Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

Measurement of secondary neutron spectra induced by 480 MeV proton and 430 MeV/u ^{4}He beams with a thick aluminum target

IPRD23, 27/09/2023
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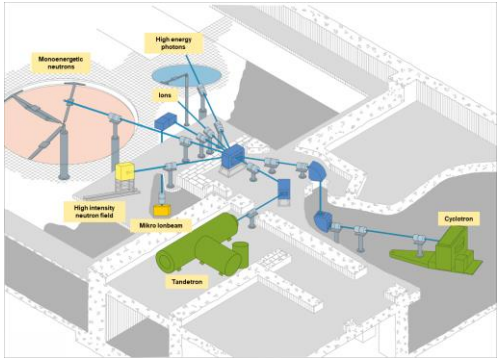
GSI: D. Boscolo, F. Luoni, E. Kozlova, U. Weber

Physikalisch-Technische Bundesanstalt (PTB)

Braunschweig, Germany

Department 6.4 "Neutron Radiation"



Mono-energetic Neutrons

^{65}Cu (p,n) ^{65}Zn:	1.2 keV
^{45}Sc (p,n) ^{45}Ti :	8, 27 keV
^{7}Li (p,n) ^{7}Be:	0.3 - 0.7 MeV
T (p,n) ^{3}He:	0.7 - 4 MeV
D (d,n) ^{3}He:	4 – 15 MeV
T (d,n) ^{4}He:	14 - 19 MeV

Collimated Neutron Beams with Broad Energy Distributions

^{9}Be + d (13.5 MeV) : $< E_n > \approx 5$ MeV

^{9}Be + p (19.0 MeV) : $< E_n > \approx 10$ MeV

High intensities

Pulsed beams on 30 m flight path

Irradiation facility with neutron sources

^{241}Am-Be(α,n)

^{252}Cf(sf = spontaneous fission)

^{252}Cf(sf, D_2O-moderated)

^{252}Cf(sf, D_2O-moderated + 1 mm Cd)

In accordance with ISO 8529-1

Major health risks for LEO and NEO missions

(Microgravity)

- ❖ Loss of bone mineral density, loss of muscle mass, body fluid shifts, vision impairment;
- ➢ Regular exercise routines, medications, constant health monitoring;

(Isolation, limited privacy)

- ❖ Reduced cognitive performance, anxiety, depression, loneliness, sleep problems;
- ➢ Regular psychological support, medications, social support;

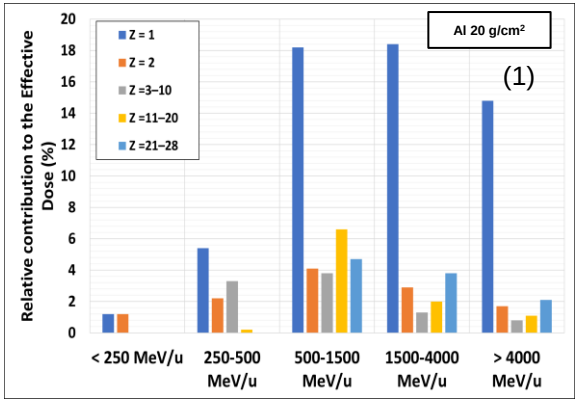
(Radiations)

- ❖ Acute radiation sickness, immune system disorders, genetic mutations, central nervous system decrements, cardiovascular disease, cataracts, increase of cancer risk;
- ➢ Passive shielding, medications, regular dose monitoring;

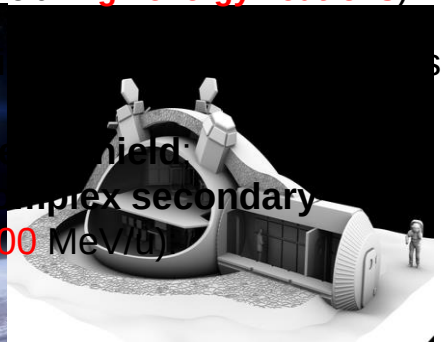
Radiation in space: characteristics and countermeasures

Main direct radiation sources in space (weak magnetic field, very scant atmosphere):

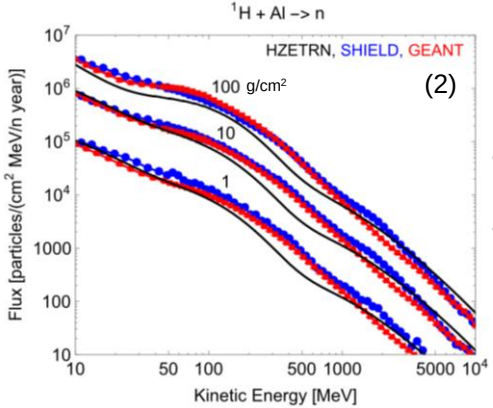
- Solar Particle Events (protons and electrons);
- Galactic cosmic radiation (GCR): omnipresent, low fluence, broad spectrum of heavy nuclei from protons up to Fe, broad energy spectrum up to several 10^3 GeV/u;

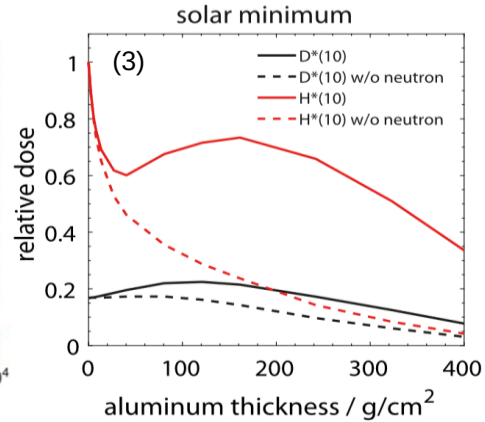


- Radiation shielding strategies:
  - **Spacecraft:** Aluminum alloys (≈25 g/cm²)
    (Secondary radiation field: **Light ions & high energy neutrons**)
  - **Moon settlements:** Moon regolith, caves or craters
    (Secondary radiation field: **high energy neutrons**)



❖ Generation of a complex secondary radiation field (> 500 MeV/u)





[1]T.C. Slaba et al. (2014), [2]J. W. Norbury et al. (2017) [3]F. Horst et al. (2022)

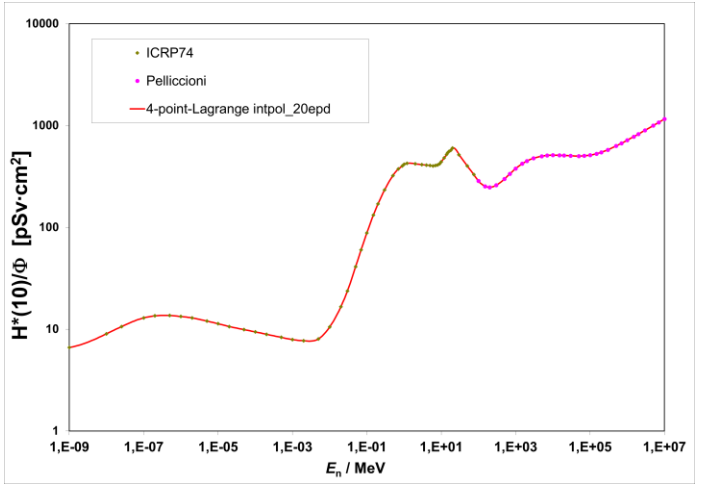
Main problems related to high-energy neutrons

Main problems related to high energies neutrons (>20 MeV):

- **High penetrating power & High relative biological effectiveness (RBE);**

- **Scarcity of high energy heavy ion beam facilities:**
  - Lack of experimental data (physical and biological);
  - Lack of nuclear cross sections (physical models only for Monte Carlo codes);
  - Uncertainties on conversion coefficients (from neutron fluence [cm^{-2}] to rad. prot. operational quantities [Sv]) which are strongly energy-dependent

