



Displacement damage, helium and hydrogen production in different materials irradiated in STIP-VI

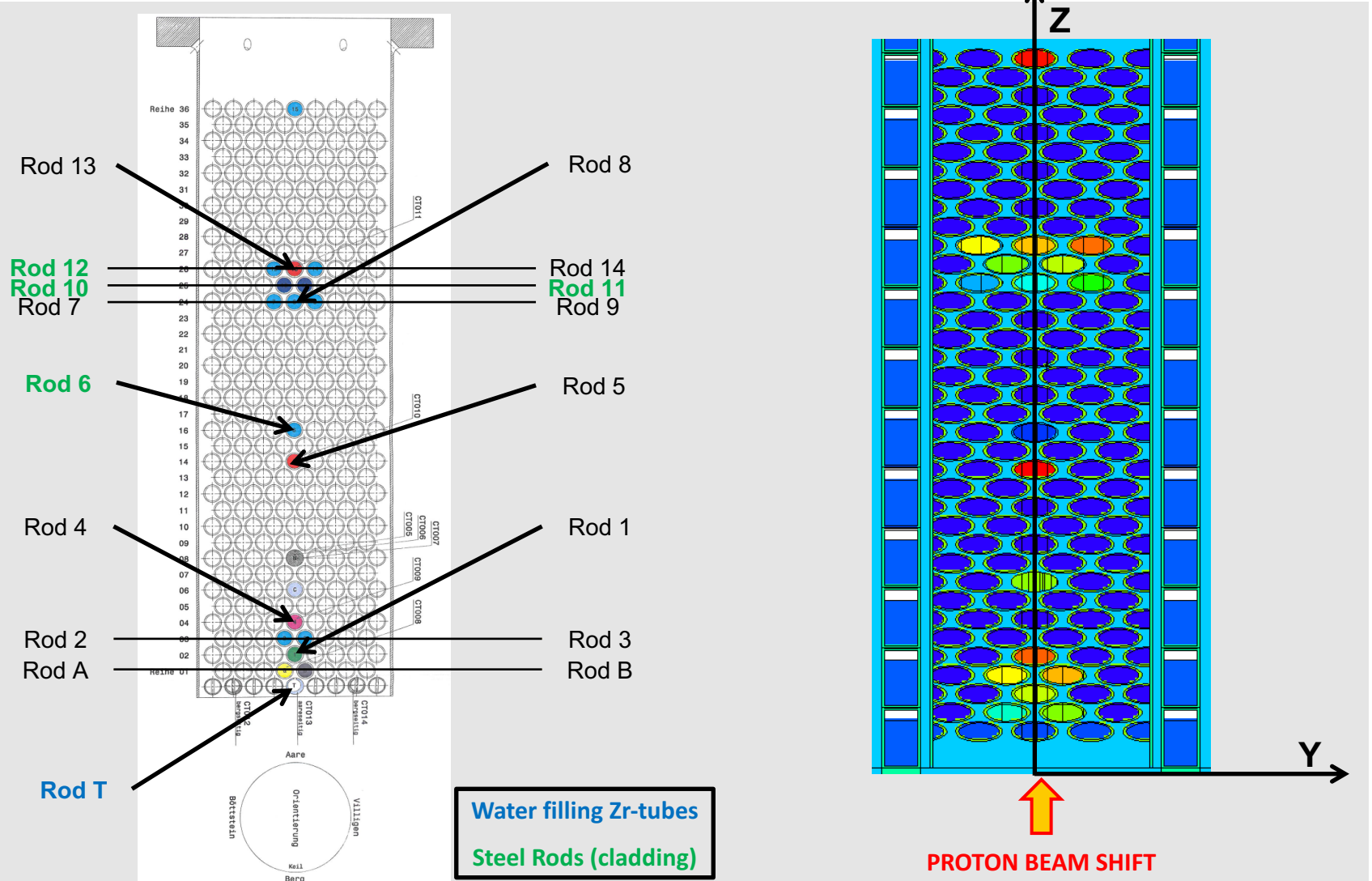
David Aulet, Ryan Bergmann, Michael Wohlmuther, Yong Dai

