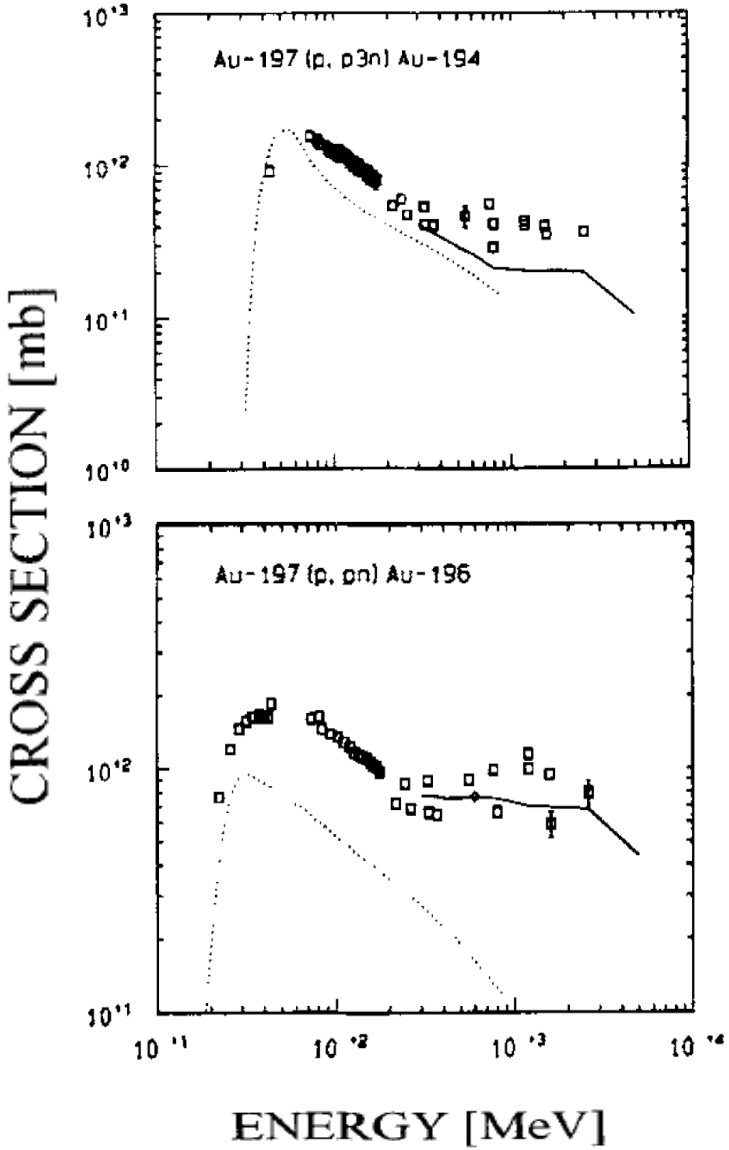
① **Good agreement between results of FLUKA & PHITS.**

② **Results of PHITS & FLUKA are more close to measured data.**

③ **Production of $^{194}Au$ is underestimated by an order magnitude approximately by FLUKA, PHITS and MCNPX.**

④ **Similar trend can be seen in the all samples**

# Reference to experimental cross-section of Proton on Au




- Experimental and theoretical excitation function for the production of $^{194}$Au and $^{196}$Au from $^{nat}$Au.
- Theoretical excitation functions were calculated by the HETC/KFA2 (full lines) and AREL (broken lines) codes.

Nuclear Instruments and Methods in Physics Research B 129 (1997) 153–193

NIM B Beam Interactions with Materials & Atoms

ELSEVIER

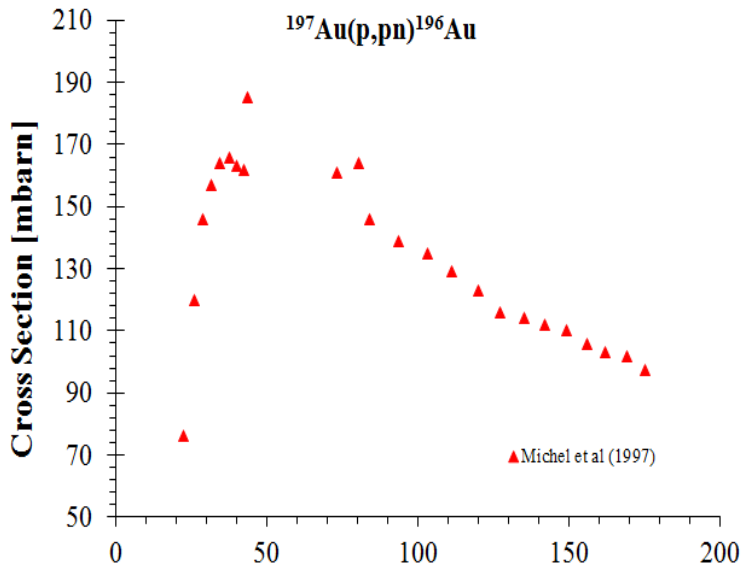
Cross sections for the production of residual nuclides by low- and medium-energy protons from the target elements C, N, O, Mg, Al, Si, Ca, Ti, V, Mn, Fe, Co, Ni, Cu, Sr, Y, Zr, Nb, Ba and Au

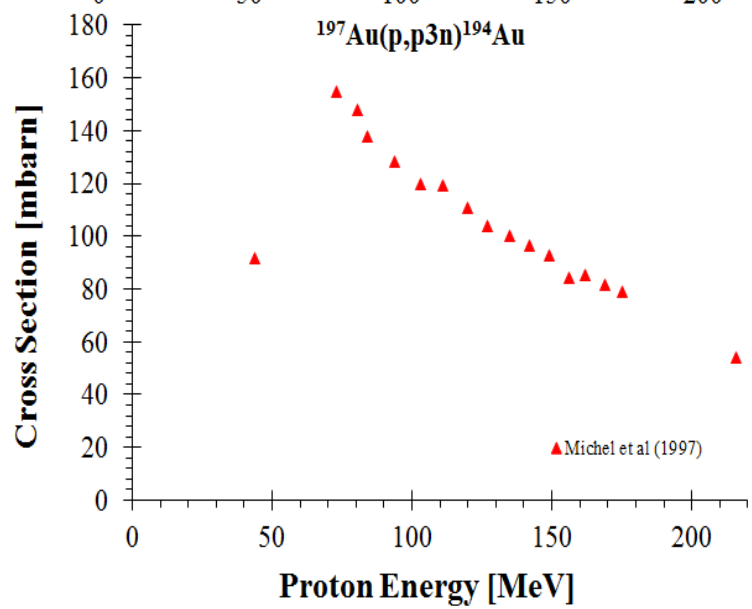
R. Michel [a,*], R. Bodemann [a], H. Busemann [a], R. Daunke [a], M. Gloris [a], H.-J. Lange [a], B. Klug [a], A. Krins [a], I. Leya [a], M. Lüpke [a], S. Neumann [a], H. Reinhardt [a], M. Schnatz-Büttgen [a], U. Herpers [b], Th. Schiekel [b], F. Sudbrock [b], B. Holmqvist [c], H. Condé [d], P. Malmborg [e], M. Suter [f], B. Dittrich-Hannen [f], P.-W. Kubik [g], H.-A. Synal [g], D. Filges [h]

[a] Center for Radiation Protection and Radioecology, University of Hannover, Am Kleinen Felde 30, D-30 167 Hannover, Germany
[b] Department of Nuclear Chemistry, University of Cologne, Cologne, Germany
[c] Department of Neutron Research at Studsvik, University of Uppsala, Uppsala, Sweden
[d] Department of Neutron Research, University of Uppsala, Uppsala, Sweden
[e] The Svedberg Laboratory, University of Uppsala, Uppsala, Sweden
[f] Institute for Particle Physics, ETH Hönggerberg, Zürich, Switzerland
[g] Paul Scherrer Institute c/o Institute for Particle Physics, ETH Hönggerberg, Zürich, Switzerland
[h] Institute for Nuclear Physics, KFA Jülich, Jülich, Germany

Received 3 January 1997; revised form received 14 March 1997

# Experimental cross- section of Proton on Au




- Cross section Measured by Michel et al for the production of $^{196}$Au at 103 MeV is 135 mbarn.
  - ΔE = 1.43 MeV
  - Δσ = 9.51 mb
- Cross section Measured by Michel et al for the production of $^{194}$Au at 103 MeV is 120 mbarn.
  - ΔE = 1.43 MeV
  - Δσ = 13.4 mb
- Proton beam energy in our work ~ 100.5 MeV

# Calculation of Beam Intensity using 1st Au sample

*** Neglecting neutron- and photon- induced reactions**

$$A = \phi \sigma N_t \left(1 - e^{-\lambda t}\right)$$

- A = Activation yield measured by this work [Bq]
- Ø = particle flux (proton/s.cm$^2$)
- σ = Cross section measured by Michel et al [cm$^2$]
- $N_t$ = Number of Atoms of Au target = (m/w)× 6.02E+23
- m = Mass of the element in the irradiated sample
- w= Atomic weight of element
- λ = Decay constant = 0.693/$t_{1/2}$
- t = Irradiation time