- **Link between physical and biological data;**

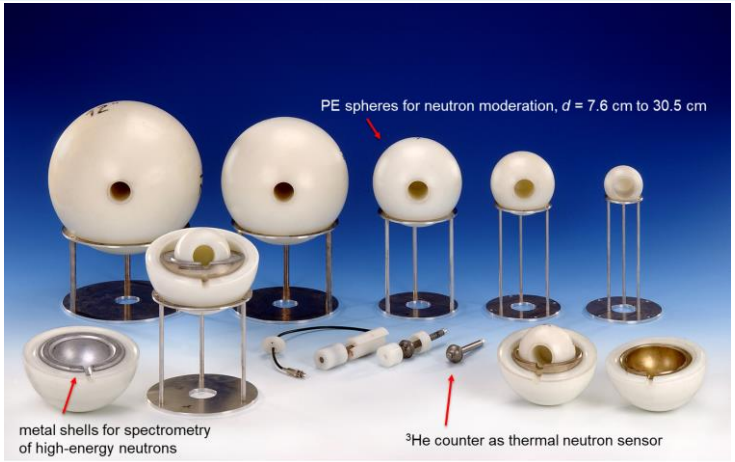


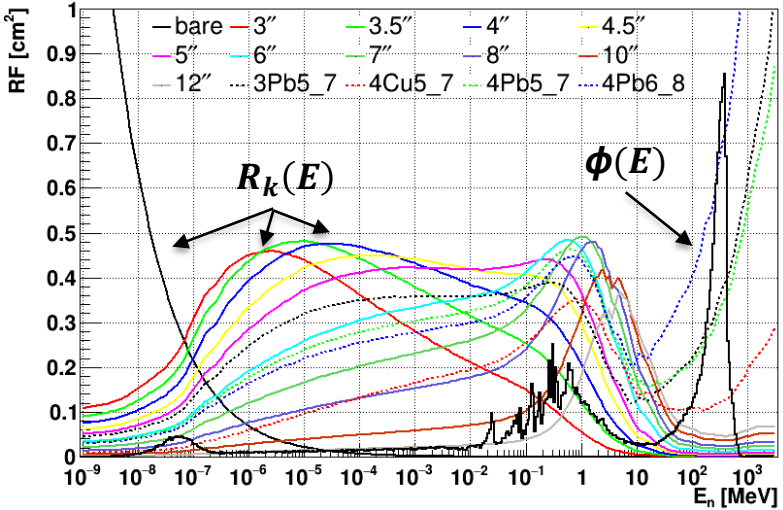
How can we measure a full neutron energy range (from thermal neutrons (≈25 meV) up to GeV?

Neutron spectrometry with Bonner Spheres

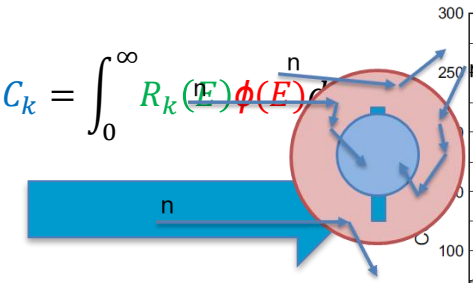
NEMUS-ERBSS (Extended range Bonner sphere spectrometer):

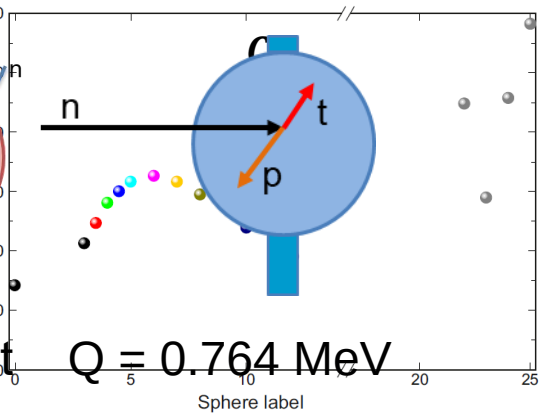
- Central thermal neutron sensor (^{3}He gas, 0.2 bar)
- From thermal neutrons up to GeV;
- Active detection of neutrons;
- Isotropic response;
- Initial information of incident neutron energy is lost (multiple measurements with different spheres required);





$$C_k = \int_0^\infty R_k(E)\,\phi(E)\,dE$$



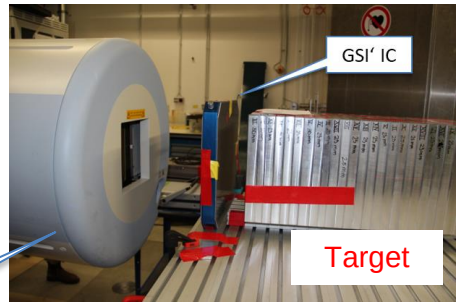


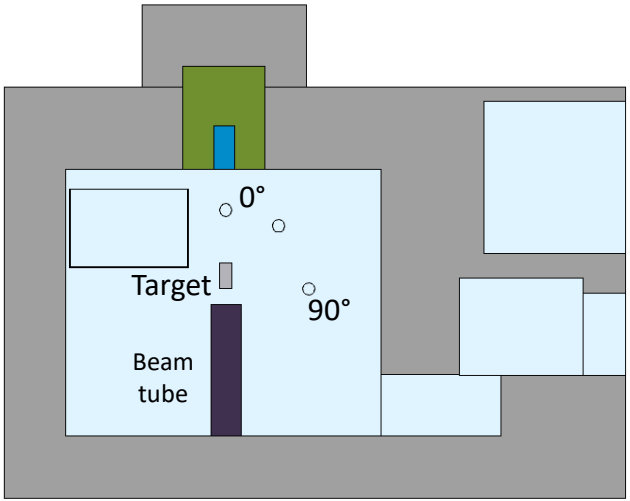
$$n + {}^3He \rightarrow p + t \qquad Q = 0.764\ MeV$$

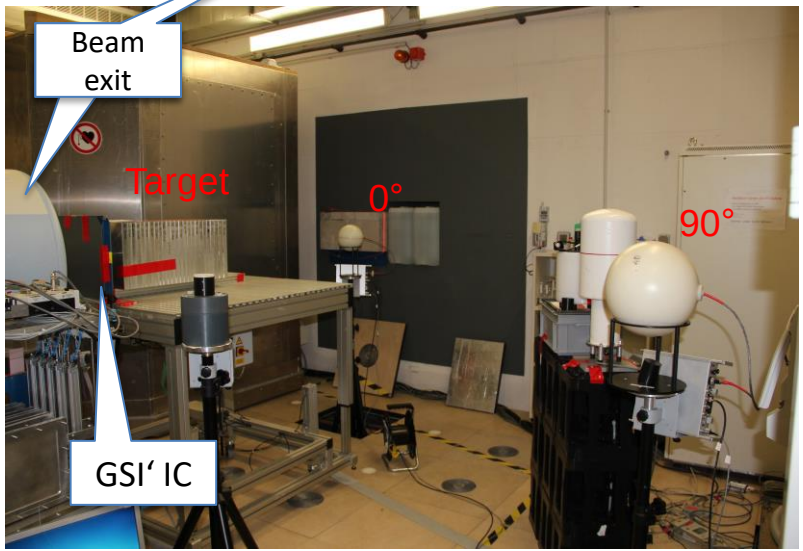
HIT and experimental setup

HIT experimental campaign (funded by ESA-CORA, DAIMOS project):

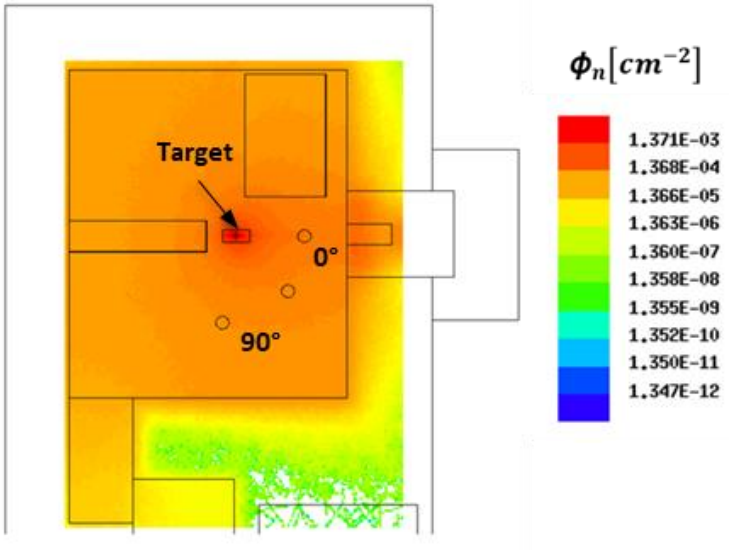
- **HIT beams used:**
  - **480 MeV protons**: 4*10^8 ion/spill (10 s per spill), FWHM: 5 mm;
  - **430 MeV/u ^{4}He**: 1*10^8 ions/spill (10 s per spill), FWHM: 10 mm;
- AlMg3 target (multi plates, total thickness 30x30x64 cm^3);
- NEMUS complete sphere set (0°, 90°, distance 2.1 m);
- Normalization (No PR or RF signal): GSI's ionization chamber (IC);

