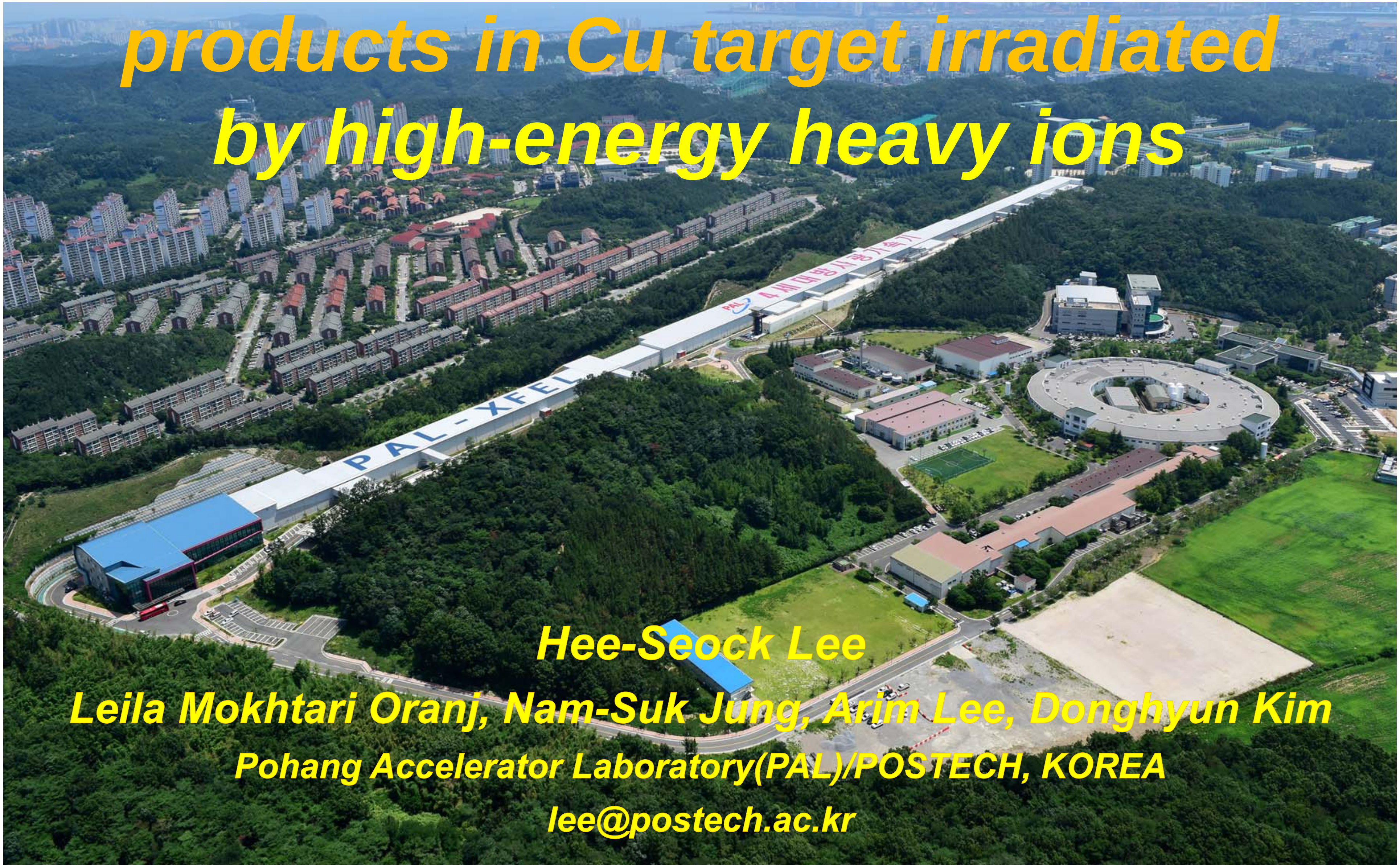
ARIA4, ESS, 2017

Benchmark studies of spallation products in Cu target irradiated by high-energy heavy ions



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Outline

- ***Introduction***
- ***Radioactivity Estimation for High Energy Accelerator***
- ***How to Benchmark at This Study***
  - *Object experiments*
  - *Calculation methods*
- ***Benchmarking Results on Thick Cu Target***
  - *Proton : 100, 230 MeV*
  - *Carbon, Argon : 100, 230, 400 MeV/n*
  - *Uranium : 500, 950 MeV/n*
- ***Summary***

Introduction

- ***Three-year Project was carried out. (Leila's presentation)***

  "Development of Core Safety Technology for Large Accelerator Facility"

  ****** Especially Rare Isotope Accelerator (RAON) was the main object of this study***

- ***Benchmarking Study for Shielding Calculation***
  - ***presented at SATIF13 & ICRS13***

- ***Benchmarking Study for Radioactivity Estimation***
  - ***presented at ARIA2017***
  - ***"Radionuclide yields of proton-induced reactions on Bismuth up to 100 MeV" (By Leila Mokhtari Oranj)***
  - ***"Leakage of radioactive materials from particle accelerator facilities by non-radiation disasters" (By Arim Lee)***

Radioactivity Estimation for HE Accel.

General Understanding:

Transport Code (including spallation)

+ Inventory Code

- **Modula Style**
- **All-in-one Style**

User's Choice

- ✓ **Accuracy**
- ✓ **Reliability**
- ✓ **Convenience**

Libraries for Calculation Process

- ***General Libraries for estimating Activation Process***

Database	Number of isotopes	Origin of data
ENDF/B-VII	3838	ENSDF, Nuclear Wallet Cards
EAF-2010 (includes spin and ncertainties)	2233	ENSDF, NUBASE, JEF2.2, JEFF-3.1.1, Browne and Firestone, Nuclear Wallet Cards
JEFF-3.1.1	3852	NUBASE, ENSDF, LNHB, UKHEDD-2.x, UKPADD-6.x

Library	Incident particles	Procedure of generation
PADF-2007	p	TALYS, ALICE/ASH, EXFOR
HEAD-2009 (IEAF2009+HEPAD2009)	p, n	(Bertini,Isabel,INCL)*(Dresner,ABLA) CASCADE, CEM03, EXFOR global
TENDL-2009	p, n, d, t, he3, α	TALYS (default and adjusted) Validated for integral isotope production crosssection
EAF-2010	p, n, d	EXFOR+TALYS+IEAF+ALICE… evaluated
JENDL-HE2007	p, n	ENDF/B-6+GNASH+ALICE-F +JAM/GEM+JQMD/GEM
JEFF-3.1	p, n	For neutrons EAF-2003 reformatted For protons TALYS

Libraries for Calculation Process

- ## *For High Energy Proton*

Library	Number of isotopes	Z range	Upper energy
EAF-2007	810	1 ~ 100	60 MeV
PADF-2007	2355	12 ~ 88	150 MeV
JENDL-HE2007	106	1 ~ 95	3 GeV
JEFF-3.1	26	20 ~ 83	200 MeV
TENDL-2009	2375	6 ~ 110	200 MeV
HEPAD-2008	682	1 ~ 84	1 GeV

- ## *For High Energy Neutron*

Library	Number of isotopes	Z range	Upper energy
EAF-2007	816	1 ~ 100	60 MeV
JENDL-HE2007	106	1 ~ 95	3 GeV
JEFF-3.1/A	774	1 ~ 100	20 MeV
MENDL-2	505	13 ~ 84	100 MeV
TENDL-2009	2375	6 ~ 110	200 MeV
IEAF-2009	682	1 ~ 84	1 GeV