# Beam Intensity determined by Activation Analysis

- $^{197}Au(p,pn)^{196}Au$ Beam Intensity: (6.41± 0.4) E+10 pps

- $^{197}Au(p,p3n)^{194}Au$ Beam Intensity: (6.85 ±0.8) E+10 pps

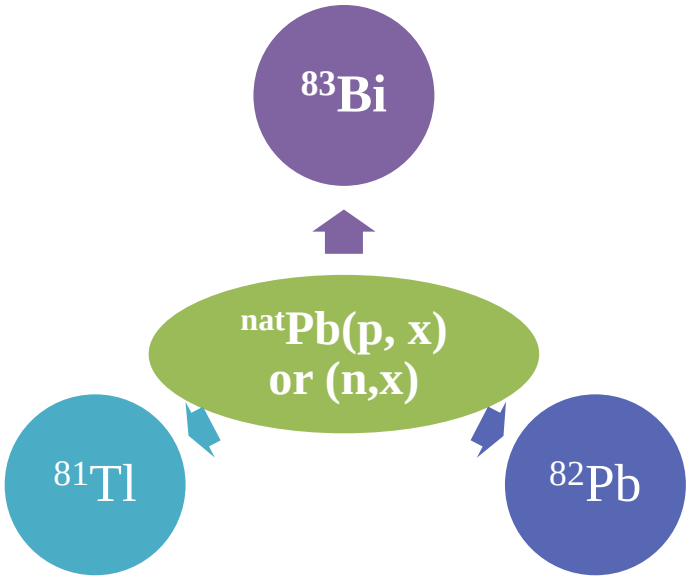
Reported Value By KOMAC group: 1.3E+10 pps
(Using Gafchromic film)

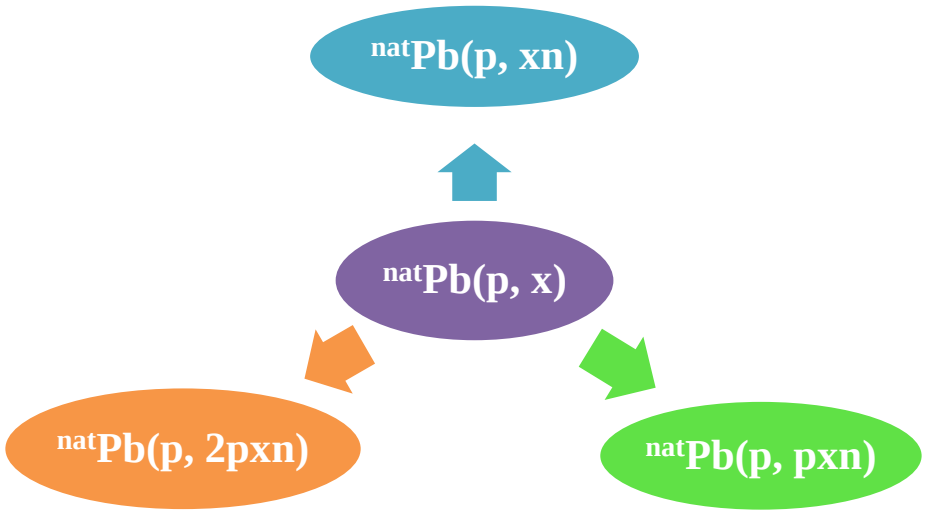
Measured/Reported ~ 4.6

# Radionuclide Production in Pb foil

# 100 MeV Proton on Pb

- Calculations (based on literature data) show three typical radio-nuclides can be produced from 100 proton on $^{nat}Pb$

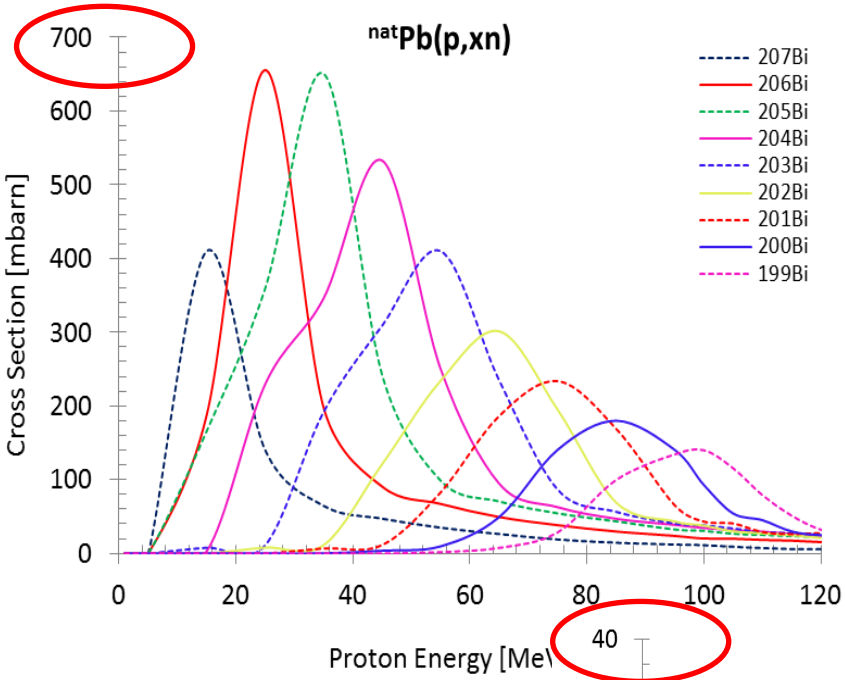


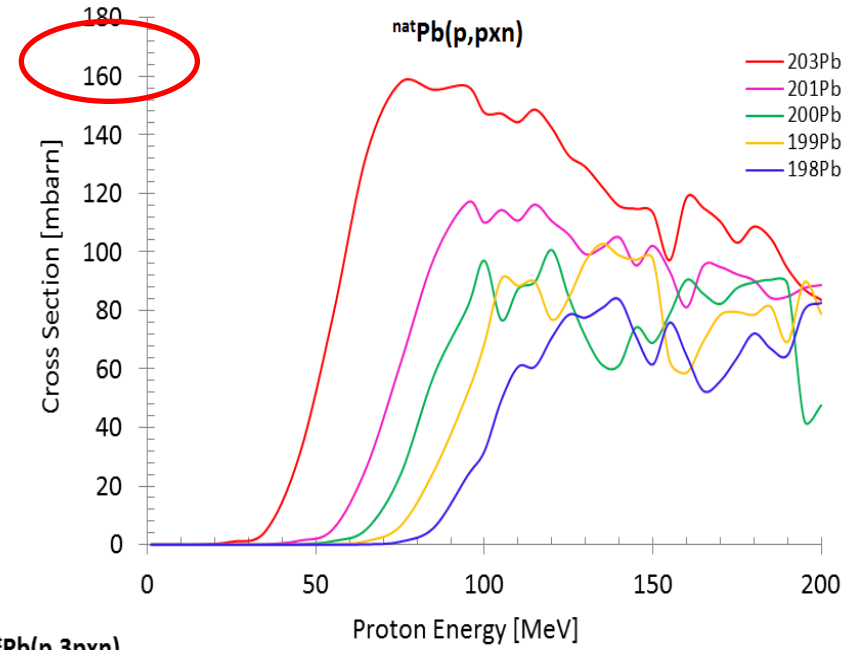



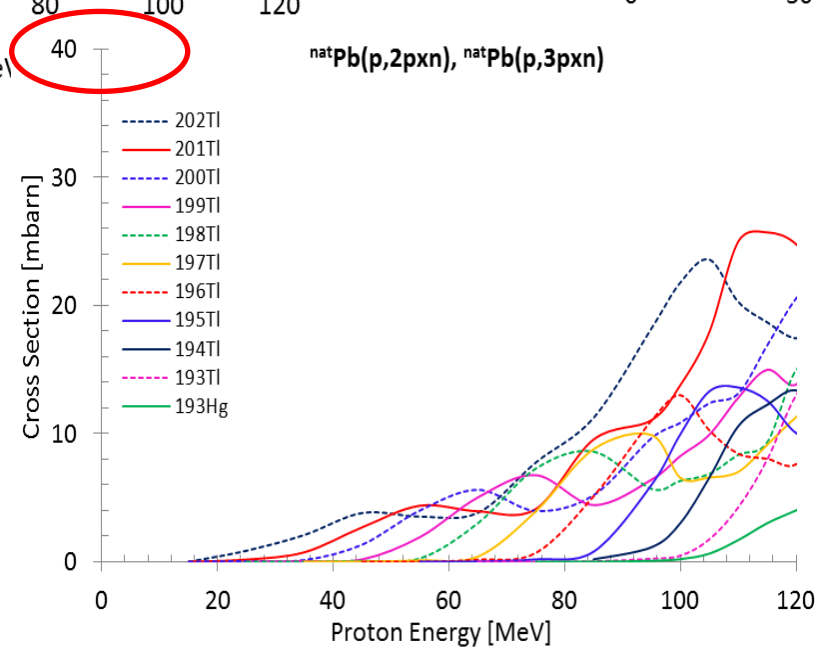

- Isotope Abundance of $^{nat}Pb$

| Element | Atomic Number | Isotope (Abundance %) |
|---|---|---|
| $^{nat}Pb$ | 82 | $^{204}Pb$ (1.4) |
| | | $^{206}Pb$ (24.1) |
| | | $^{207}Pb$ (22.1) |
| | | $^{208}Pb$ (52.4) |