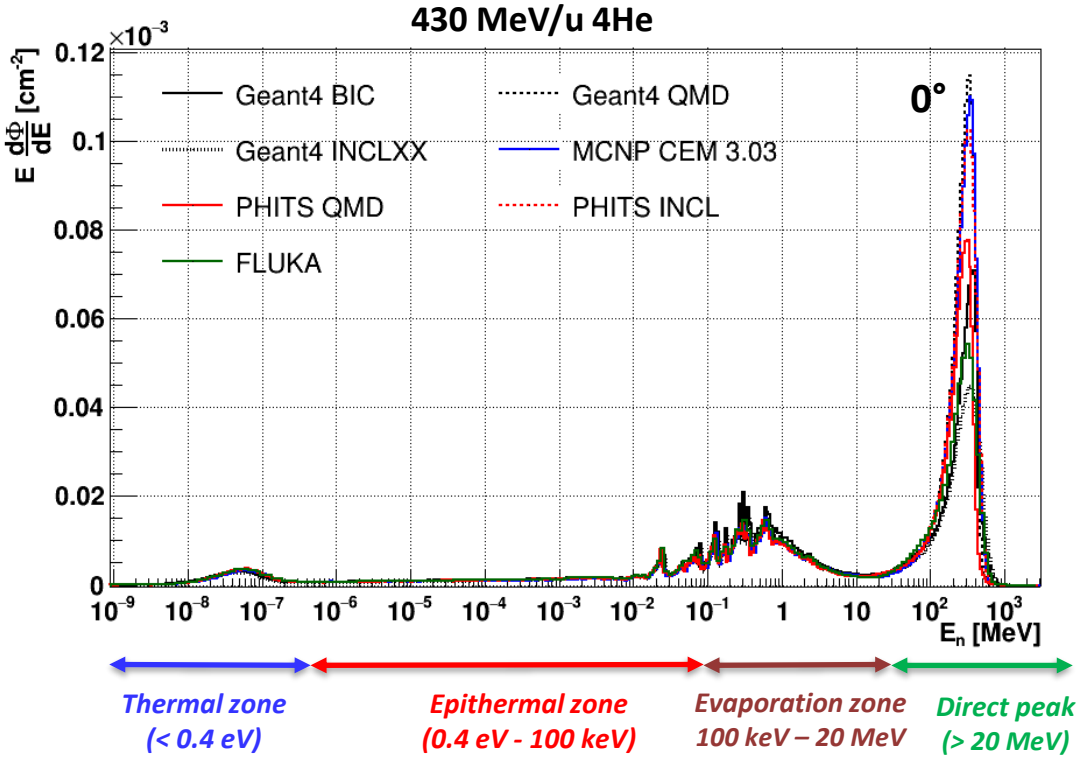






Monte Carlo simulations





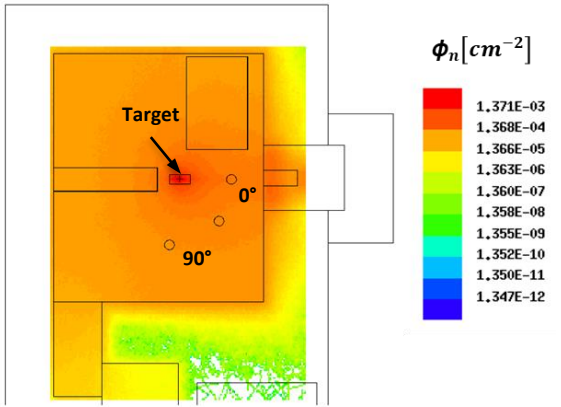
Monte Carlo codes and physical models:

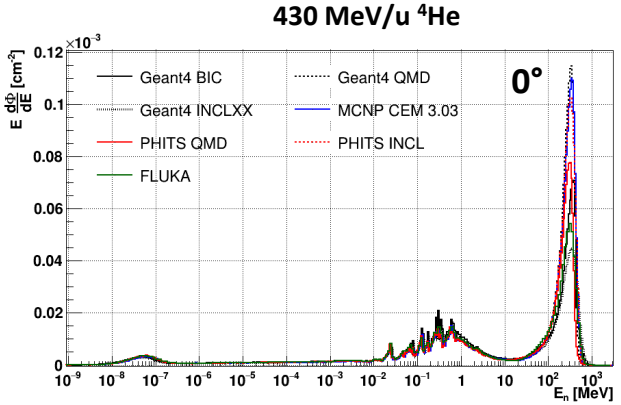
- FLUKA (RQMD, PEANUT)
- Geant4 (BIC, INCLXX, QMD)
- MCNP6 (CEM03.03)
- PHITS (QMD, INCL)

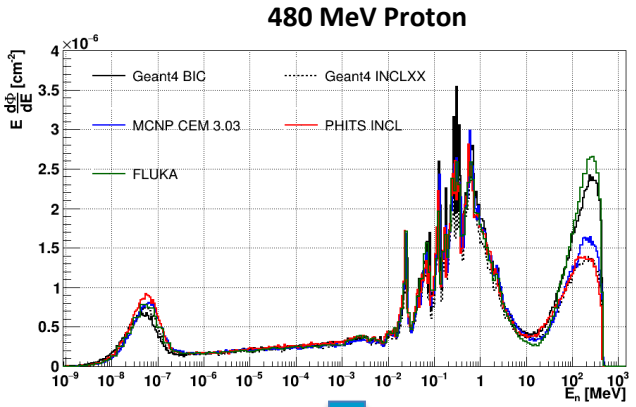
Conversion of the geometrical models using **PyG4ometry**;

Spectra are in lethargy units and normalized for simulated primary particles (PP);

Monte Carlo simulations







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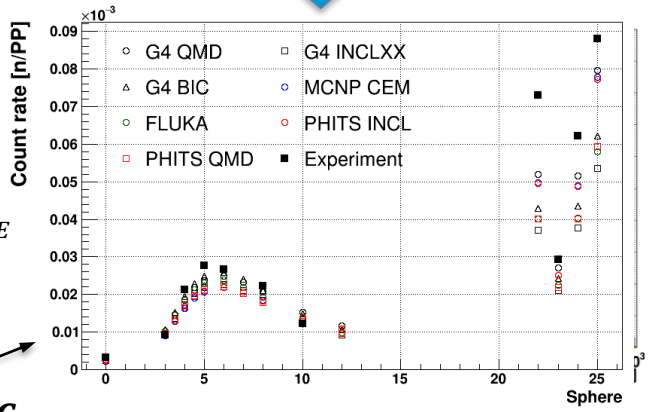
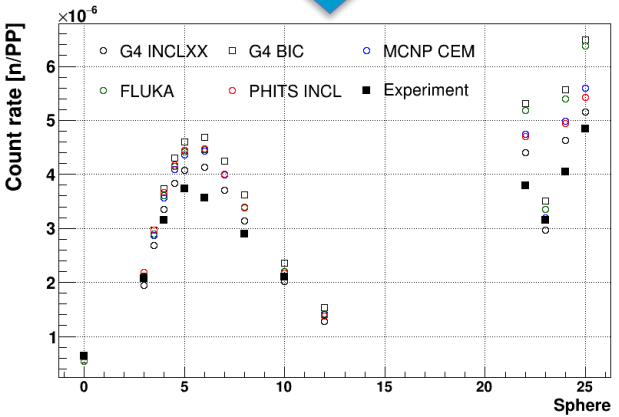
$$C_k = \int_0^\infty R_k(E)\phi(E)dE$$

Which of these MCs most realistically reproduces the direct peak?





Simulated vs NEMUS C_k

Unfolding procedure

$$C_k = \int_0^\infty R_k(E)\,\phi(E)\,dE$$

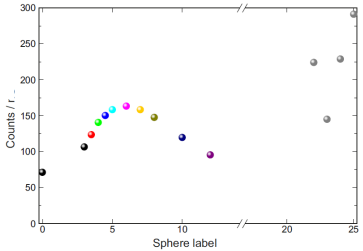
Initial neutron energy distribution ($\phi_0(E)$) (from Monte Carlo)

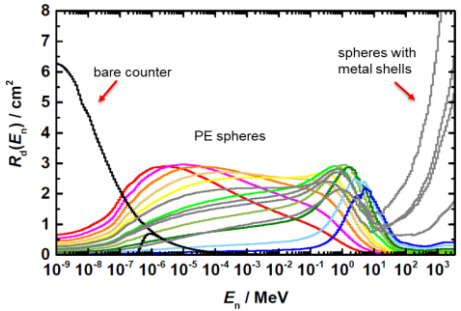
Measurement (C_k) (BSS in unknown neutron field)