Aspect of Government Authority

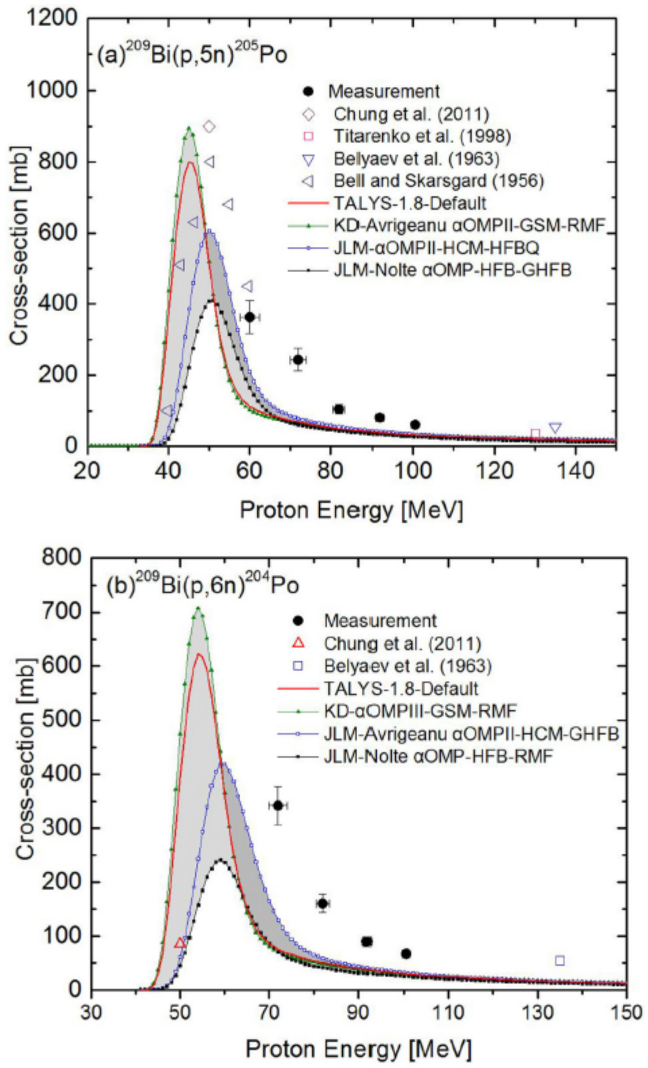


FIG. 4. Independent cross sections for the (a) ^{209}Bi(p, 5n)^{205}Po, and (b) ^{209}Bi(p, 6n)^{204}Po reactions compared with the earlier experimental data together with theoretical calculation model combinations. The experimental data are taken from Refs. [1,3–5].

- ***Reliability***
- ***Uncertainty Range***

- ***All codes can give precise results only based on the including theoretical or experimental data even though those has large certainty.***

- ***Authority require to prove the quality of each code used for analysis.***

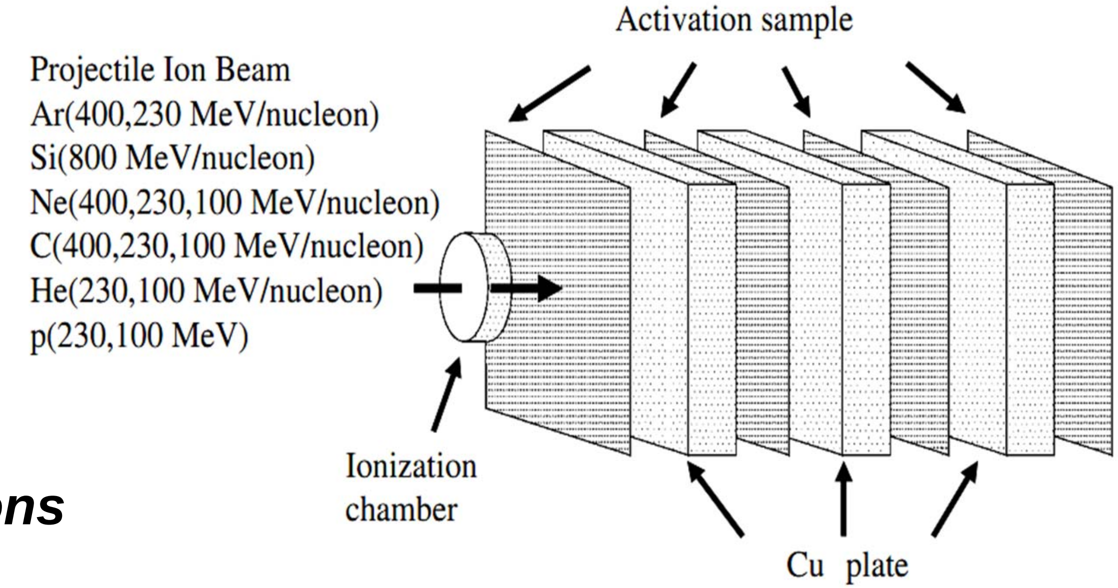
How to Benchmark at this study?

- **Object Experimental Data**
  - **Experiments at HIMAC**
  - **Experiments at GSI**
  - **(proton) Experiments at KOMAC**

- **Combination of Transport Code and Inventory Code**
  - **MCNPX2.7+SP-FISPACT2007**
  - **PHITS 2.64+ Dchain-SP2001**
  - **FLUKA2011**

Experimental Data (by Yashima)

- ***Performed at HIMAC***
- ***Proton & Heavy Ions***
- ***Stack-type Cu target***



- ***Benchmarked Conditions***

Projectile Energy [MeV/n]	Target Dimension (w) × (h) × (t) mm
proton (100)	100 × 100 × 2.2
proton (230)	100 × 100 × 10.1
C (100)	100 × 100 × 1.2
C (230)	100 × 100 × 5.2
C (400)	100 × 100 × 10.1
Ar (230)	100 × 100 × 2.2
Ar (400)	100 × 100 × 5.2

Experimental Data (by Yashima)

- ***Considered Irradiation Information***

Projectile Energy [MeV/n]	Intensity [particles/sec]	Irradiation Time (min)		Target Thickness [g/cm²]		Range [g/cm²]
		Short	Long	Short	Long	
Ar (230)	2.78×10^{8}	60	444	10.68		6.07
Ne (230)	5.03×10^{8}	61	364	9.89	14.62	9.79
C (230)	1.84×10^{9}	36	359	14.51	19.24	16.29
He (230)	9.15×10^{9}	21	304	55.6		48.86
p (230)	2.28×10^{10}	10	312	55.6		48.86
Ne (100)	7.40×10^{8}	31	366	5.06		2.37
C (100)	1.95×10^{8}	60	405	6.22		3.93
He (100)	1.05×10^{9}	48	360	14.79		11.76
p (100)	2.04×10^{10}	46	301	14.79		11.75
Ar (400)	2.37×10^{10}	61	489	24.080		14.90
Ne (400)	7.62×10^{8}	60	463	33.539		24.09
C (400)	1.77×10^{9}	58	457	55.599		40.13
Si (800)	2.60×10^{8}	61	435	64.529		48.92

Experimental Data (at GSI)

- **500 MeV/n U-238 + Cu**
  - Beam : 500 MeV/n, Φ=0.8 cm
  - Irradiation : 20 hours, 6.472 × 10^6 pps
  - Foil thickness : 1 mm (purity 99.995%, 8.92 g/cm^3)
    0.5 mm (purity 99.9%, 8.96 g/cm^3)
  - Number of targets/samples : 23/12
  - Total length of stacks : 1.07 cm
  - Benchmarking radionuclide :Sc-46, Cr-51, Mn-52, 54, Fe-59, Co-56, 57, 58

- 950 MeV/n U-238 + STS
  - Beam : 950 MeV/n, Φ=0.8 cm
  - Irradia
  - Foil th

Table 1
Geometrical configuration of the stainless steel target – foil number and its thickness

Foil number	1	2	3	4	5	6	7
Foil thickness (mm)	0.11	0.49	1.03	0.49	1.98	0.49	1.98
Foil number	8	9	10	11	12	13	14
Foil thickness (mm)	0.50	1.98	0.50	1.99	0.49	1.03	0.49
Foil number	15	16	17	18	19	20	21
Foil thickness (mm)	0.56	0.42	0.49	0.49	0.49	1.98	0.49
Foil number	22	23	24	25	26	27	28
Foil thickness (mm)	1.98	0.49	1.98	0.49	5.12	0.49	5.10
Foil number	29	30	31	32	33	34	35
Foil thickness (mm)	0.49	20.06	0.49	20.06	0.49	20.07	0.49
Foil number	36	37	38	39	40		
Foil thickness (mm)	20.04	0.50	20.06	1.03	0.49		

The target consisted of 40 foils. The overall target thickness was 138.4 mm. The foil thickness was measured by an electronic micrometer in several foil points. Average values are given in the table. The foils thinner than 1 mm were used for gamma-spectroscopy measurements to sample the depth-profile of residual activity. The foils thicker than 1 mm defined the distance between sampling-points.