Laboratory for Nuclear Materials, Paul Scherrer Institut

IWSMT-13, 04.11.2016, Chattanooga, USA

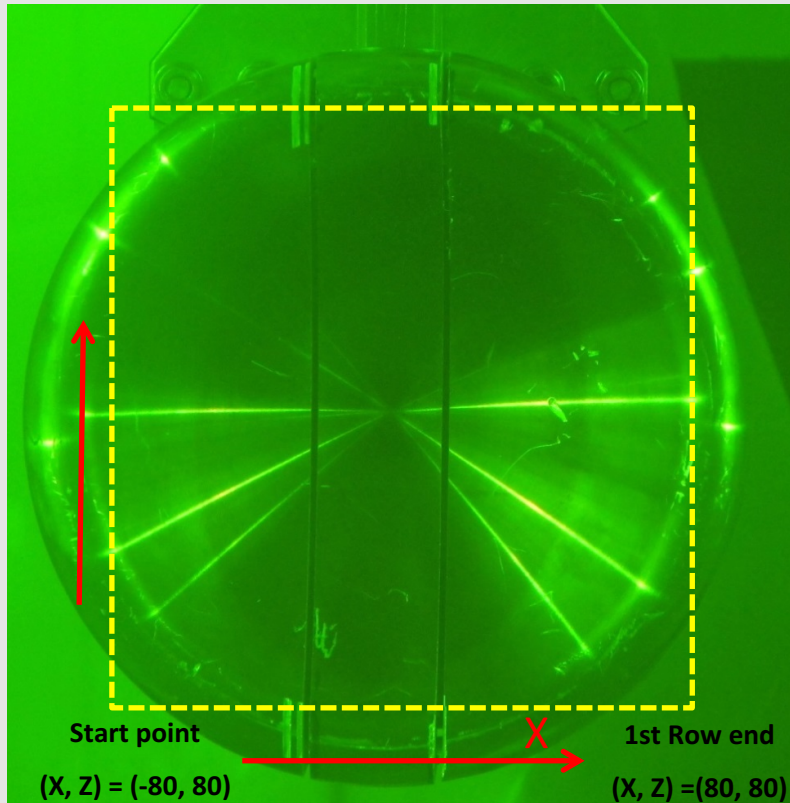
STIP VI – TARGET 9. ROD'S POSITION

2

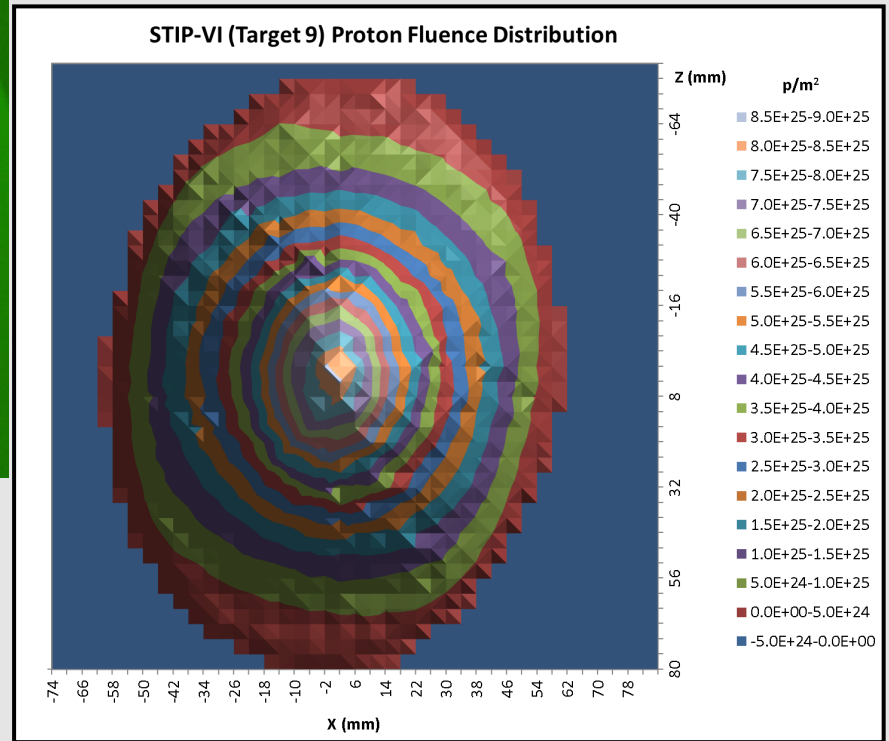


STIP VI – TARGET 9. GAMMA – MAPPING

2

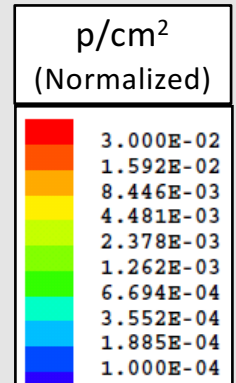