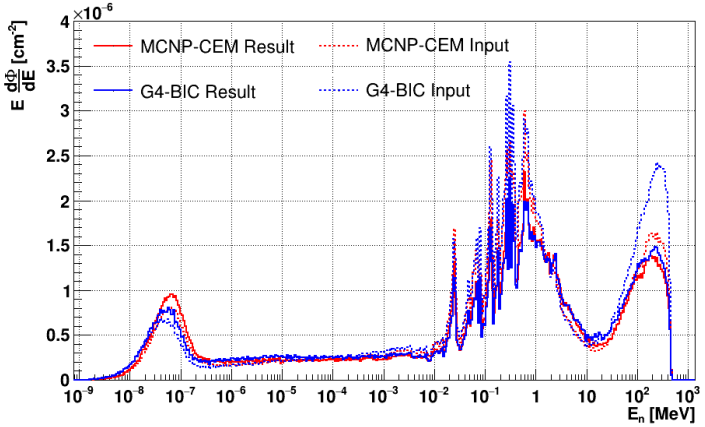
Unfolding procedure (with MAXED[1])

Experimental neutron energy distribution ($\phi(E)$)

Response matrix ($R_k(E)$) (response functions)



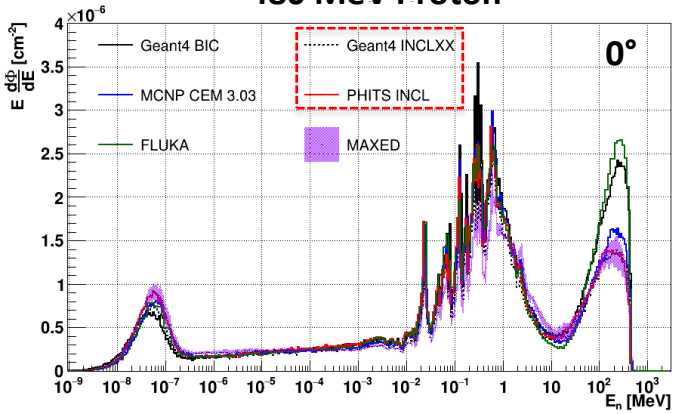


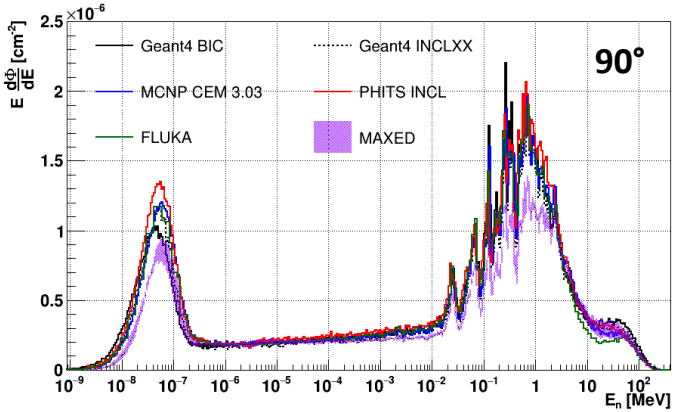


[1]"Spectrum unfolding, sensitivity analysis and propagation of uncertainties with the maximum entropy deconvolution code MAXED", M. Reginatto et al. 2002.

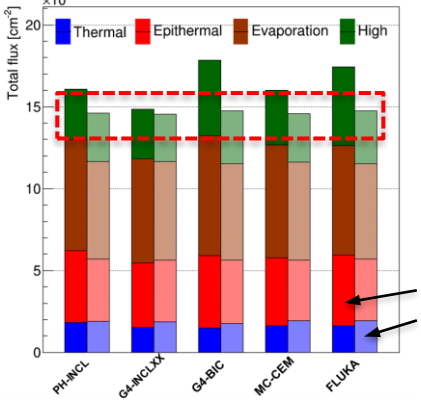
Neutron spectra unfolding and Ambient Dose Equivalent analysis

480 MeV Proton



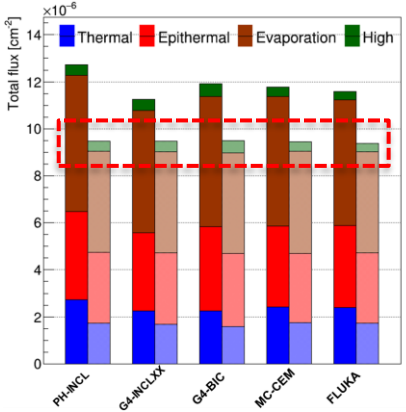


Integral fluences



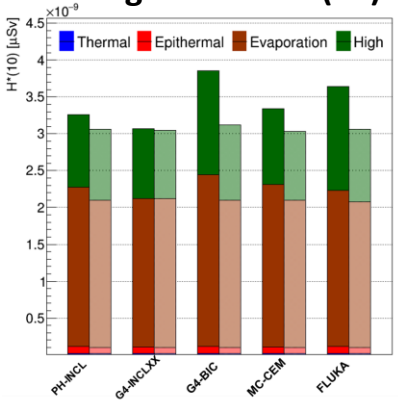
Direct peak std 5%
Total flux std 0.69%

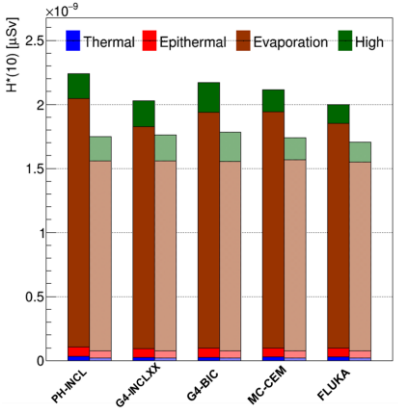
MC result
MAXED result



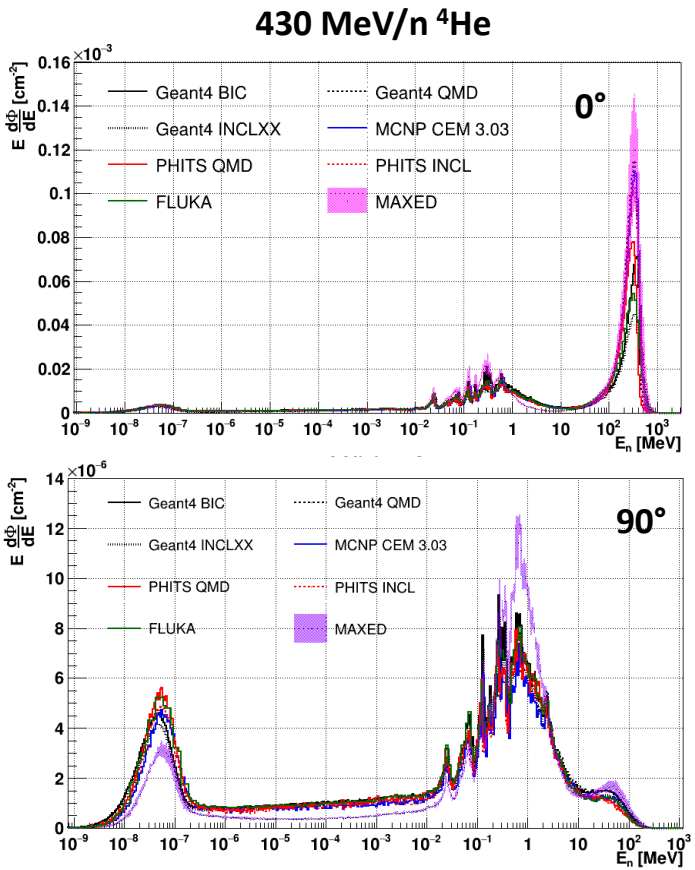
Direct peak std 14%
Total flux std 0.49%

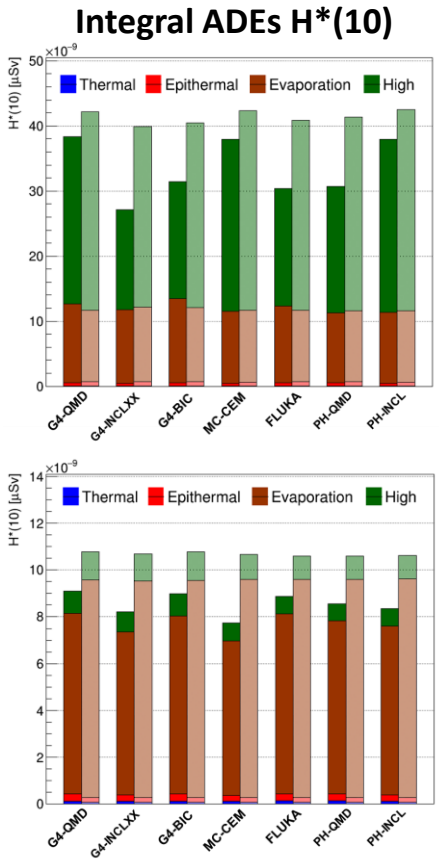
Integral ADEs H*(10)