Experimental Data (at GSI)

- 950 MeV/n U-238 + STS
  - Beam : 950 MeV/n, Φ=0.8 cm
  - Irradiation : 28.08 hours,
    8.586×10^5 pps
  - Foil thickness :
    - Number of targets/samples : 17/23
    - Total length of stacks: 138.39 cm
  - Benchmarking radionuclide: Mn-54, Co-58

- Experiment Records of GSI

Year	Projectile	Energy [MeV/n]	Target
2003	C-12	200, 300, 400	STS, Cu
2005-2006	U-238	120, 500, 950	STS, Cu
2009	Ar-40	500, 1000	Cu, Al
2008	U-238	1000	STS
2010	U-238	500, 950	Al
2014	Ta-181, U-238	500	C

Calculation Details in MC codes

<table>
<tr><th colspan="4">MCNPX 2.7.0</th></tr>
<tr><td rowspan="3">Neutron transport</td><td colspan="2">≤ 20 MeV
(Cross section library)</td><td>ENDF-VII</td></tr>
<tr><td rowspan="2">> 20 MeV
(Physics model)</td><td>Cascade</td><td>Bertini</td></tr>
<tr><td>Evaporation</td><td>Dresner-RAL</td></tr>
<tr><td colspan="3">Tally type</td><td>Volume flux (F4 tally)</td></tr>
<tr><td colspan="3">Neutron energy group</td><td>VITAMIN-J (175 group)</td></tr>
<tr><th colspan="4">SP-FISPACT 2007</th></tr>
<tr><td colspan="3">Cross section library</td><td>EAF-2010</td></tr>
</table>

<table>
<tr><th colspan="4">PHITS 2.64</th></tr>
<tr><td rowspan="3">Neutron transport</td><td colspan="2">≤ 20 MeV
(Cross section library)</td><td>ENDF-VII</td></tr>
<tr><td rowspan="2">> 20 MeV
(Physics model)</td><td>Cascade</td><td>INCL 4.6</td></tr>
<tr><td>Evaporation</td><td>GEM</td></tr>
<tr><td colspan="3">Tally type</td><td>Volume flux (T-track)</td></tr>
<tr><td colspan="3">Neutron energy group</td><td>VITAMIN-J (175 group)</td></tr>
<tr><th colspan="4">DCHAIN-SP 2001</th></tr>
<tr><td colspan="3">Cross section library</td><td>FENDL/A-2.0</td></tr>
</table>