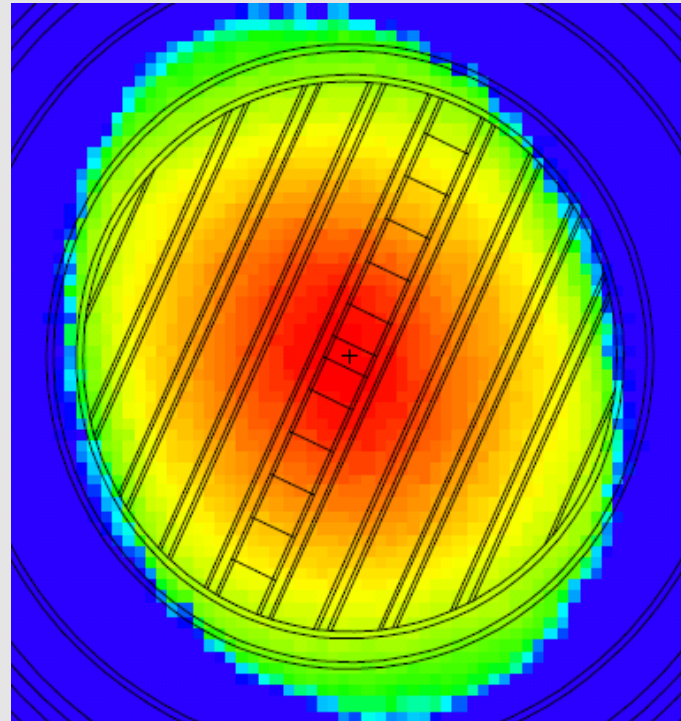
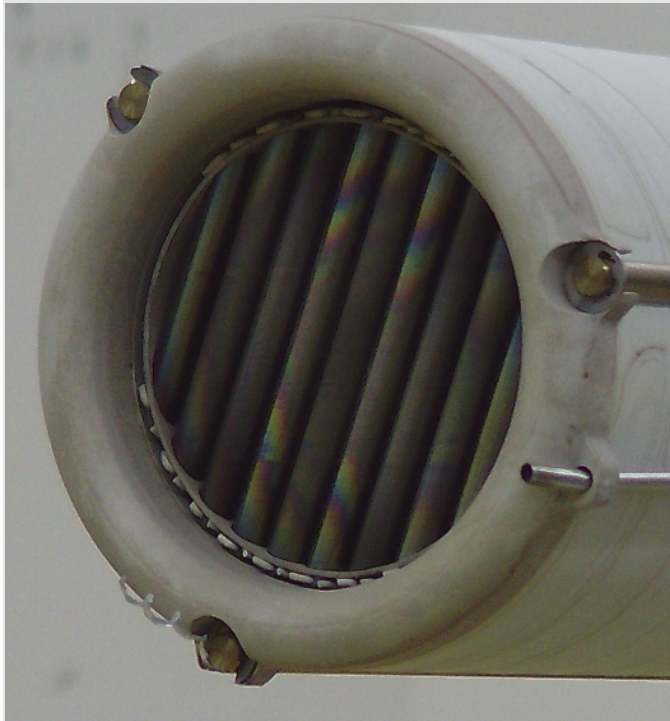


1. Na-22 Net Counts
2. Geometry Corrections
3. Convert Factors -> **PROTON FLUENCE**



- PROTON FLUENCE DISTRIBUTION

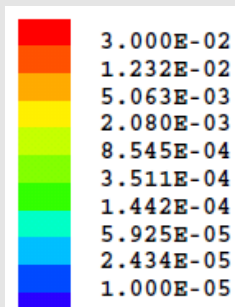
Proton fluence (p/m^2) in XY plane (cm)