# Typical produced radionuclides from proton on $^{nat}Pb$ calculated by TALYS code



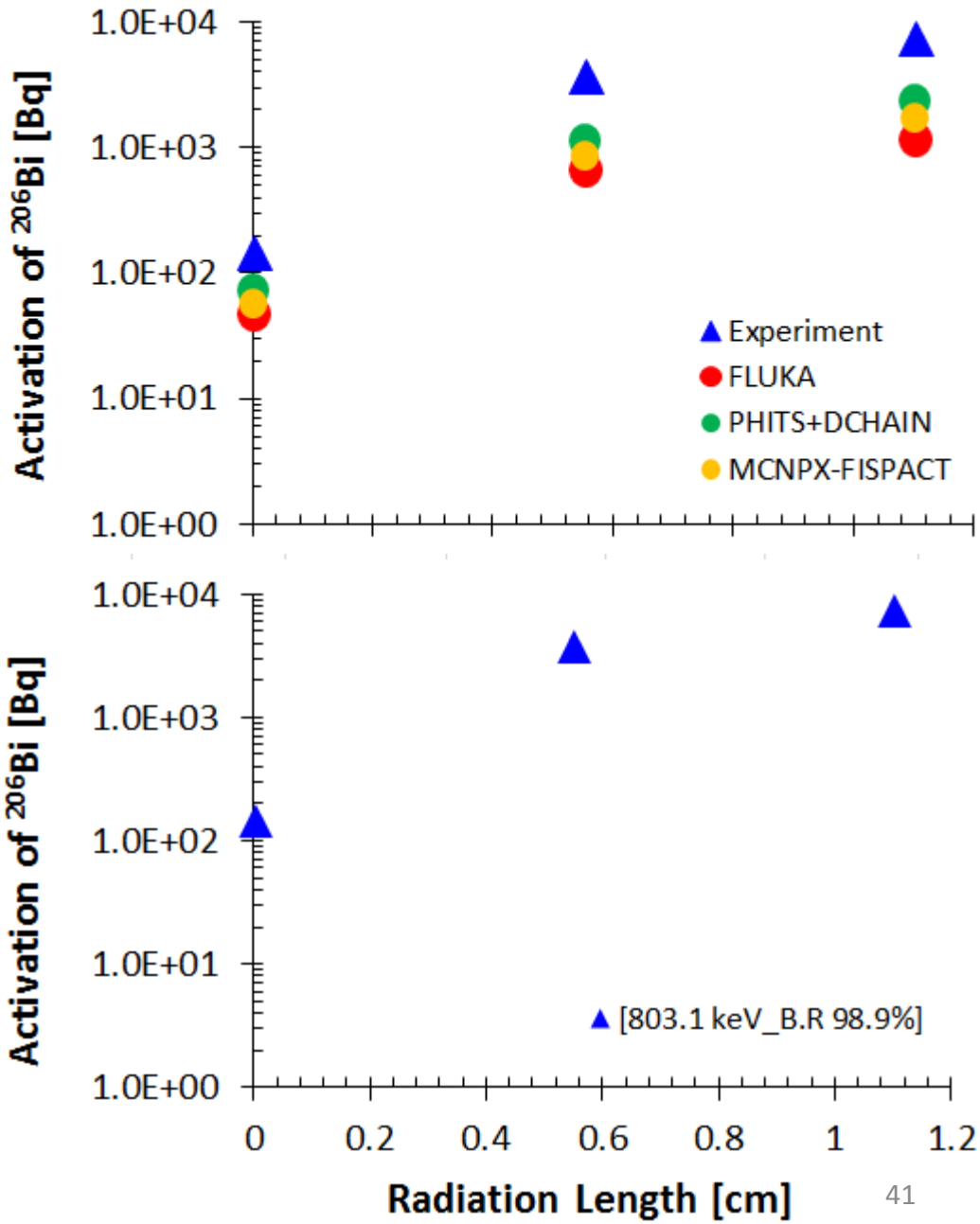
# Nuclear data of the investigated radionuclides by gamma spectrum analysis

| Nuclides | Half-life | Gamma-ray energy (keV) | Branching ratio(%) | Decay mode |
|---|---|---|---|---|
| $^{206}$Bi | 6.24 d | 803.1 | 98.9 | EC(100%) |
| $^{205}$Bi | 15.3 d | 703.5<br>987.66<br>1764.3 | 31.1<br>16.1<br>32.5 | EC(100%) |
| $^{204}$Bi | 11.22 h | 911.96<br>983.9 | 11.1<br>59 | EC(100%) |
| $^{203}$Bi | 11.76 h | 1847.3 | 11.4 | EC(100%)<br>A(0.00001) |
| $^{202}$Bi | 1.72 h | 422.1<br>960.67 | 83.7<br>99.27 | EC(100%)<br>A(0.00001) |
| $^{201}$Bi | 108 min | 629.1<br>936.2 | 26<br>11.3 | EC(100%)<br>A(0.0001) |
| $^{203}$Pb | 51.8 h | 279.19<br>401.32 | 81<br>3.35 | EC(100%) |
| $^{201}$Pb | 9.33 h | 331.17<br>361.27<br>945.96 | 76.9<br>9.9<br>7.4 | EC(100%) |
| $^{200}$Pb | 21.5 h | 142.29<br>147.7 | 3.16<br>37.7 | EC(100%) |
| $^{198}$Pb | 2.4 h | 173.4<br>259.5 | 18<br>5.8 | EC(100%) |
| $^{202}$Tl | 12.23 d | 439.5 | 91 | EC(100%) |
| $^{201}$Tl | 72.9 h | 167.43 | 10 | EC(100%) |
| $^{200}$Tl | 26.1 h | 579.28 | 13.8 | EC(100%) |