Benchmarking Results

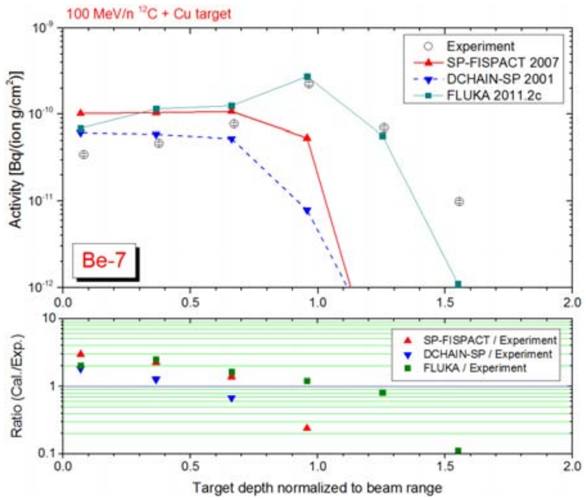
SP-FISPACT → MCNPX2.7 + SP-FISPACT2007

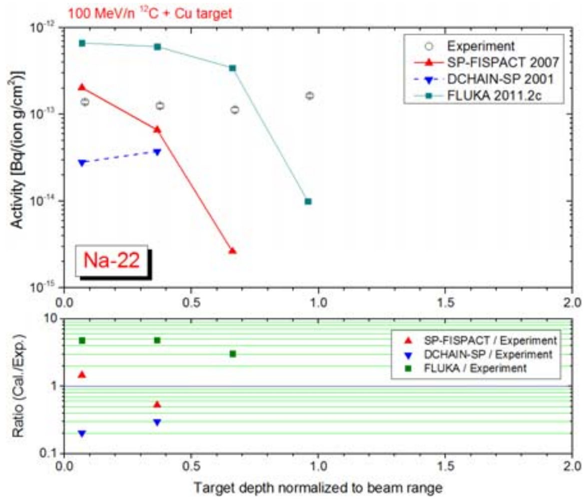
DChain-SP → PHItS2.64 + Dchain-SP2001

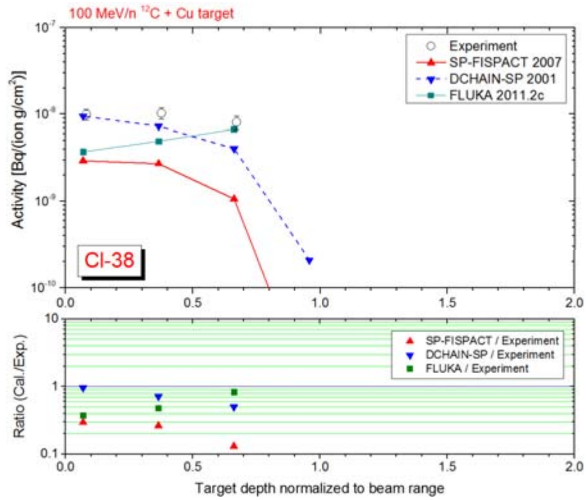
FLUKA → FLUKA2011.2c.x

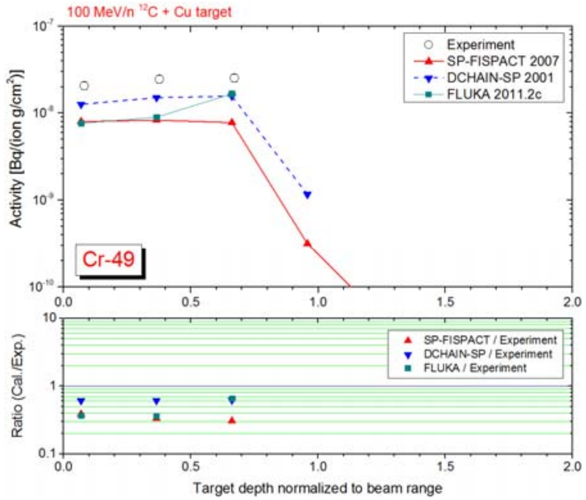
Activation Profiles – Carbon beam

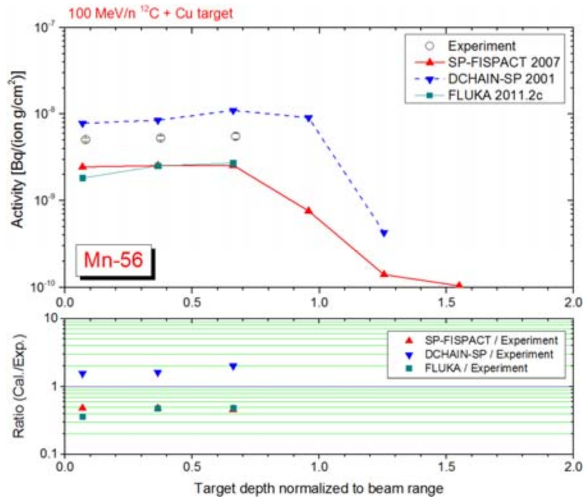
100 MeV/n C on Cu @ HIMAC

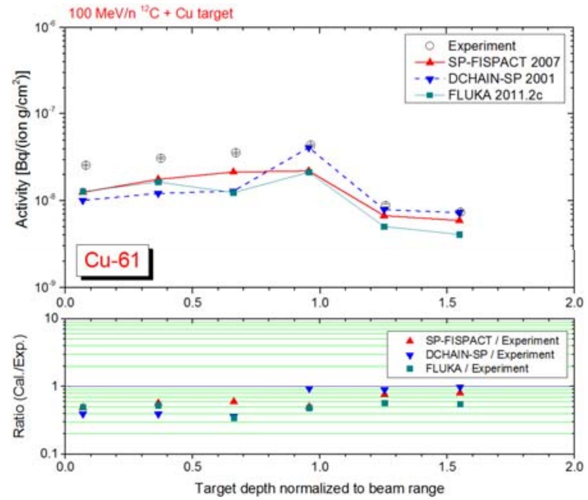






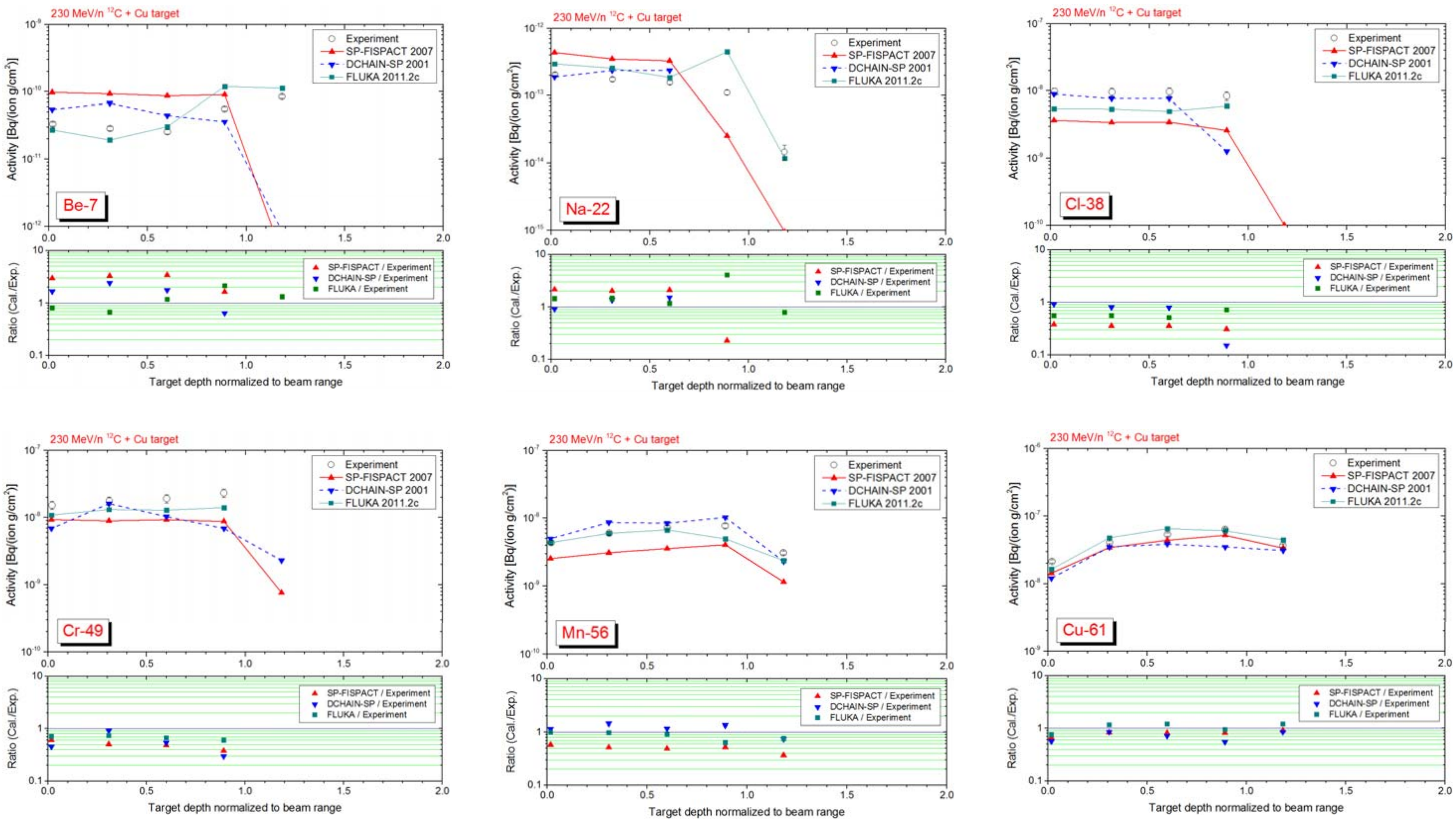






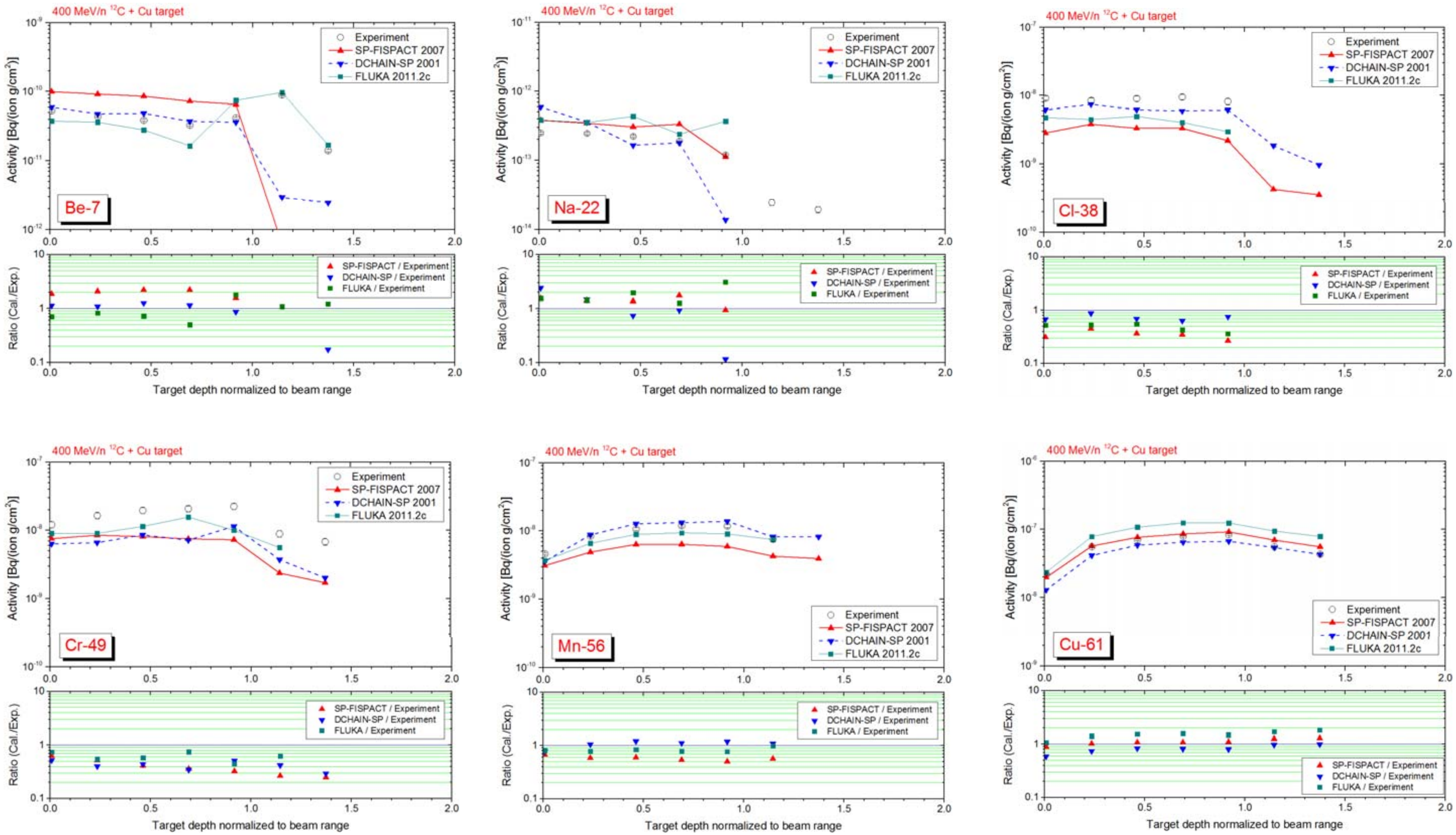
Activation Profiles – Carbon beam