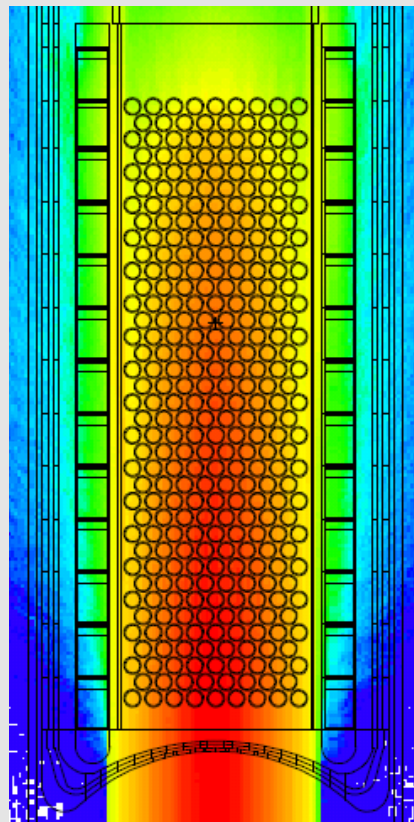
BOTTOM VIEW

- PROTON AND NEUTRON FLUENCE OVER THE TARGET

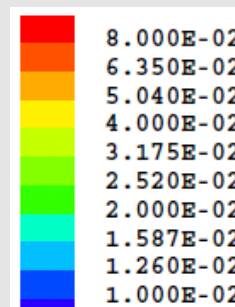
Protons