# $^{nat}Pb(p,xn)^{206}Bi$

**Half-Life of $^{206}Bi$ : 6.24 d**

- $^{206}Pb(p,n)^{206}Bi$
- $^{207}Pb(p,2n)^{206}Bi$
- $^{208}Pb(p,3n)^{206}Bi$




① **Good agreement between results of codes.**

② **Reasonable agreement between results of codes and our measurement.**

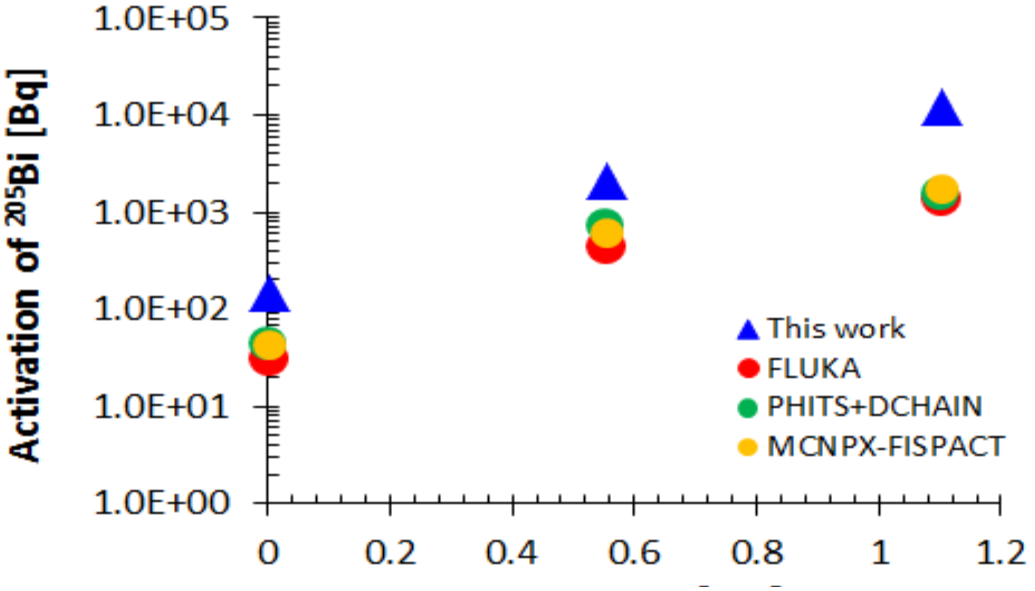
# $^{nat}Pb(p,xn)^{205}Bi$

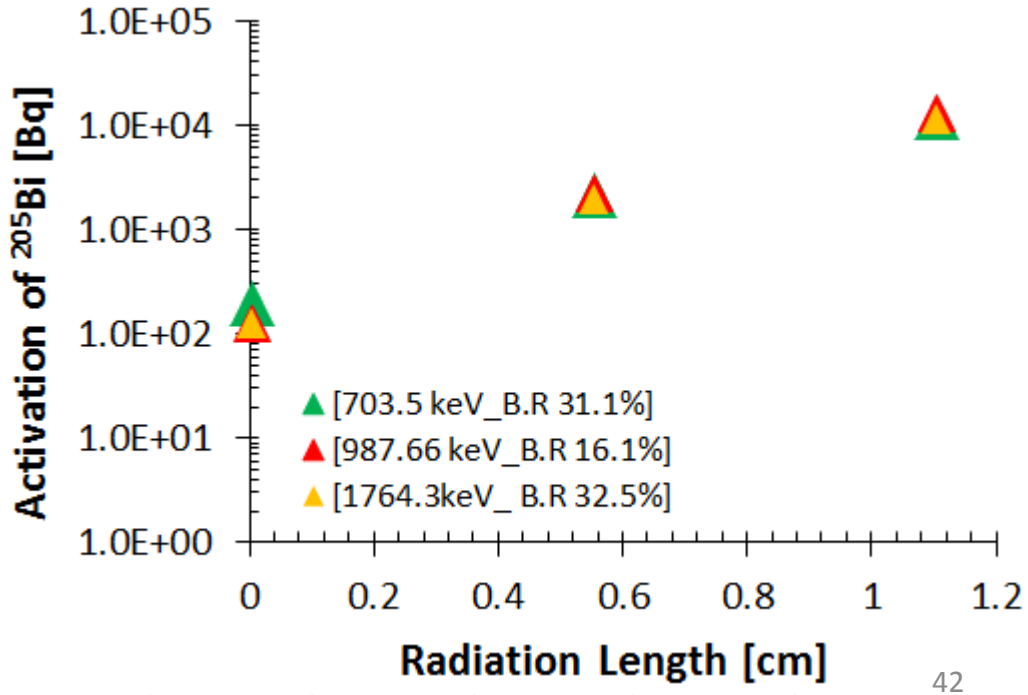
**Half-Life of $^{205}Bi$ : 15.3 d**

- $^{204}Pb(p,\gamma)^{205}Bi$
- $^{206}Pb(p,2n)^{205}Bi$
- $^{207}Pb(p,3n)^{205}Bi$
- $^{208}Pb(p,4n)^{205}Bi$

① Very good agreement between results of codes.

② Good agreement between results of codes and our measurement at the 1st and 2nd samples.



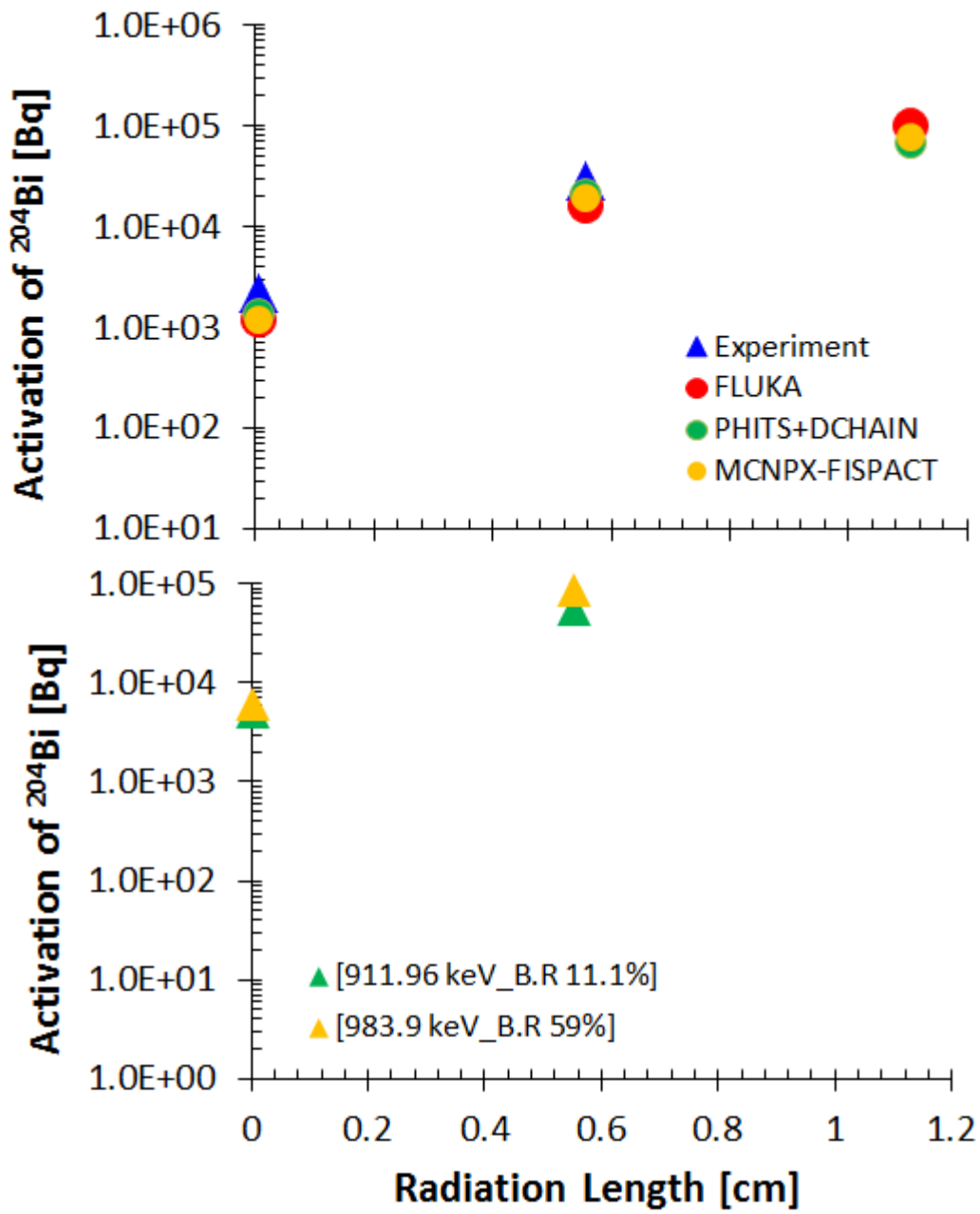
# $^{nat}Pb(p,xn)^{204}Bi$

**Half-Life of $^{204}Bi$ : 11.22 h**

- $^{204}Pb(p,n)^{204}Bi$
- $^{206}Pb(p,3n)^{204}Bi$
- $^{207}Pb(p,4n)^{204}Bi$
- $^{208}Pb(p,5n)^{204}Bi$

① Very Good agreement between results of codes.

② Good agreement between results of codes and our measurement.



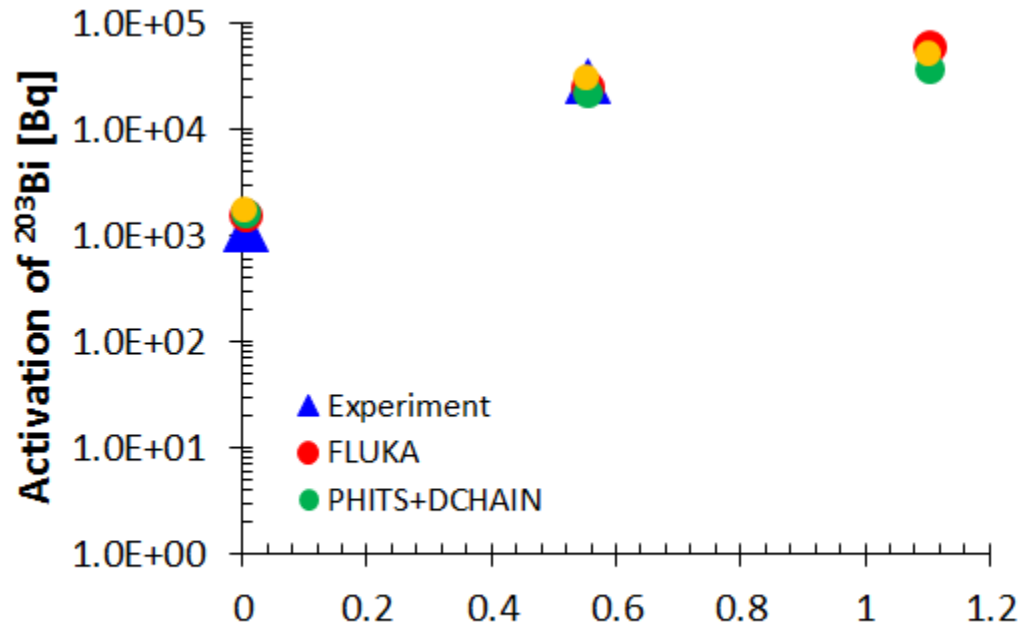
# $^{nat}Pb(p,xn)^{203}Bi$

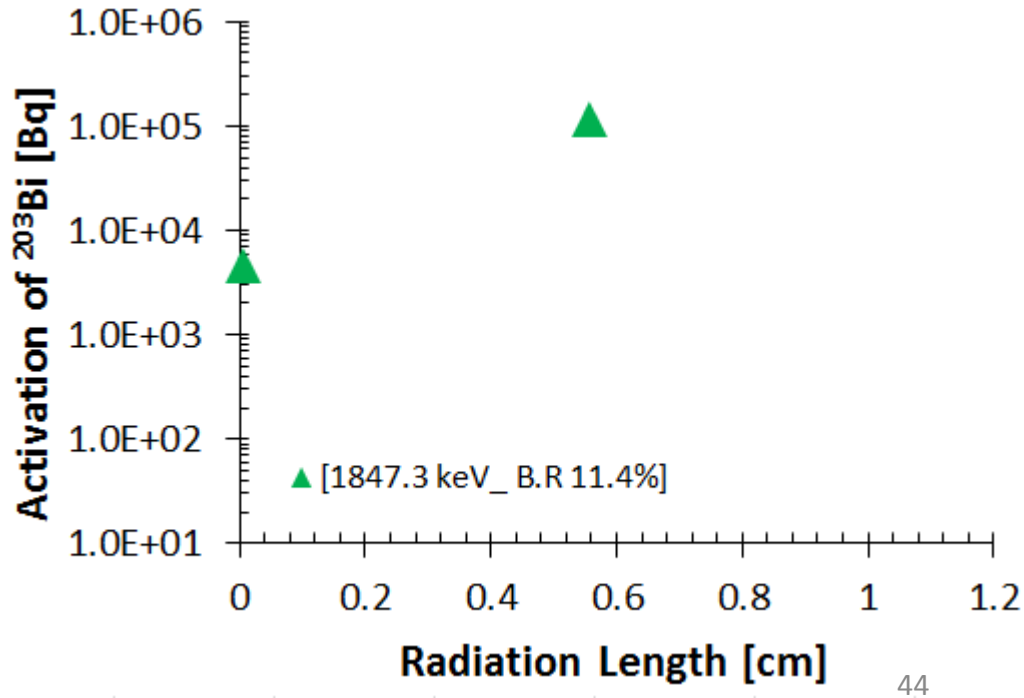
**Half-Life of $^{203}Bi$ : 11.76 h**

- $^{204}Pb(p,2n)^{203}Bi$
- $^{206}Pb(p, 4n)^{203}Bi$
- $^{207}Pb(p,5n)^{203}Bi$
- $^{208}Pb(p,6n)^{203}Bi$