230 MeV/n C on Cu @ HIMAC



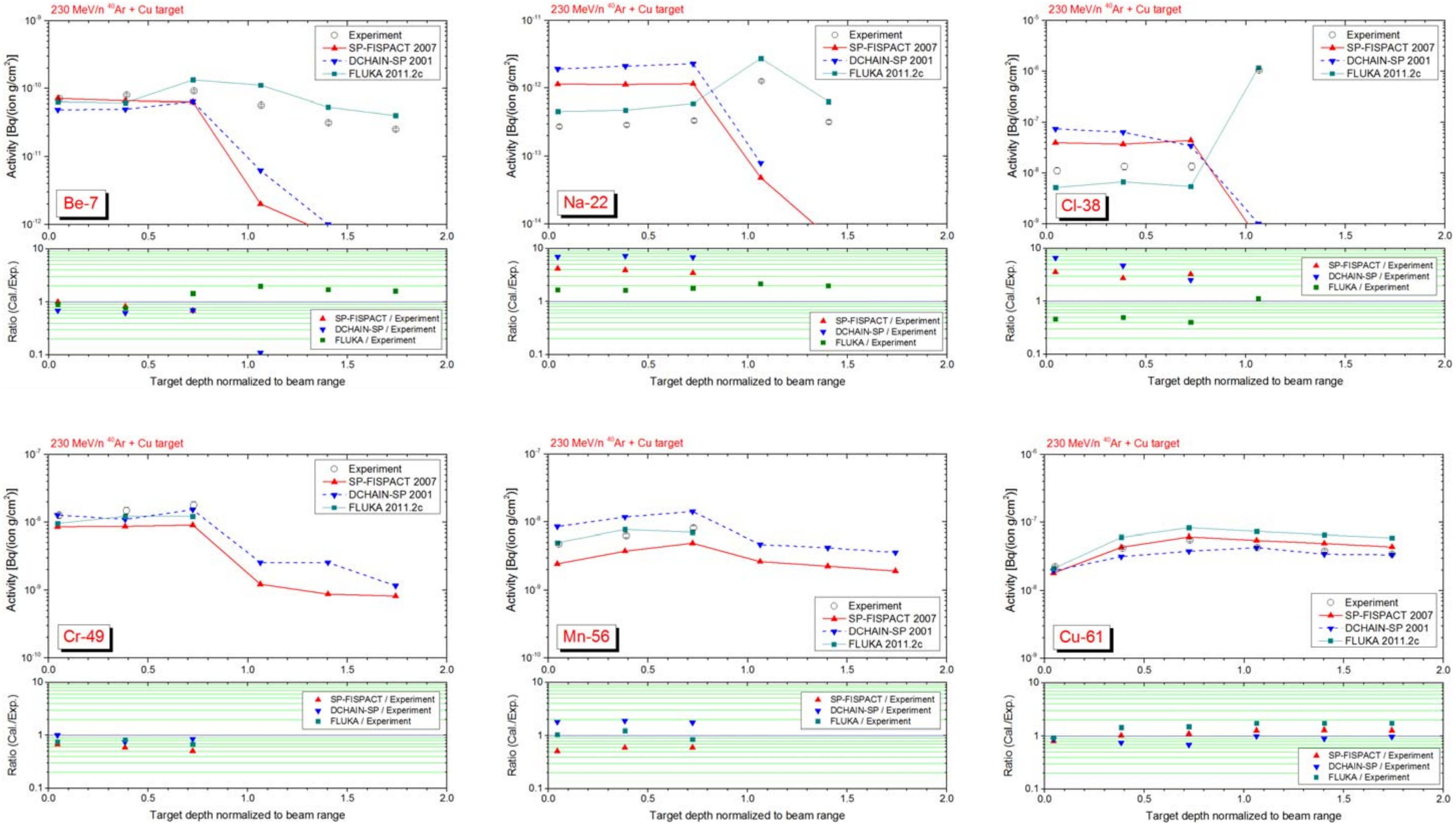
Activation Profiles – Carbon beam

430 MeV/n C on Cu @ HIMAC



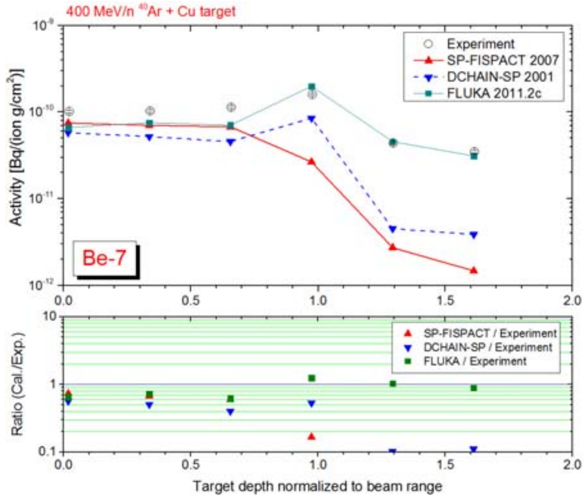
Activation Profiles – Argon beam

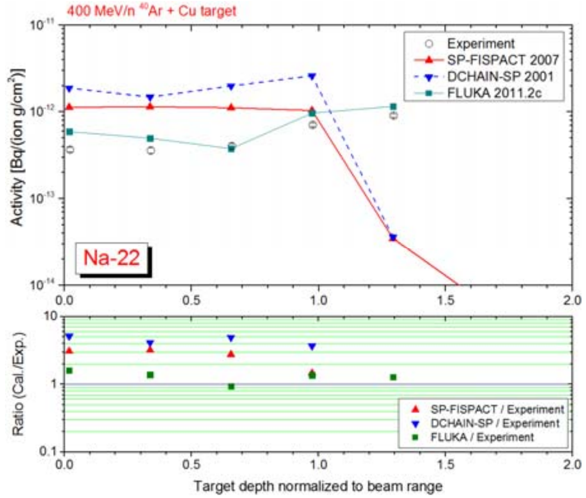
230 MeV/n Ar on Cu @ HIMAC

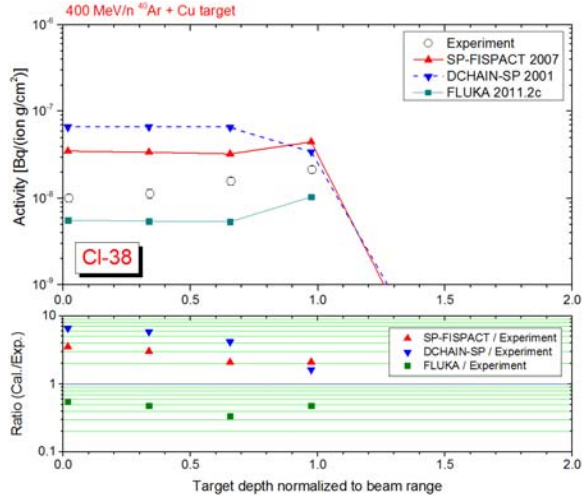


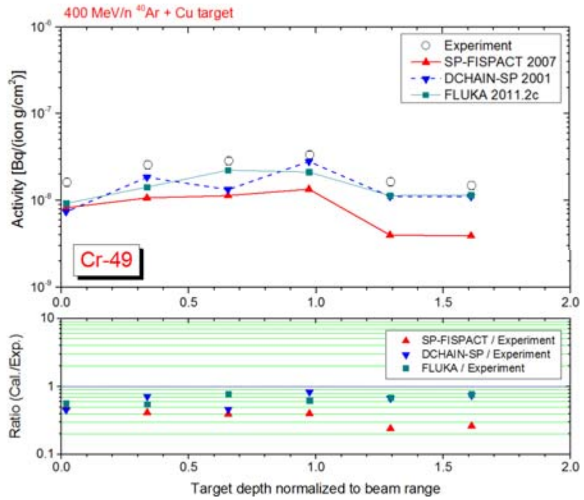
Activation Profiles – Argon beam

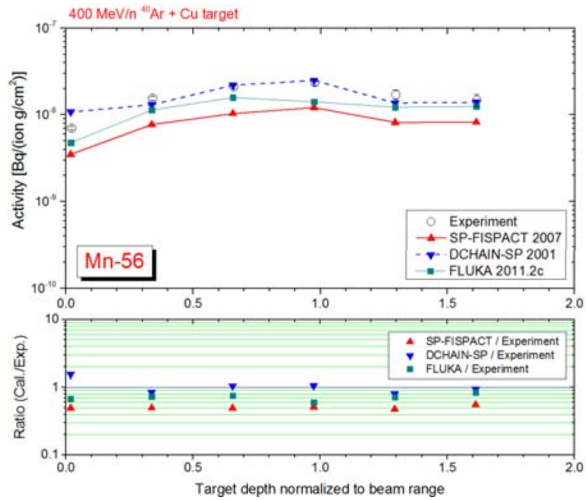
400 MeV/n Ar on Cu @ HIMAC

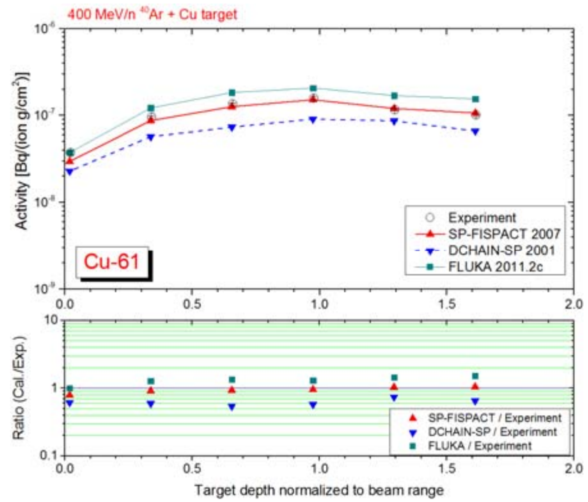






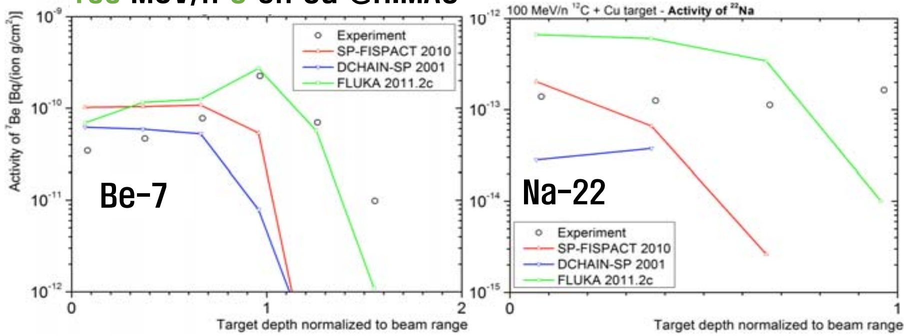