Neutron spectra unfolding and Ambient Dose Equivalent analysis





Neutron spectra (direct peak)

- MCNP-CEM, PHITS-INCL and G4-QMD give the best results (dev 11% - 14%);

Integral neutron flux and ADEs

(0°): Direct peak std (5.25%);
Total spectrum std (2.78%);
(90°): Direct peak std (9.36%);
Total spectrum std (0.29%);

Stable results with different input spectra (from different MC codes)

Conclusion and future works

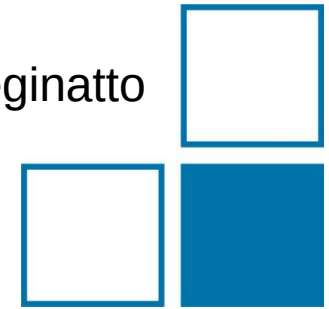
- **Monte Carlo calculations:**
  - Direct communication between FLUKA, MCNP, PHITS and Geant4 (using **PyG4ometry**);
  - Simulation of the HIT neutron field with different physical models;

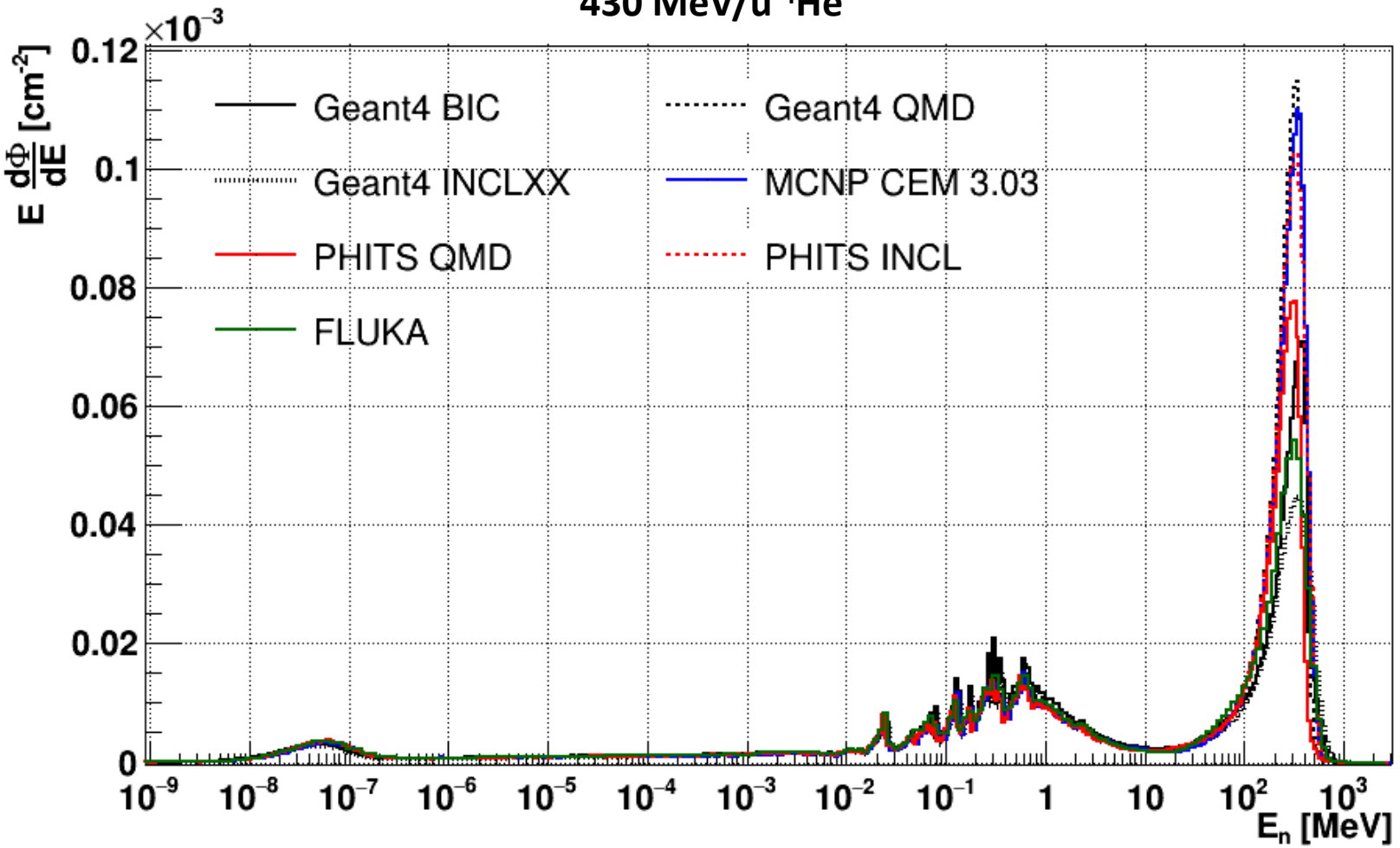
- **Neutron spectra unfolding (from NEMUS data):**
  - Characterization of two high-energy neutron spectra (at **0°**):
    - ^{4}He 430 MeV/u beam with a direct neutron peak of ≈343 MeV;
    - Proton 480 MeV beam with a direct neutron peak of ≈250 MeV;
  - Monte Carlo codes and corresponding physical models that best reproduced the direct peak are:
    - ^{4}He 430 MeV/u: MCNP-CEM, PHITS-INCL and G4-QMD;
    - Proton 480 MeV: PHITS-INCL and G4-INCLXX;
  - Total integral fluence and H*(10) values are similar starting from different calculated input neutron spectra (2.78% for ^{4}He and 0.69% for proton);

- **Future works:**
  - Repetition of the measurement campaign with more angles and with higher statistics;
  - Use of GSI Thermoluminescent dosimeters (TLDs) for a comparative analysis of experimental doses;