① **Very Good agreement between results of codes.**

② **Good agreement between results of codes and our measurement.**



# $^{nat}Pb(p,xn)^{202}Bi$

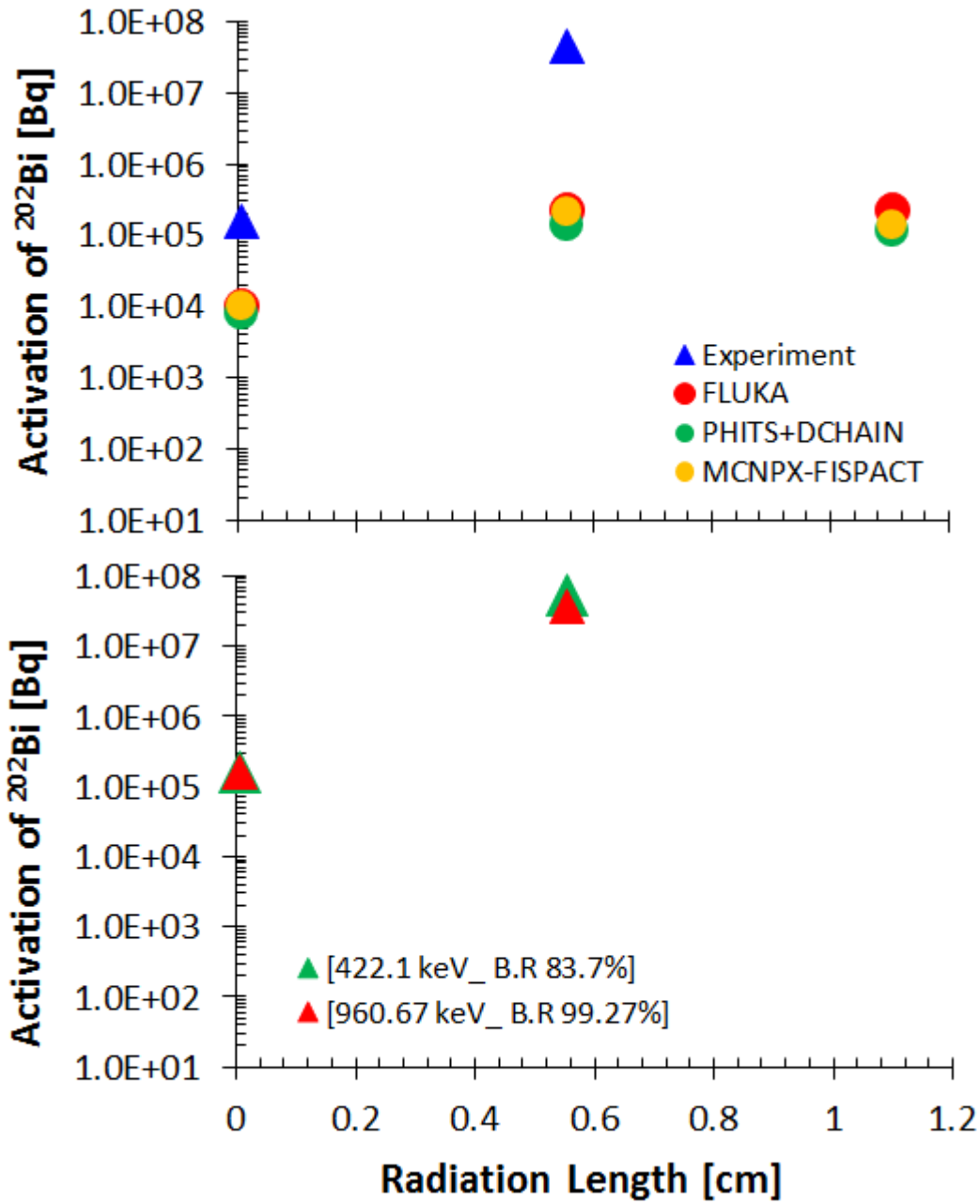
**Half-Life of $^{202}Bi$ : 1.72 h**

- $^{204}Pb(p,3n)^{202}Bi$
- $^{206}Pb(p, 5n)^{202}Bi$
- $^{207}Pb(p,6n)^{202}Bi$
- $^{208}Pb(p,7n)^{202}Bi$

① Very Good agreement between results of codes.

② an order difference between results of codes and our measurement at the 1st sample.

③ Production of $^{202}Bi$ is underestimated by more than 2 orders magnitude by codes at the 2nd sample.



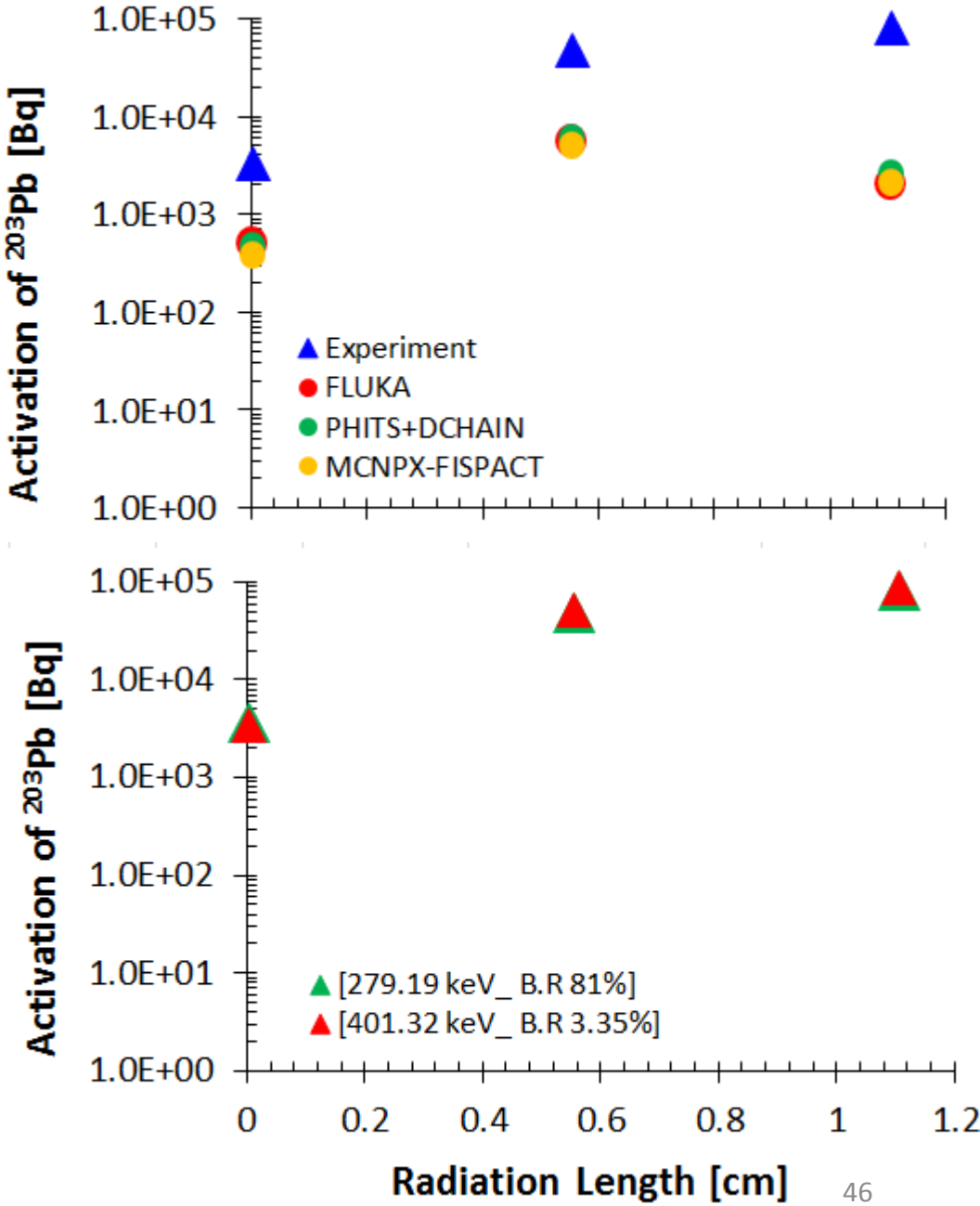
# $^{nat}Pb(p,pxn)^{203}Pb$

**Half-Life of $^{203}Pb$ : 51.8 h**

- $^{204}Pb(p,pn)^{203}Pb$
- $^{206}Pb(p,p3n)\,^{203}Pb$
- $^{207}Pb(p,p4n)\,^{203}Pb$
- $^{208}Pb(p,p5n)\,^{203}Pb$
- $^{208}Pb(n,5n)\,^{203}Pb$

① Very good agreement between results of codes.