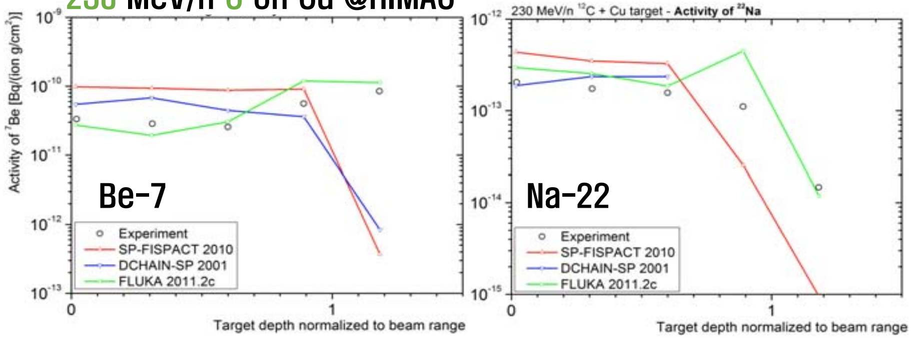


Activation Benchmark – Heavy Ions

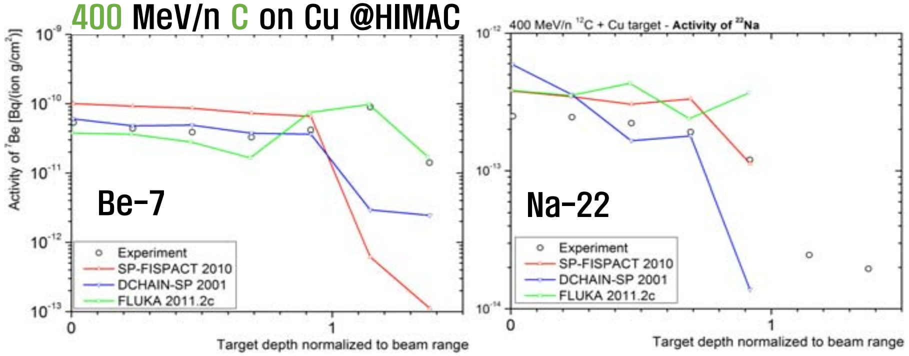
100 MeV/n C on Cu @HIMAC



230 MeV/n C on Cu @HIMAC

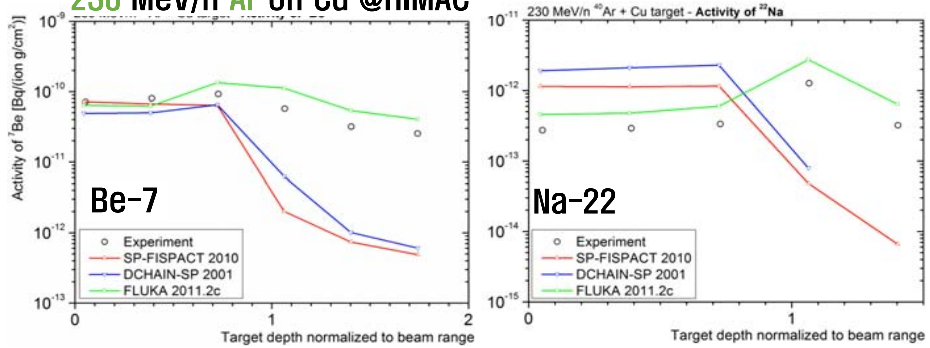


400 MeV/n C on Cu @HIMAC

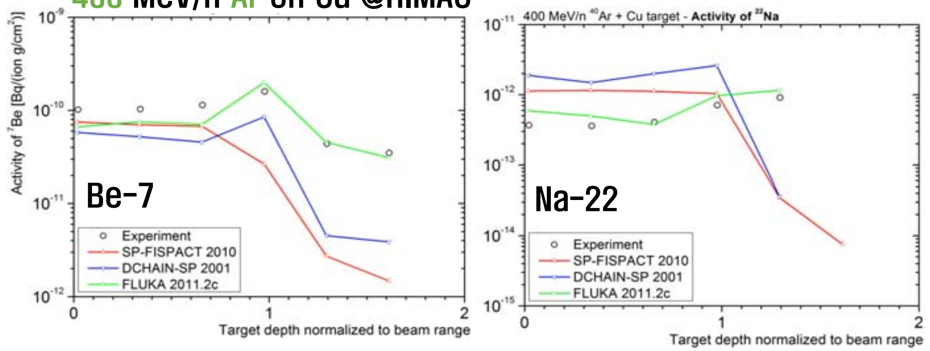


- ➢ Fragment of incident particle (Be-7)
  ⇒ Decrease after the particle range
  Be-7 was not underestimated relatively
- ➢ Nuclide from target (Na-22)
  ⇒ At higher energy, higher Z isotopes, the good agreement was shown.
- ➢ Heavier ions increase activities at target.