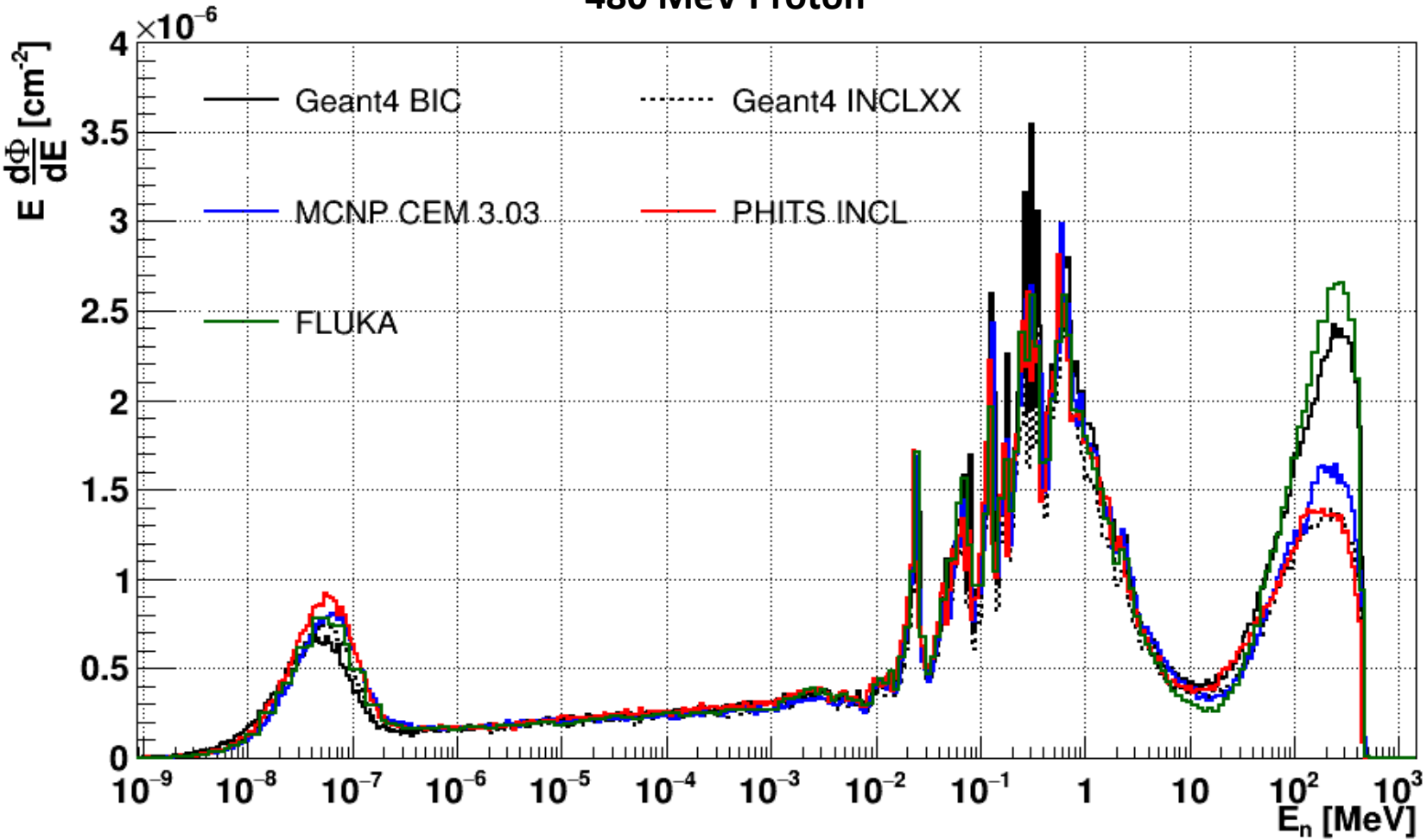
Thank you for your attention

Thank for the support
PTB team: A. Di Chicco, M. Zbořil, A. Luecke, T. Klages, M. Reginatto
GSI team: D. Boscolo, F. Luoni, E. Kozlova, U. Weber
HIT team: S. Scheloske, S. Brons




430 MeV/u ^{4}He
$\times 10^{-3}$
$E \frac{d\Phi}{dE}$ [cm^{-2}]
0.12
0.1
0.08
0.06
0.04
0.02
0
Geant4 BIC
Geant4 INCLXX
PHITS QMD
FLUKA
Geant4 QMD
MCNP CEM 3.03
PHITS INCL
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^{2} 10^{3}
E_n [MeV]

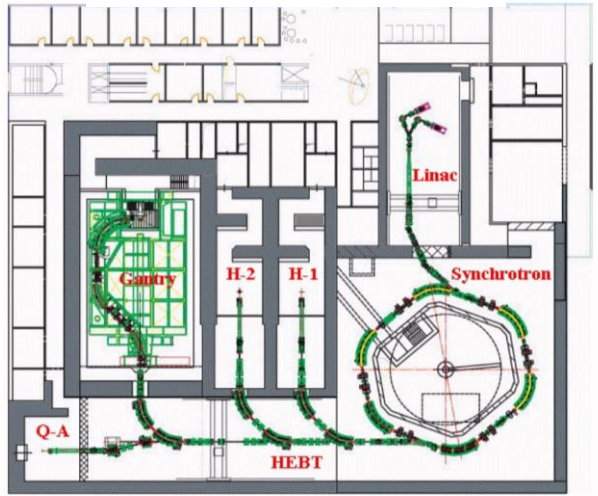
480 MeV Proton



HIT and experimental setup

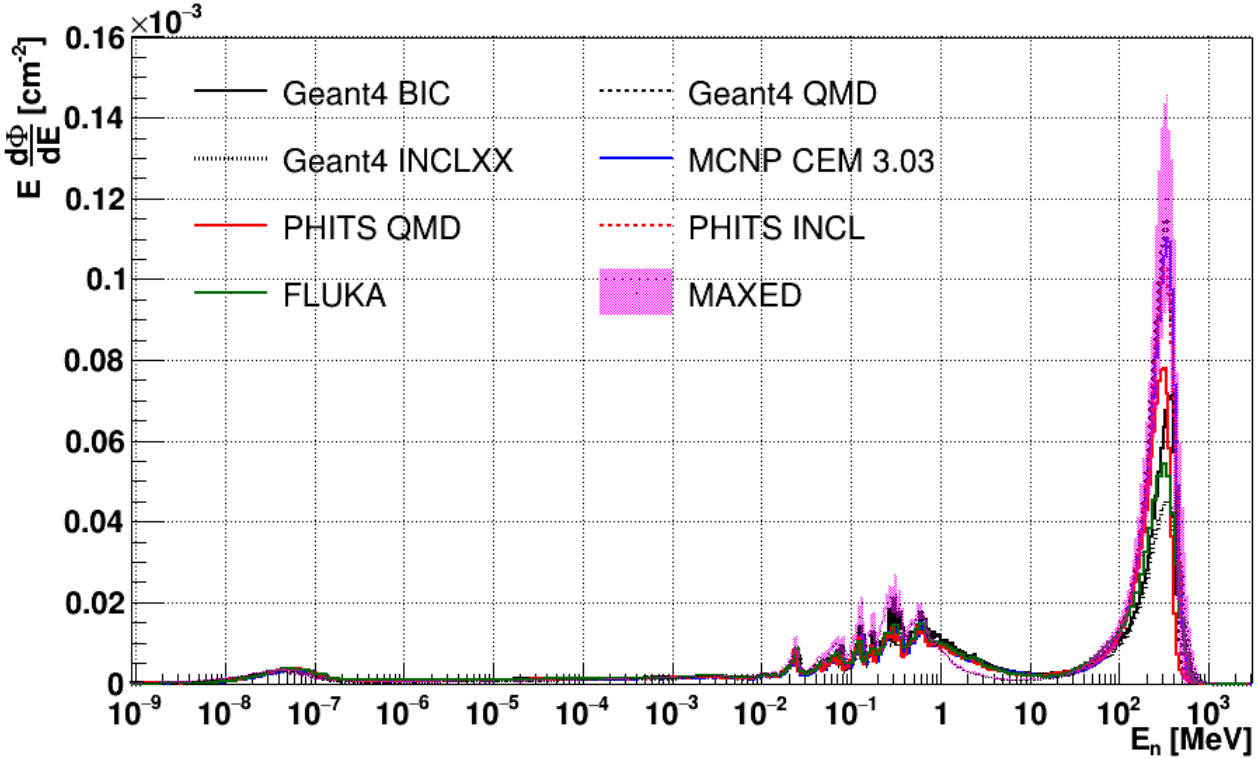
HIT beam <u>possible</u> parameters:

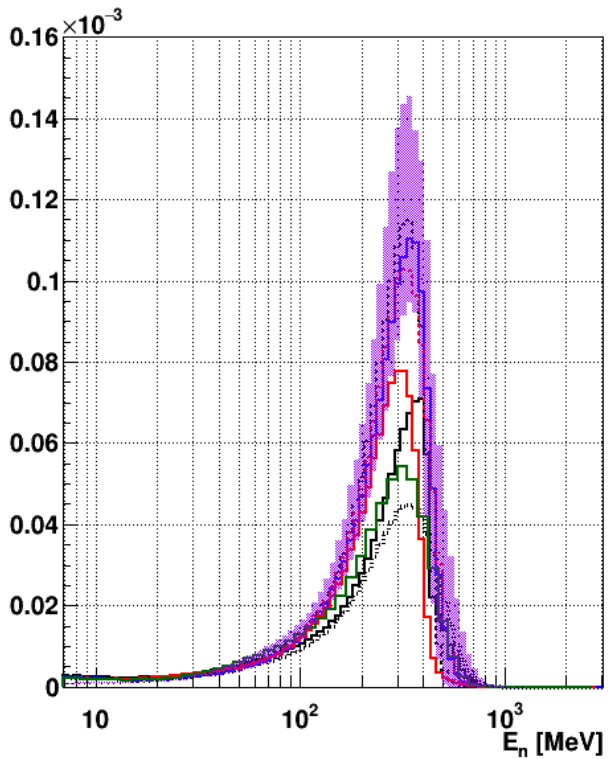
- Ion species: proton, ^{4}He and ^{12}C;
- Ion energies: 48 – 430 MeV/u (p: 480 MeV);
- Ions/spill: $1 \cdot 10^{7}$ - $1 \cdot 10^{10}$;
- Ion beam FWHM: 4 – 20 mm;



https://www.klinikum.uni-heidelberg.de/interdisziplinaere-zentren/heidelberger-ionenstrahl-therapiezentrum-hit

Neutron spectra induced by 430 MeV/u ^{4}He





Tables

		Proton Monte Carlo (Neutron Flux)					MAXED				
	E_n	PH-INCL	INCLXX	G4-BIC	CEM	FLUKA	PH-INCL	INCLXX	G4-BIC	CEM	FLUKA
0°	Thermal	1,81E-06	1,51E-06	1,50E-06	1,63E-06	1,61E-06	1,91E-06	1,86E-06	1,76E-06	1,94E-06	1,93E-06
	Epithermal	4,40E-06	3,96E-06	4,41E-06	4,15E-06	4,34E-06	3,78E-06	3,79E-06	3,89E-06	3,69E-06	3,78E-06
	Evaporation	6,78E-06	6,35E-06	7,31E-06	6,90E-06	6,70E-06	5,95E-06	5,99E-06	5,88E-06	5,98E-06	5,82E-06
	High	3,10E-06	3,03E-06	4,62E-06	3,34E-06	4,79E-06	2,97E-06	2,91E-06	3,22E-06	2,96E-06	3,21E-06
	Total	1,61E-05	1,49E-05	1,78E-05	1,60E-05	1,74E-05	1,46E-05	1,45E-05	1,48E-05	1,46E-05	1,48E-05