② Production of $^{203}Pb$ is underestimated by an order magnitude by MC codes at the 1st and 2nd samples. At the 3rd sample underestimation of codes are 2 orders approximately.



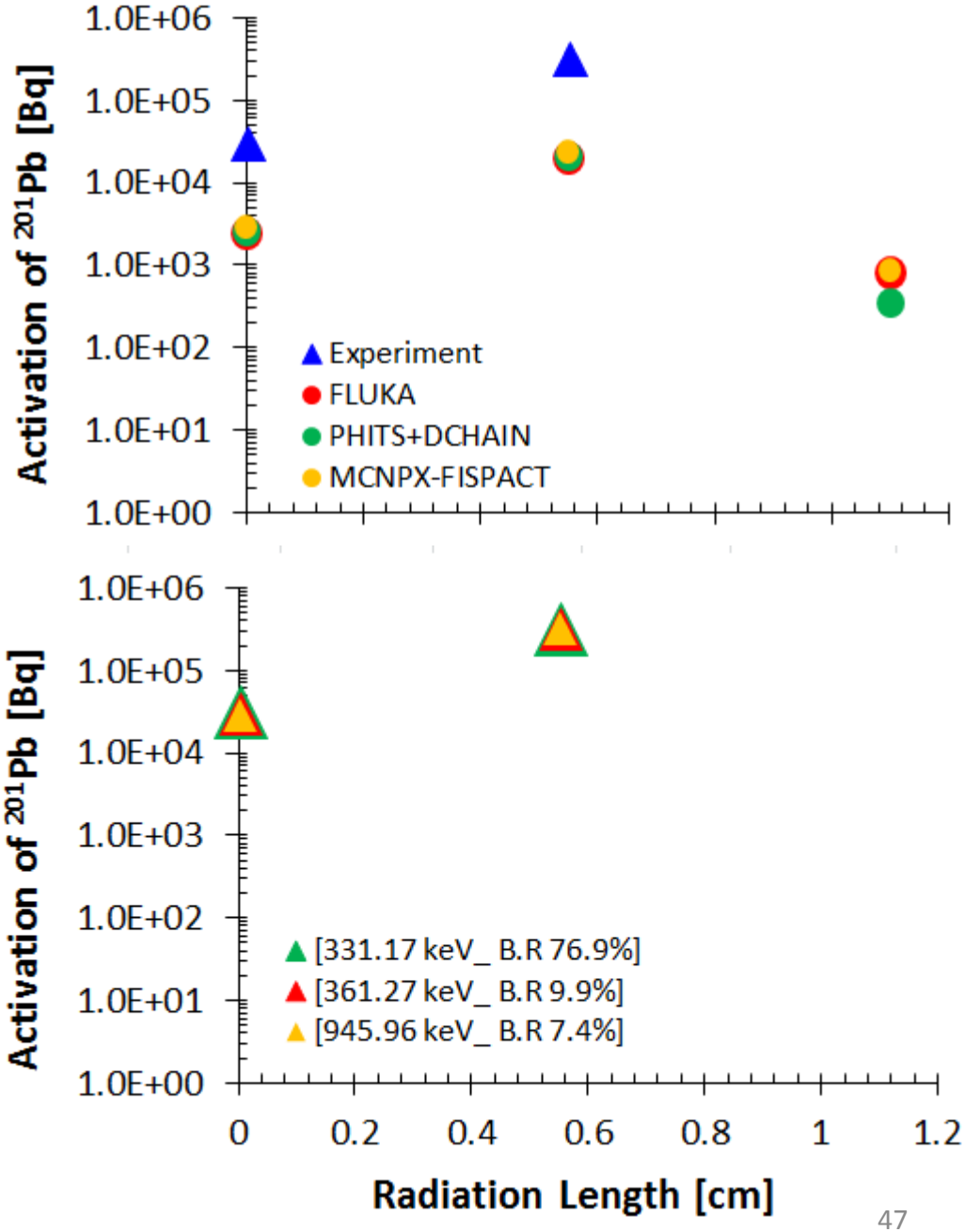
# $^{nat}Pb(p,pxn)^{201}Pb$

**Half-Life of $^{201}Pb$ : 9.33 h**

- $^{204}Pb(p,p3n)^{201}Pb$
- $^{206}Pb(p,p5n)\,^{201}Pb$
- $^{207}Pb(p,p6n)\,^{201}Pb$
- $^{208}Pb(p,p7n)\,^{201}Pb$
- $^{208}Pb(n,7n)\,^{201}Pb$

① Good agreement between results of codes.

② Production of $^{201}Pb$ is underestimated by an order magnitude by codes at the 1st and 2nd samples.



# $^{nat}Pb(p,pxn)^{200}Pb$

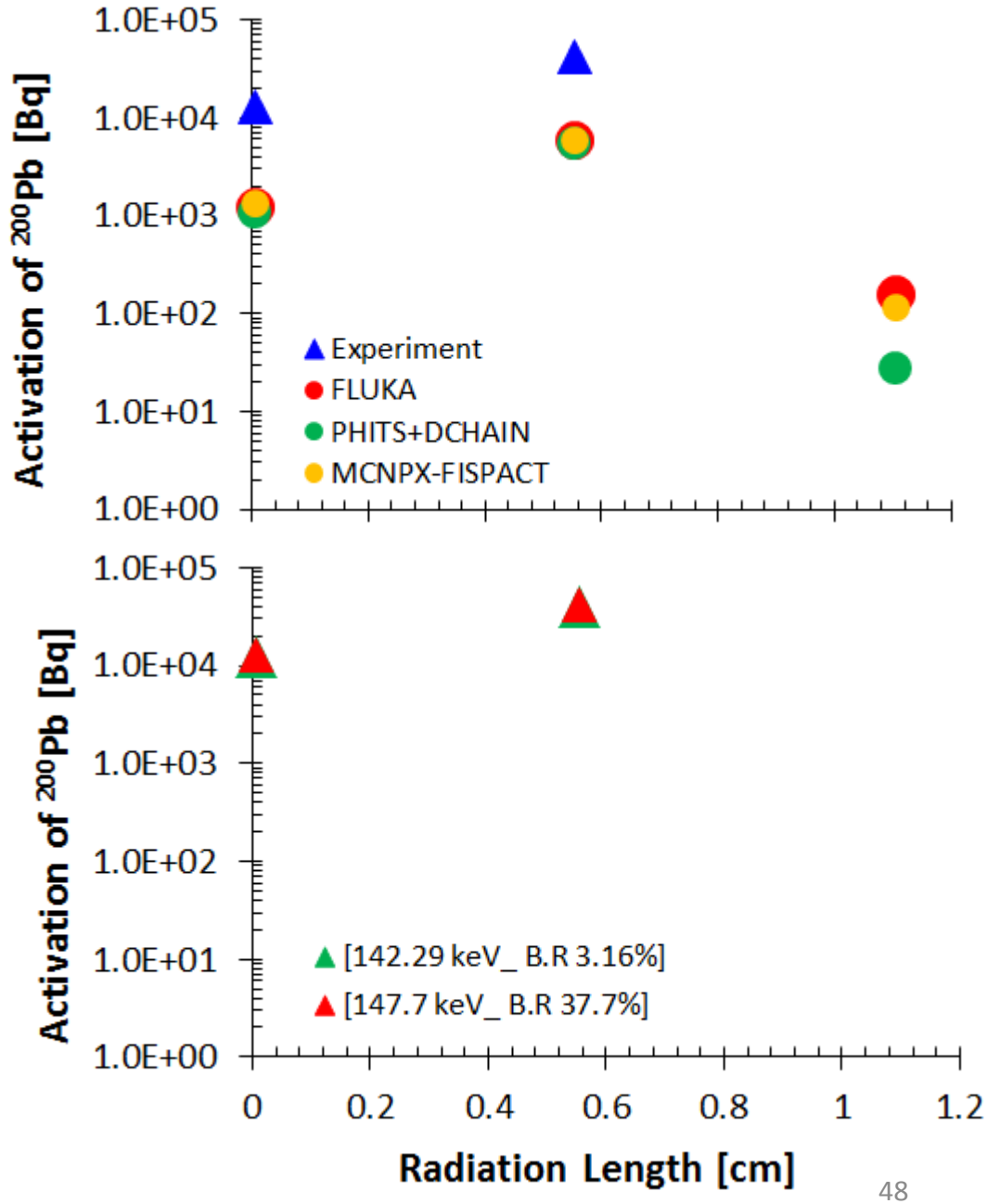
**Half-Life of $^{200}Pb$ : 21.5 h**

- $^{204}Pb(p,p4n)^{200}Pb$
- $^{206}Pb(p,p6n)^{200}Pb$
- $^{207}Pb(p,p7n)^{200}Pb$
- $^{208}Pb(p,p8n)^{200}Pb$
- $^{208}Pb(n,8n)^{200}Pb$

① Good agreement between results of codes at the 1st and 2nd samples.