230 MeV/n Ar on Cu @HIMAC

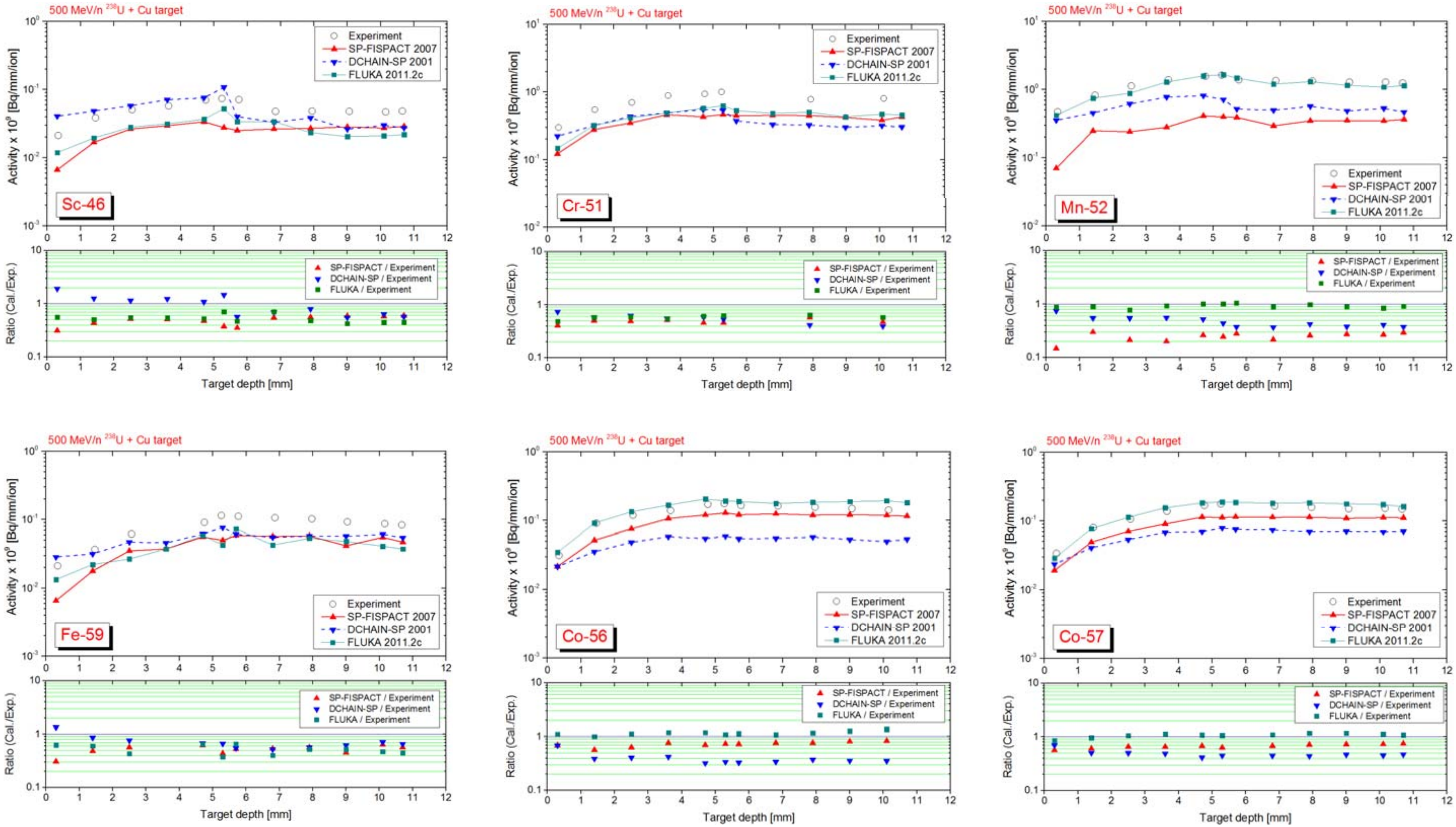


400 MeV/n Ar on Cu @HIMAC



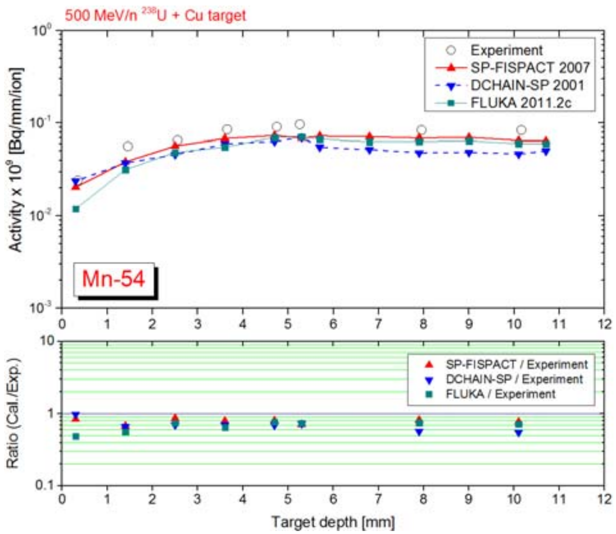
Activation – High Energy Uranium beam

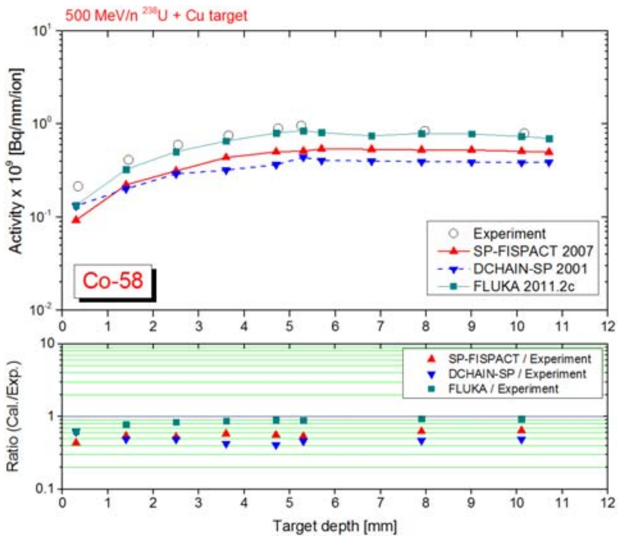
500 MeV/n U-238 on Cu @ GSI



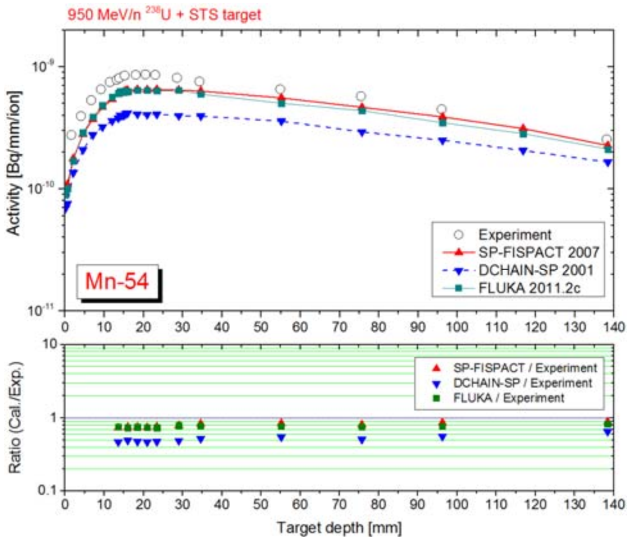
Activation Profiles – Uranium beam

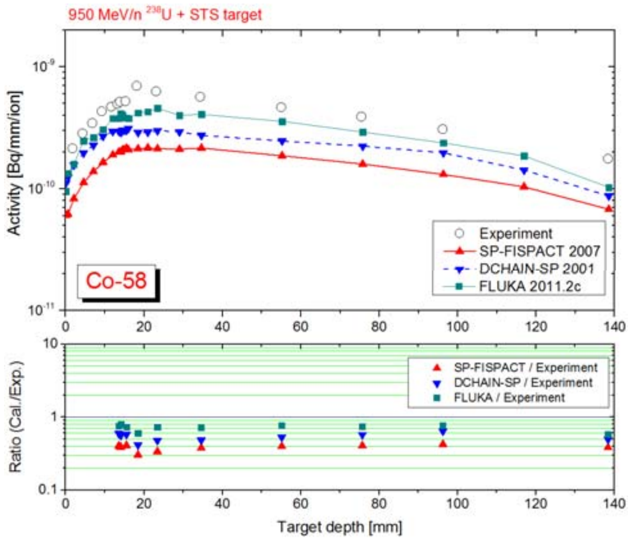
500 MeV/n U-238 on Cu





950 MeV/n U-238 on STS

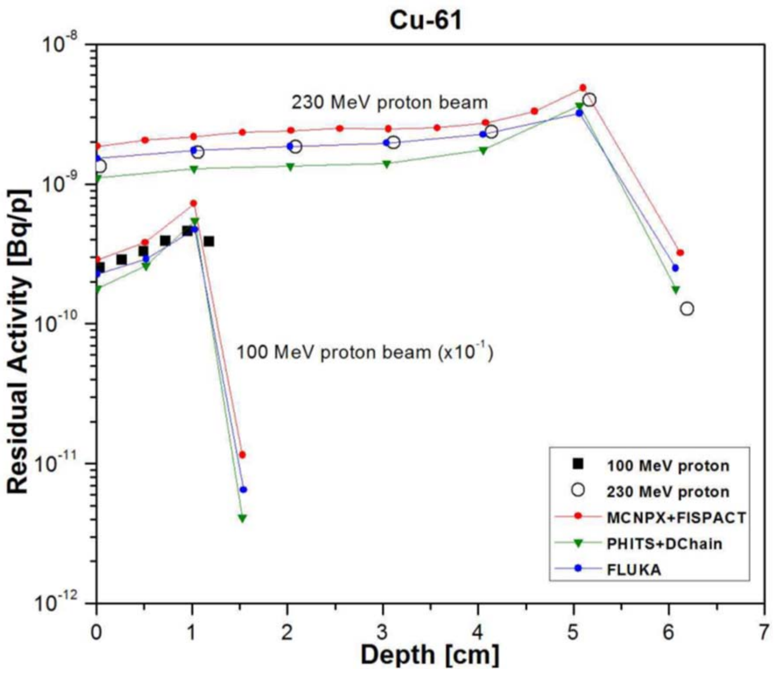


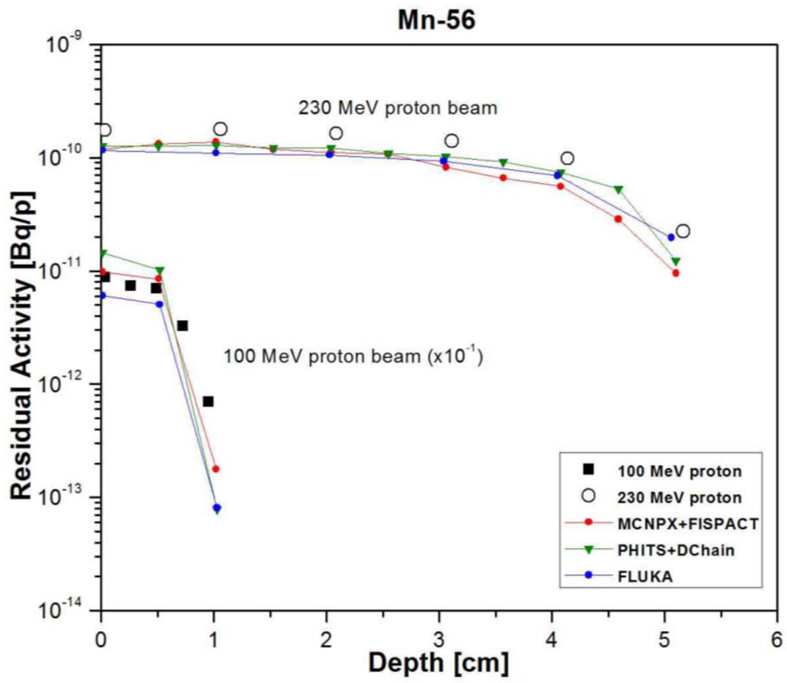


- Calculations underestimate experimental data in most cases
- FLUKA shows better agreements with experimental data
- The activation is not small in deep positions, which is different to results at HIMAC.