		Proton Monte Carlo (Neutron Flux)					MAXED				
	E_n	PH-INCL	INCLXX	G4-BIC	CEM	FLUKA	PH-INCL	INCLXX	G4-BIC	CEM	FLUKA
90°	Thermal	1,81E-06	1,51E-06	1,50E-06	1,63E-06	1,61E-06	1,91E-06	1,86E-06	1,76E-06	1,94E-06	1,93E-06
	Epithermal	4,40E-06	3,96E-06	4,41E-06	4,15E-06	4,34E-06	3,78E-06	3,79E-06	3,89E-06	3,69E-06	3,78E-06
	Evaporation	6,78E-06	6,35E-06	7,31E-06	6,90E-06	6,70E-06	5,95E-06	5,99E-06	5,88E-06	5,98E-06	5,82E-06
	High	3,10E-06	3,03E-06	4,62E-06	3,34E-06	4,79E-06	2,97E-06	2,91E-06	3,22E-06	2,96E-06	3,21E-06
	Total	1,61E-05	1,49E-05	1,78E-05	1,60E-05	1,74E-05	1,46E-05	1,45E-05	1,48E-05	1,46E-05	1,48E-05

Tables

	Proton MAXED (Neutron Flux)				Dev. (%)				
	E_n	Mean	Std	Std %	PH-INCL	INCLXX	G4-BIC	CEM	FLUKA
0°	Thermal	1,88E-06	7,77E-08	4,13%	4,17	24,40	25,09	15,38	17,12
	Epithermal	3,79E-06	7,31E-08	1,93%	-13,91	-4,46	-14,25	-8,77	-12,78
	Evaporation	5,93E-06	7,10E-08	1,20%	-12,60	-6,67	-18,92	-14,17	-11,52
	High	3,05E-06	1,51E-07	4,94%	-1,53	0,93	-33,91	-8,50	-36,17
	Total	1,46E-05	1,01E-07	0,69%	-8,94	-1,37	-17,94	-8,58	-15,96

	Proton MAXED (Neutron Flux)				Dev. (%)				
	E_n	Mean	Std	Std %	PH-INCL	INCLXX	G4-BIC	CEM	FLUKA
90°	Thermal	1,70E-06	7,02E-08	4,12%	-37,46	-24,78	-24,61	-29,74	-28,74
	Epithermal	3,01E-06	6,45E-08	2,14%	-19,97	-9,28	-15,81	-12,59	-14,05
	Evaporation	4,30E-06	2,88E-08	0,67%	-25,80	-17,45	-22,56	-22,08	-19,62
	High	4,36E-07	6,17E-08	14,17%	-0,53	-6,74	-20,14	7,96	24,13
	Total	9,45E-06	4,27E-08	0,45%	-25,70	-16,07	-20,81	-19,85	-18,49

Tables

		Proton Monte Carlo (Neutron H*(10) [pSv])					MAXED [pSv]				
	E_n	PH-INCL	INCLXX	G4-BIC	CEM	FLUKA	PH-INCL	INCLXX	G4-BIC	CEM	FLUKA
0°	Thermal	2,12E-05	1,77E-05	1,72E-05	1,94E-05	1,90E-05	2,27E-05	2,19E-05	2,04E-05	2,32E-05	2,30E-05
	Epithermal	9,20E-05	8,75E-05	9,88E-05	9,03E-05	9,50E-05	7,43E-05	7,64E-05	7,72E-05	7,45E-05	7,49E-05
	Evaporation	2,16E-03	2,02E-03	2,33E-03	2,20E-03	2,12E-03	2,00E-03	2,02E-03	2,00E-03	2,00E-03	1,98E-03
	High	9,89E-04	9,45E-04	1,40E-03	1,03E-03	1,41E-03	9,65E-04	9,28E-04	1,02E-03	9,29E-04	9,84E-04
	Total	3,26E-03	3,07E-03	3,85E-03	3,34E-03	3,64E-03	3,06E-03	3,05E-03	3,12E-03	3,03E-03	3,06E-03

		Proton Monte Carlo (Neutron H*(10) [pSv])					MAXED [pSv]				
	E_n	PH-INCL	INCLXX	G4-BIC	CEM	FLUKA	PH-INCL	INCLXX	G4-BIC	CEM	FLUKA
90°	Thermal	1,81E-06	1,51E-06	1,50E-06	1,63E-06	1,61E-06	1,91E-06	1,86E-06	1,76E-06	1,94E-06	1,93E-06
	Epithermal	4,40E-06	3,96E-06	4,41E-06	4,15E-06	4,34E-06	3,78E-06	3,79E-06	3,89E-06	3,69E-06	3,78E-06
	Evaporation	6,78E-06	6,35E-06	7,31E-06	6,90E-06	6,70E-06	5,95E-06	5,99E-06	5,88E-06	5,98E-06	5,82E-06
	High	3,10E-06	3,03E-06	4,62E-06	3,34E-06	4,79E-06	2,97E-06	2,91E-06	3,22E-06	2,96E-06	3,21E-06
	Total	1,61E-05	1,49E-05	1,78E-05	1,60E-05	1,74E-05	1,46E-05	1,45E-05	1,48E-05	1,46E-05	1,48E-05

Tables

	Proton MAXED (Neutron H*(10) [pSv])				Dev. (%)				
	E_n	Mean	Std	Std %	PH-INCL	INCLXX	G4-BIC	CEM	FLUKA
0°	Thermal	2,22E-05	1,13E-06	5,10%	4,68	25,84	29,00	14,74	17,29
	Epithermal	7,54E-05	1,28E-06	1,69%	-18,04	-13,80	-23,66	-16,46	-20,62
	Evaporation	2,00E-03	1,50E-05	0,75%	-7,27	-0,80	-14,15	-9,19	-5,44
	High	9,66E-04	3,95E-05	4,09%	-2,39	2,15	-31,26	-5,84	-31,54
	Total	3,06E-03	3,44E-05	1,12%	-6,02	-0,11	-20,44	-8,22	-15,83

	Proton MAXED (Neutron H*(10) [pSv])				Dev. (%)				
	E_n	Mean	Std	Std %	PH-INCL	INCLXX	G4-BIC	CEM	FLUKA
90°	Thermal	2,02E-05	1,03E-06	5,07%	-36,21	-22,80	-21,04	-29,11	-27,65
	Epithermal	5,64E-05	1,59E-06	2,82%	-23,59	-17,88	-23,23	-16,97	-18,73
	Evaporation	1,48E-03	6,67E-06	0,45%	-23,69	-14,49	-19,41	-19,70	-15,59
	High	1,89E-04	2,85E-05	15,03%	-2,29	-6,43	-19,43	8,57	28,95
	Total	1,75E-03	2,89E-05	1,65%	-22,01	-13,91	-19,56	-17,41	-12,59

Tables

		4He Monte Carlo (Neutron Flux)							MAXED						
	E_n	QMD	INCLXX	Std Phy	CEM	FLUKA	PH-QMD	PH-INCL	QMD	INCLXX	Std Phy	CEM	FLUKA	PH-QMD	PH-INCL
0°	Thermal	6,65E-06	6,12E-06	6,73E-06	6,64E-06	7,40E-06	7,40E-06	6,92E-06	7,10E-06	6,73E-06	6,86E-06	7,82E-06	7,36E-06	7,42E-06	7,74E-06
	Epithermal	2,00E-05	1,86E-05	2,07E-05	1,77E-05	2,09E-05	1,93E-05	1,82E-05	2,22E-05	2,19E-05	2,19E-05	2,14E-05	2,21E-05	2,18E-05	2,15E-05
	Evaporation	3,76E-05	3,51E-05	4,03E-05	3,43E-05	3,68E-05	3,39E-05	3,40E-05	3,92E-05	4,17E-05	4,13E-05	3,93E-05	4,05E-05	4,02E-05	3,92E-05
	High	9,46E-05	5,39E-05	6,38E-05	9,71E-05	6,42E-05	7,06E-05	9,70E-05	1,13E-04	9,96E-05	1,03E-04	1,13E-04	1,06E-04	1,11E-04	1,14E-04
	Total	1,59E-04	1,14E-04	1,32E-04	1,56E-04	1,29E-04	1,31E-04	1,56E-04	1,82E-04	1,70E-04	1,73E-04	1,82E-04	1,76E-04	1,80E-04	1,82E-04