② Result of PHITS code underestimate results of FLUKA and MCNPX at the 3rd sample.

③ Production of $^{201}Pb$ is underestimated by an order magnitude by codes at the 1st and 2nd samples.



# $^{nat}Pb(p,2pxn)^{202}Tl$

**Half-Life of $^{202}Tl$ : 12.23 d**

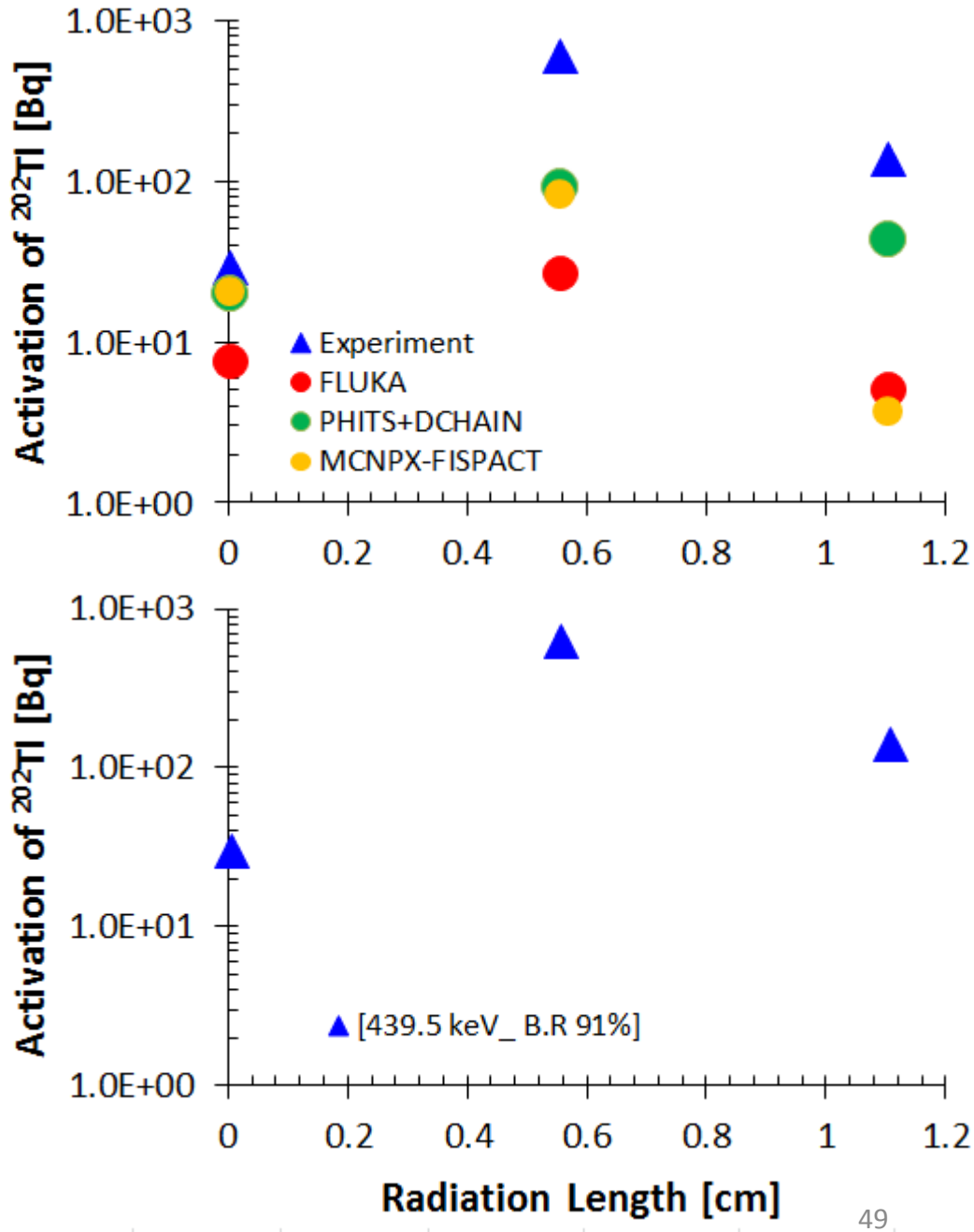
- $^{204}Pb(p,2pn)^{202}Tl$
- $^{206}Pb(p,2p3n)\,^{202}Tl$
- $^{207}Pb(p,2p4n)\,^{202}Tl$
- $^{208}Pb(p,2p5n)\,^{202}Tl$
- $^{208}Pb(n,p5n)\,^{202}Tl$ …

① Very good agreement between results of PHITS and MCNPX and our measurement at the 1st samples.

② Production of $^{202}Tl$ is underestimated by 1 order magnitude by PHITS and MCNPX codes at the 2nd sample.

③ Result of PHITS code is in good agreement with our measurement at 3rd sample.

④ Production of $^{202}Tl$ is underestimated by 2 orders magnitude by FLUKA and MCNPX codes at the 3rd sample.



# $^{nat}Pb(p,2pxn)^{201}Tl$

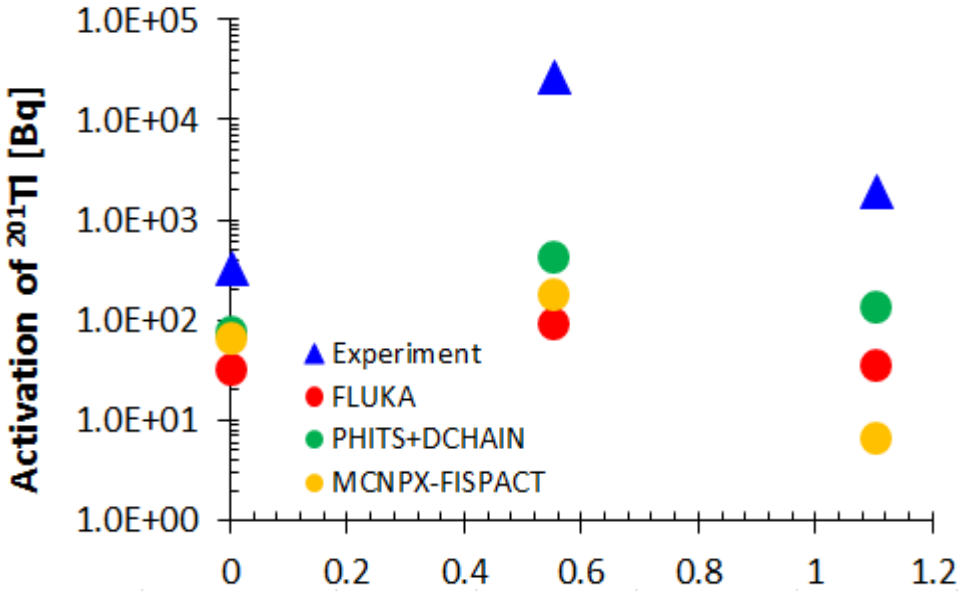
**Half-Life of $^{201}Tl$ : 72.91 h**

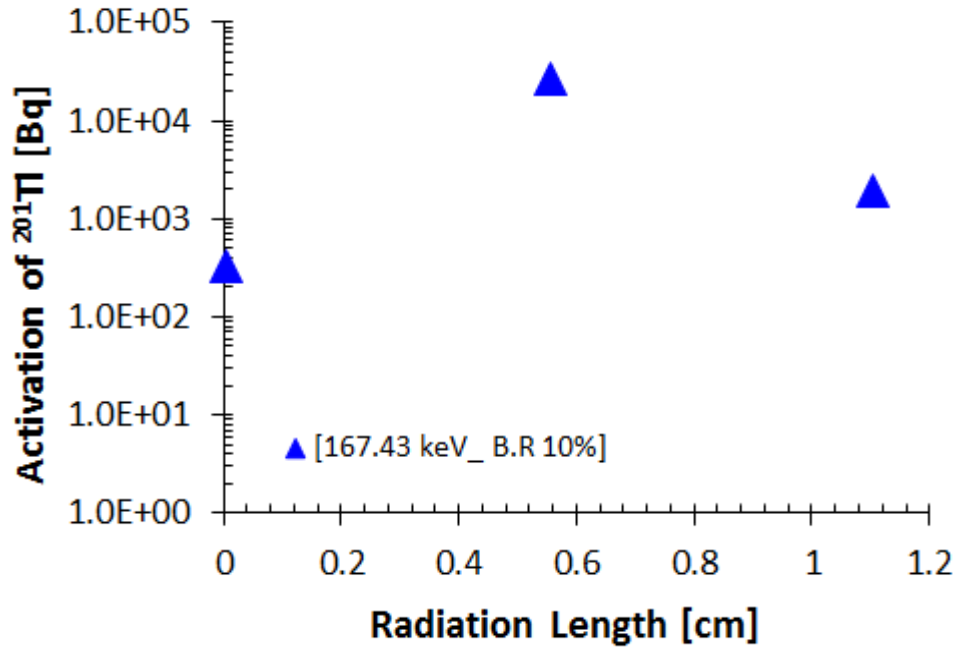
- $^{204}Pb(p,2p2n)^{201}Tl$
- $^{206}Pb(p,2p4n)\,^{201}Tl$
- $^{207}Pb(p,2p5n)\,^{201}Tl$
- $^{208}Pb(p,2p6n)\,^{201}Tl$
- $^{208}Pb(n,p6n)\,^{201}Tl$ …

① An order difference between results of codes and our measurement at the 1st sample.