Activation Profiles – Proton Beam

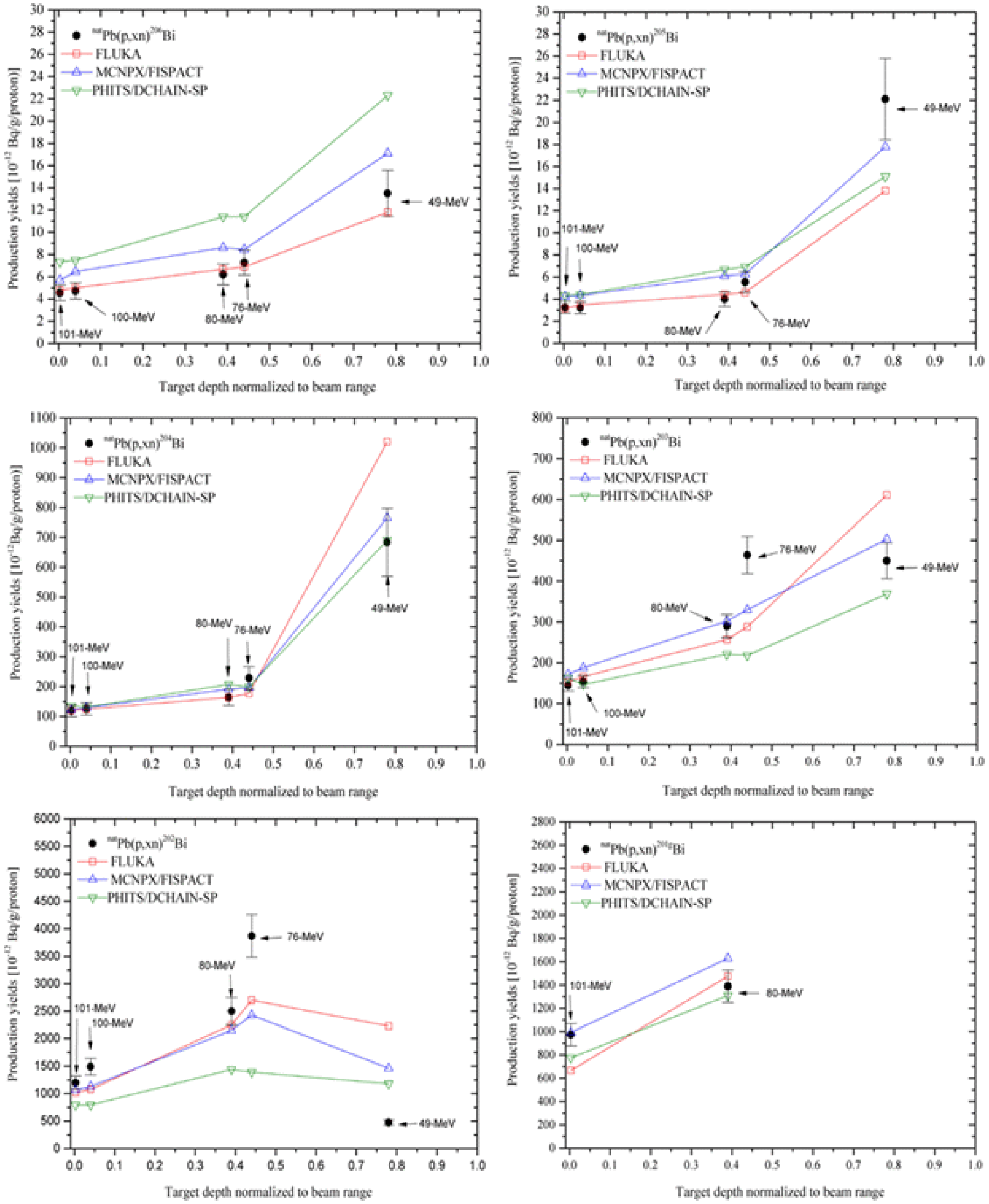
100, 230 MeV/n P on Cu @ HIMAC





Radionuclide Production at High Z element

- **100 MeV Proton**
- **At KOMAC**
- **MC comparison**



Summary

- ***Three MC methods of activity estimation were tested for high-energy heavy ion induced experimental data.***
- ***In many cases of benchmarking, calculation results underestimate the measured data.***
- ***No general trend, but FLUKA reproduced the measured data a little better, relatively.***
- ***The level of discrepancy between each calculation and experimental data was in factor of 2 or 3***
- ***This results can give practical users an idea of safety margin and a credit to their calculations.***
- ***The latest version of MC codes and inventory codes may give better agreements, so those will be tested in near future.***

Thanks for Your Attentions

Radionuclide Production at High Z element

- **100 MeV Proton**
- **At KOMAC**
- **MC comparison**

Proton energy [MeV]	Production yield ratio [calculation/measurement]																	
	^{206}Bi			^{205}Bi			^{204}Bi			^{203}Bi			^{202}Bi			^{201g}Bi		
	FLUKA	MCNPX+SP–FISPACT	PHITS+DCHAIN–SP	FLUKA	MCNPX+SP–FISPACT	PHITS+DCHAIN–SP	FLUKA	MCNPX+SP–FISPACT	PHITS+DCHAIN–SP	FLUKA	MCNPX+SP–FISPACT	PHITS+DCHAIN–SP	FLUKA	MCNPX+SP–FISPACT	PHITS+DCHAIN–SP	FLUKA	MCNPX+SP–FISPACT	PHITS+DCHAIN–SP
101±1.0	1.0	1.2	1.6	1.0	1.3	1.3	1.0	1.0	1.1	1.1	1.2	1.1	0.8	0.9	0.6	0.7	1.0	0.7
100±1.0	1.1	1.4	1.6	1.1	1.3	1.4	1.0	1.0	1.0	1.1	1.2	1.0	0.7	0.7	0.5	–	–	–
80±2.0	1.1	1.4	1.8	1.1	1.5	1.7	1.0	1.2	1.3	0.9	1.0	0.8	0.9	0.9	0.6	1.0	1.1	0.9
76±2.0	0.9	1.2	1.6	0.8	1.1	1.2	0.8	0.9	0.9	0.6	0.7	0.5	0.7	0.6	0.4	–	–	–
49±3.0	0.9	1.3	1.6	0.6	0.8	0.7	1.5	1.1	1.0	1.4	1.1	0.8	4.7	3.0	2.5	–	–	–

Proton energy [MeV]	Activity ratio [calculation/measurement]																			
	^{207}Po		^{206}Po		^{205}Po		^{204}Po		^{203}Po		^{207}Bi		^{206}Bi		^{205}Bi		^{204}Bi		^{203}Bi	
	FLUKA	MARS	FLUKA	MARS	FLUKA	MARS	FLUKA	MARS	FLUKA	MARS	FLUKA	MARS	FLUKA	MARS	FLUKA	MARS	FLUKA	MARS	FLUKA	MARS
100.5 ±0.5	0.9	0.9	0.9	0.9	1.1	1.0	1.2	1.3	0.6	0.8	0.8	0.7	0.9	0.9	0.7	0.8	0.9	1.1	1.1	1.2
91.8±1.0	0.9	0.9	1.0	0.9	0.8	0.8	1.0	1.0	0.5	0.5	0.7	0.8	0.9	0.9	0.8	0.9	0.9	1.1	1.2	1.2
82±1.5	0.9	0.9	0.8	0.9	0.7	0.8	0.7	0.7	0.5	0.5	0.8	0.8	1.0	1.0	0.9	1.0	1.1	1.3	1.3	1.1
72±2.0	0.7	0.8	0.6	0.7	0.4	0.4	0.6	0.5	--	--	0.8	0.8	1.0	1.1	0.9	1.0	2.3	2.0	--	--
60±2.5	0.4	0.6	--	--	0.5	0.5	--	--	--	--	0.7	0.8	--	--	1.4	1.3	--	--	--	--