		4He Monte Carlo (Neutron Flux)							MAXED						
	E_n	QMD	INCLXX	Std Phy	CEM	FLUKA	PH-QMD	PH-INCL	QMD	INCLXX	Std Phy	CEM	FLUKA	PH-QMD	PH-INCL
90°	Thermal	9,67E-06	8,87E-06	9,72E-06	9,09E-06	1,07E-05	1,09E-05	9,84E-06	5,85E-06	5,80E-06	5,84E-06	6,27E-06	6,25E-06	6,26E-06	6,23E-06
	Epithermal	1,54E-05	1,41E-05	1,55E-05	1,31E-05	1,57E-05	1,50E-05	1,37E-05	8,52E-06	8,58E-06	8,54E-06	8,24E-06	8,24E-06	8,30E-06	8,25E-06
	Evaporation	2,33E-05	2,11E-05	2,31E-05	1,99E-05	2,34E-05	2,23E-05	2,17E-05	2,77E-05	2,76E-05	2,76E-05	2,78E-05	2,78E-05	2,77E-05	2,78E-05
	High	2,16E-06	2,05E-06	2,21E-06	1,79E-06	1,74E-06	1,66E-06	1,67E-06	2,86E-06	2,81E-06	2,91E-06	2,55E-06	2,42E-06	2,36E-06	2,36E-06
	Total	5,05E-05	4,62E-05	5,05E-05	4,38E-05	5,16E-05	4,99E-05	4,70E-05	4,49E-05	4,48E-05	4,49E-05	4,48E-05	4,47E-05	4,46E-05	4,46E-05

Tables

	4He MAXED (Neutron Flux)				Dev. (%)						
	E_n	Mean	Std	Std %	G4-QMD	G4-INCLXX	G4-BIC	CEM	FLUKA	PH-QMD	PH-INCL
0°	Thermal	7,29E-06	4,16E-07	5,70%	9,58	19,09	8,39	9,81	-1,44	-1,48	5,27
	Epithermal	2,18E-05	3,03E-07	1,39%	8,96	17,39	5,51	22,99	4,23	13,18	19,94
	Evaporation	4,02E-05	1,01E-06	2,51%	6,91	14,43	-0,23	17,37	9,18	18,51	18,23
	High	1,09E-04	5,70E-06	5,25%	14,73	101,20	70,14	11,77	69,13	53,69	11,84
	Total	1,78E-04	4,95E-06	2,78%	11,94	56,30	35,25	14,19	37,52	35,53	13,89

	4He MAXED (Neutron Flux)				Dev. (%)						
	E_n	Mean	Std	Std %	G4-QMD	G4-INCLXX	G4-BIC	CEM	FLUKA	PH-QMD	PH-INCL
90°	Thermal	6,07E-06	2,30E-07	3,78%	-37,21	-31,58	-37,51	-33,23	-43,44	-44,37	-38,31
	Epithermal	8,38E-06	1,57E-07	1,88%	-45,52	-40,66	-45,97	-35,85	-46,51	-44,07	-39,03
	Evaporation	2,77E-05	7,37E-08	0,27%	18,92	31,12	20,02	39,17	18,29	24,15	27,60
	High	2,61E-06	2,44E-07	9,36%	20,74	27,35	18,11	45,92	50,21	57,15	55,99
	Total	4,48E-05	1,30E-07	0,29%	-11,38	-3,06	-11,40	2,07	-13,18	-10,25	-4,71

Tables

		4He Monte Carlo (Neutron H*(10) [pSv])							MAXED [pSv]						
	E_n	G4-QMD	G4-INCLXX	G4-BIC	CEM	FLUKA	PH-QMD	PH-INCL	G4-QMD	G4-INCLXX	G4-BIC	CEM	FLUKA	PH-QMD	PH-INCL
0°	Thermal	7,64E-05	7,02E-05	7,72E-05	7,88E-05	8,73E-05	8,70E-05	8,14E-05	7,68E-05	7,15E-05	7,33E-05	8,74E-05	8,04E-05	8,11E-05	8,60E-05
	Epithermal	4,55E-04	4,23E-04	4,73E-04	3,97E-04	4,64E-04	4,16E-04	3,94E-04	5,89E-04	6,10E-04	6,06E-04	5,60E-04	6,05E-04	5,83E-04	5,44E-04
	Evaporation	1,21E-02	1,13E-02	1,29E-02	1,10E-02	1,18E-02	1,08E-02	1,09E-02	1,10E-02	1,15E-02	1,14E-02	1,10E-02	1,10E-02	1,09E-02	1,10E-02
	High	2,57E-02	1,53E-02	1,80E-02	2,65E-02	1,80E-02	1,94E-02	2,66E-02	3,05E-02	2,77E-02	2,84E-02	3,07E-02	2,92E-02	2,98E-02	3,09E-02
	Total	3,84E-02	2,70E-02	3,14E-02	3,80E-02	3,03E-02	3,07E-02	3,79E-02	4,22E-02	3,99E-02	4,05E-02	4,24E-02	4,10E-02	4,14E-02	4,25E-02

		4He Monte Carlo (Neutron H*(10) [pSv])							MAXED [pSv]						
	E_n	G4-QMD	G4-INCLXX	G4-BIC	CEM	FLUKA	PH-QMD	PH-INCL	G4-QMD	G4-INCLXX	G4-BIC	CEM	FLUKA	PH-QMD	PH-INCL
90°	Thermal	1,10E-04	1,01E-04	1,10E-04	1,07E-04	1,26E-04	1,27E-04	1,15E-04	6,83E-05	6,75E-05	6,81E-05	7,46E-05	7,43E-05	7,43E-05	7,38E-05
	Epithermal	3,13E-04	2,87E-04	3,15E-04	2,57E-04	3,08E-04	2,93E-04	2,68E-04	2,07E-04	2,07E-04	2,07E-04	1,96E-04	1,95E-04	1,96E-04	1,92E-04
	Evaporation	7,72E-03	6,96E-03	7,60E-03	6,61E-03	7,70E-03	7,40E-03	7,22E-03	9,30E-03	9,26E-03	9,28E-03	9,33E-03	9,33E-03	9,33E-03	9,35E-03
	High	9,47E-04	8,73E-04	9,60E-04	7,74E-04	7,47E-04	7,39E-04	7,42E-04	1,21E-03	1,16E-03	1,22E-03	1,07E-03	1,01E-03	1,01E-03	1,01E-03
	Total	9,09E-03	8,22E-03	8,98E-03	7,74E-03	8,88E-03	8,56E-03	8,35E-03	1,08E-02	1,07E-02	1,08E-02	1,07E-02	1,06E-02	1,06E-02	1,06E-02

Tables

	4He MAXED (Neutron H*(10) [pSv])				Dev. (%)						
	E_n	Mean	Std	Std %	G4-QMD	G4-INCLXX	G4-BIC	CEM	FLUKA	PH-QMD	PH-INCL
0°	Thermal	7,95E-05	6,05E-06	7,60%	4,11	13,20	3,00	0,92	-8,99	-8,58	-2,37
	Epithermal	5,85E-04	2,50E-05	4,27%	28,72	38,25	23,73	47,34	26,20	40,81	48,39
	Evaporation	1,11E-02	2,15E-04	1,93%	-7,91	-1,16	-14,04	0,96	-5,55	2,55	2,24
	High	2,96E-02	1,22E-03	4,11%	15,02	93,89	64,87	11,81	64,48	52,73	11,45
	Total	4,14E-02	1,02E-03	2,46%	7,94	53,22	31,64	9,01	36,49	34,69	9,17

	4He MAXED (Neutron H*(10) [pSv])				Dev. (%)						
	E_n	Mean	Std	Std %	G4-QMD	G4-INCLXX	G4-BIC	CEM	FLUKA	PH-QMD	PH-INCL
90°	Thermal	7,16E-05	3,39E-06	4,73%	-34,81	-28,97	-35,13	-33,13	-43,03	-43,72	-37,63
	Epithermal	2,00E-04	6,65E-06	3,33%	-36,13	-30,39	-36,65	-22,13	-35,03	-31,81	-25,56
	Evaporation	9,31E-03	3,14E-05	0,34%	20,65	33,80	22,56	40,92	20,99	25,86	28,92
	High	1,10E-03	9,68E-05	8,81%	16,05	25,85	14,52	41,99	47,06	48,63	48,06
	Total	1,07E-02	7,66E-05	0,72%	17,55	29,95	18,91	37,92	20,34	24,82	27,95