② Results of codes underestimate result of our measurement by more than 2 orders magnitude at the 2nd sample.

③ Production of $^{201}Tl$ is underestimated by more than 2 orders magnitude by FLUKA and MCNPX codes and an order by PHITS code at the 3rd sample.



# $^{nat}Pb(p,2pxn)^{200}Tl$

**Half-Life of $^{200}Tl$ : 26.1 h**

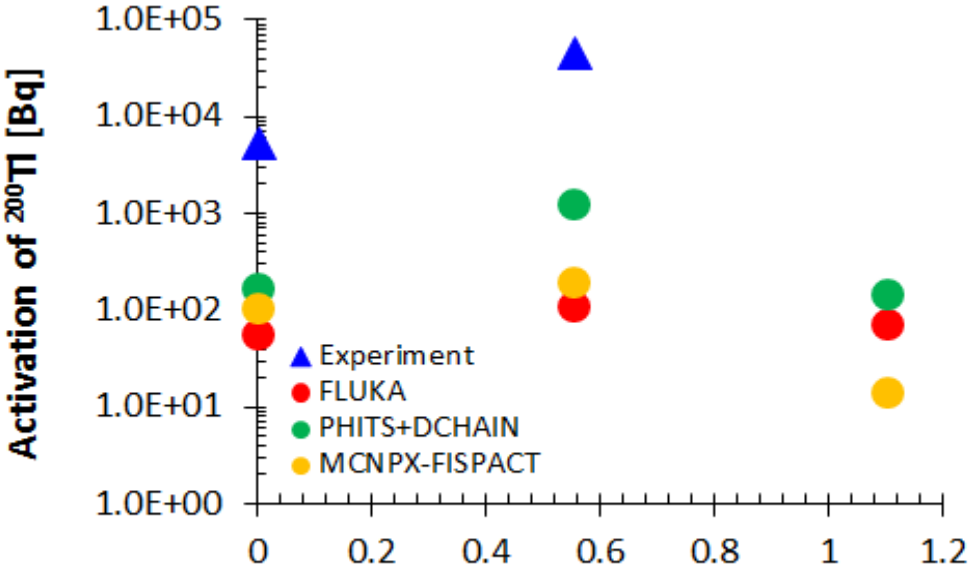
- $^{204}Pb(p,2p3n)^{200}Tl$
- $^{206}Pb(p,2p5n)^{200}Tl$
- $^{207}Pb(p,2p6n)^{200}Tl$
- $^{208}Pb(p,2p7n)^{200}Tl$
- $^{208}Pb(n,p7n)^{200}Tl$ …

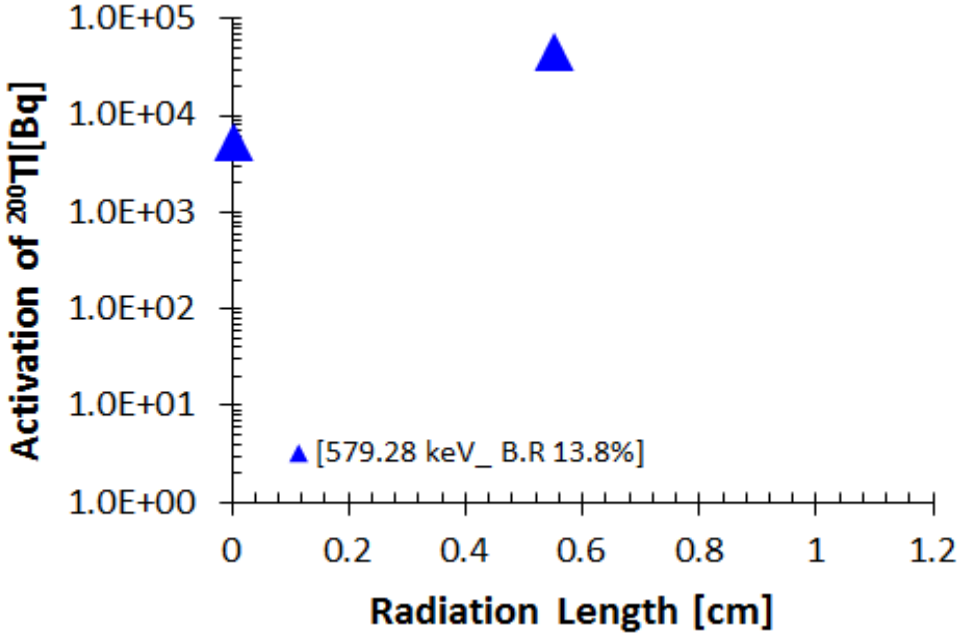
① Reasonable agreement between results of codes at the 1st sample.

② Results of codes underestimate result of our measurement by more than an order magnitude at the 1st sample.

③ Production of $^{200}Tl$ is underestimated by more than an order magnitude by PHITS and more than 2 orders by FLUKA and PHITS codes at the 3rd sample.

④ MCNPX results underestimate one of FLUKA and PHITS codes at 3rd sample.



# Preliminary Comparison Results

## - Reaction cross-sections evaluated in this work, reported by Gloris et al., and calculated by TALYS1.6 code

$$A = \phi \sigma N_t \left(1 - e^{-\lambda t}\right)$$

A = Activation yield measured by this work [Bq]

Ø = particle flux (proton/s.cm$^2$): 2.9E+9

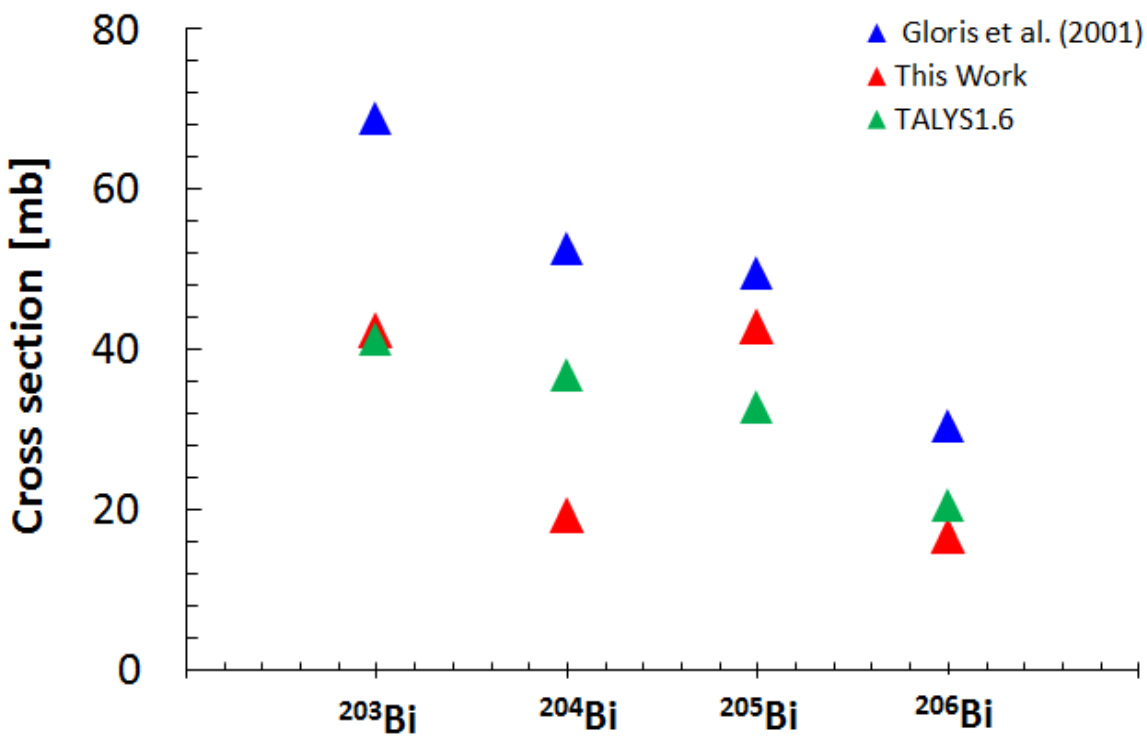
$N_t$ = Number of Atoms of Pb target = (m/w)× 6.02E+23

m = Mass of the element in the irradiated sample

w= Atomic weight of element

λ = Decay constant = 0.693/$t_{1/2}$

t = Irradiation time = 600 s




Beam intensity: 6.4E+10 proton/s [ measured by Au foils reaction]

# Summary

- Irradiation experiments and activation analysis using KOMAC 100 MeV protons for new benchmarking date was performed and gave the reasonable results.
- Activation analysis using Au foil demonstrates the accuracy of the beam intensity monitoring of KOMAC proton beam.
- Monte Carlo codes with inventory codes showed a little discrepancy with experimental data for high- Z element, Pb and Au, especially large discrepancy in case of multi-particle production.
- Naturally the discrepancy increase with thicker target layer
- Cross-section comparison with TALYS is also in a progress.

# Thank You for Your Attentions !