Units (normalized)
p/cm²

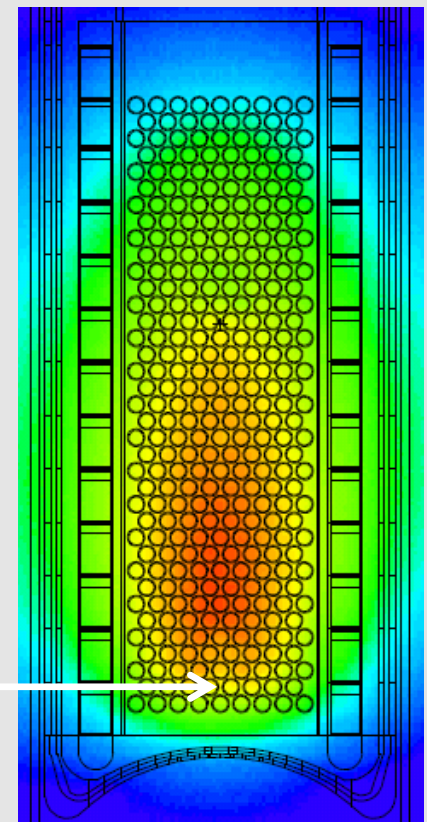


Neutrons

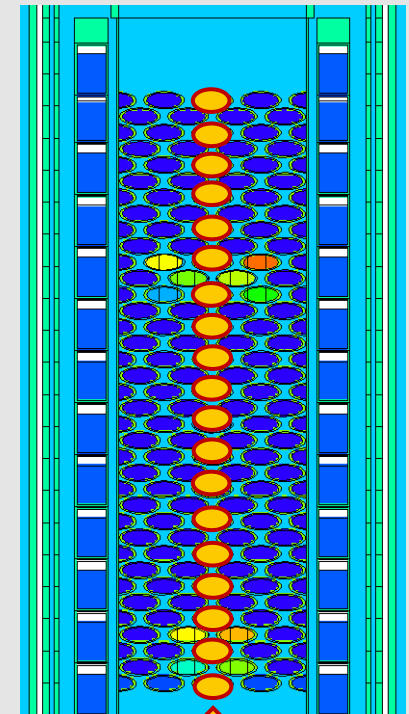
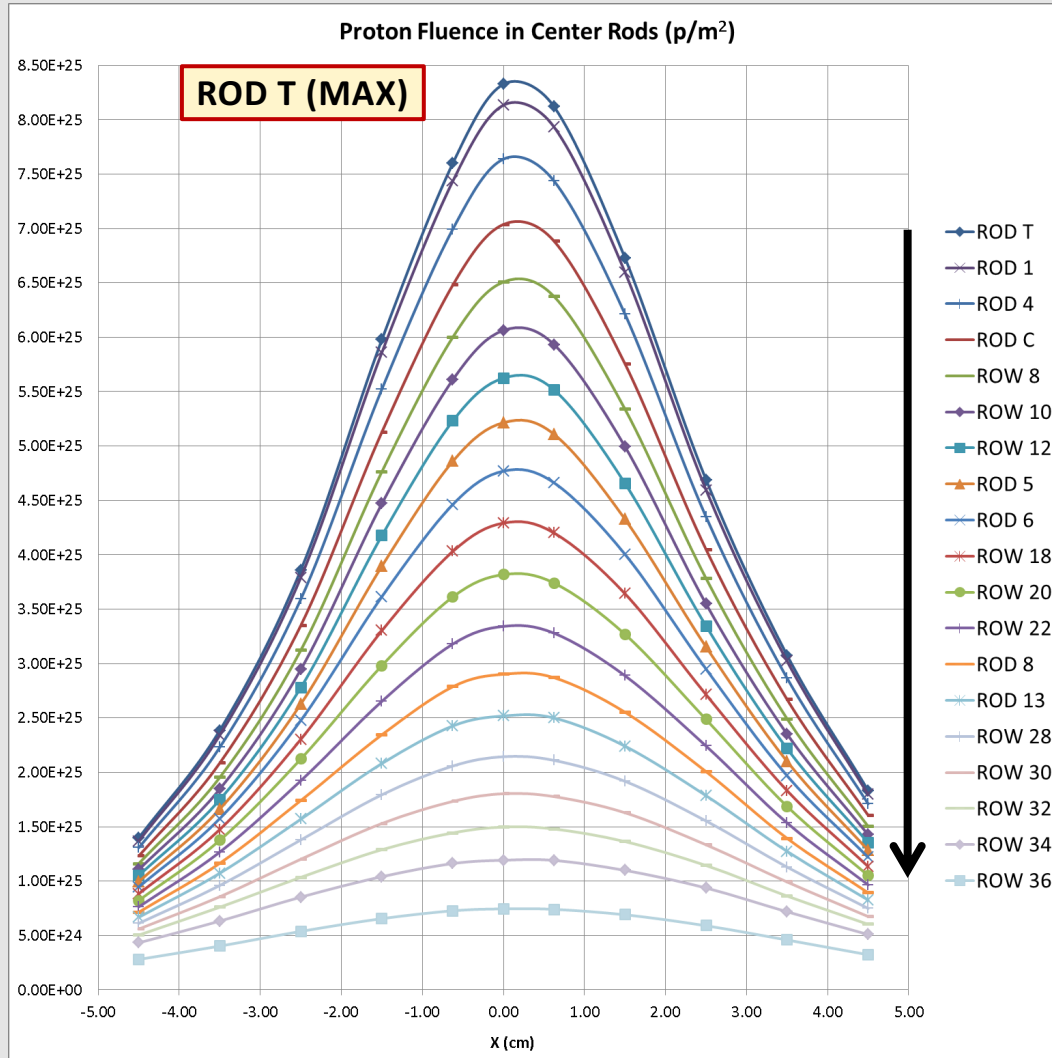


Units (normalized)
n/cm²

Spallation starts



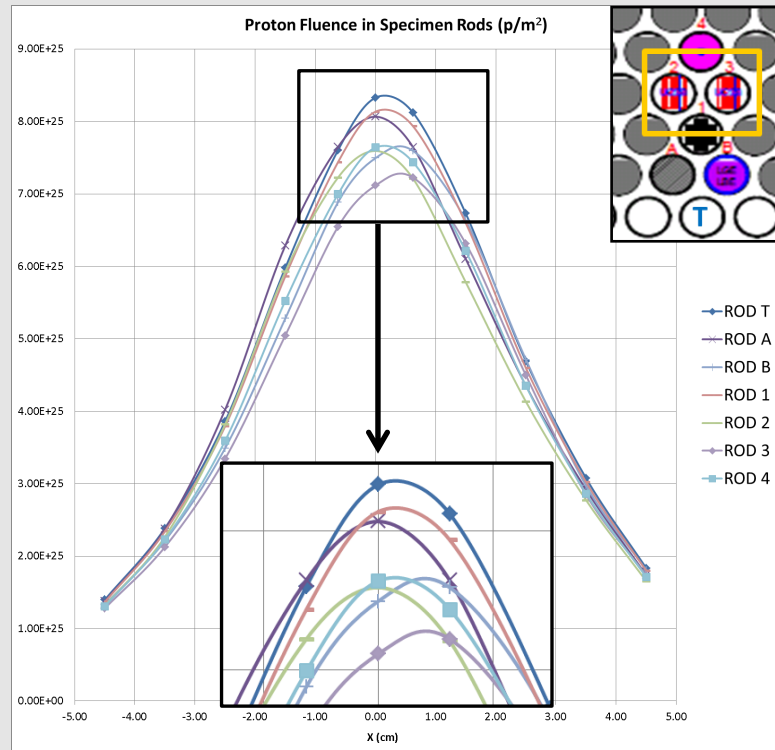
- PROTON FLUENCE DISTRIBUTION OF CENTER RODS



Center Rods

- PROTON FLUENCE DISTRIBUTION OF SPECIMEN RODS

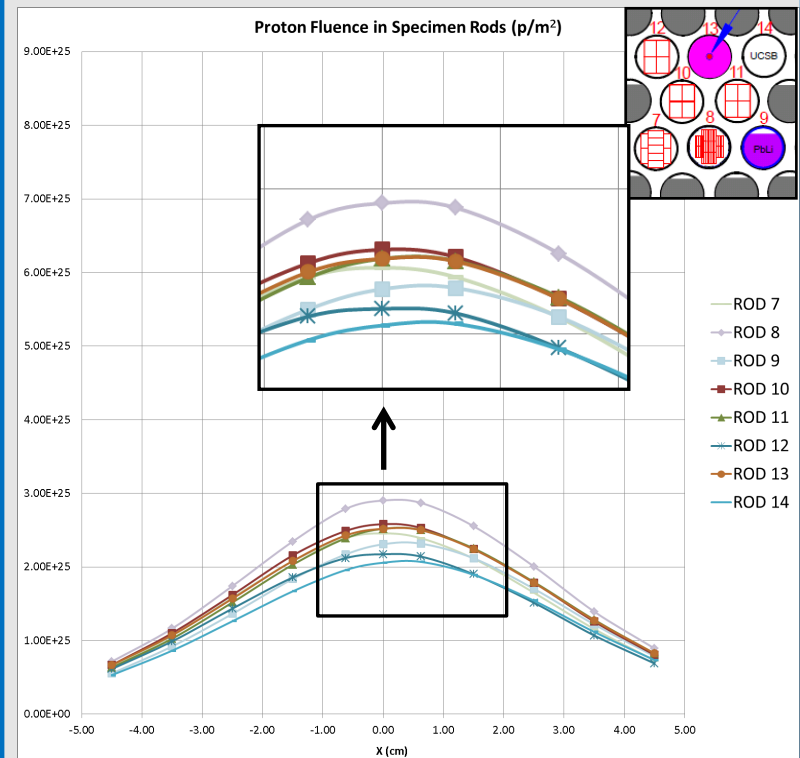
Lower part of the target



BEAM SHIFT
 Fluence: Rod A > Rod B
 Fluence: Rod 2 > Rod 3

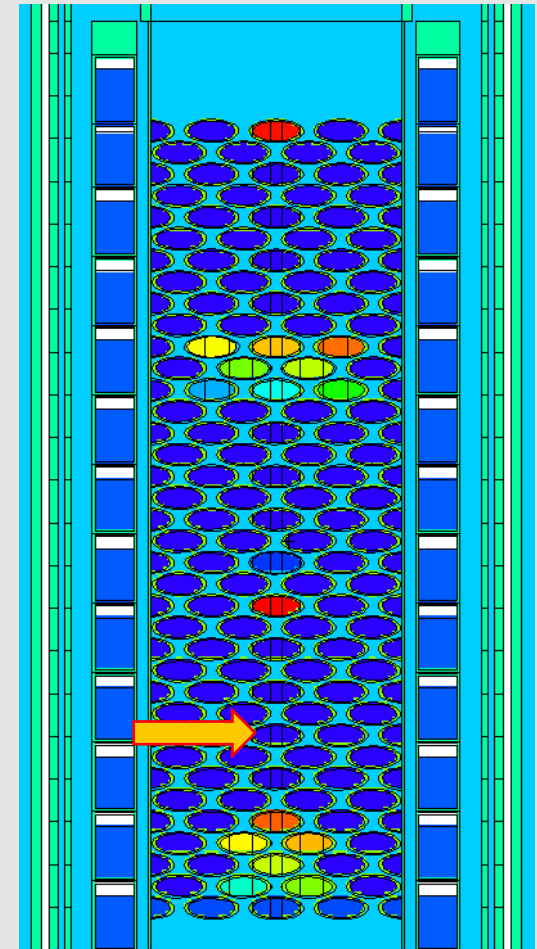
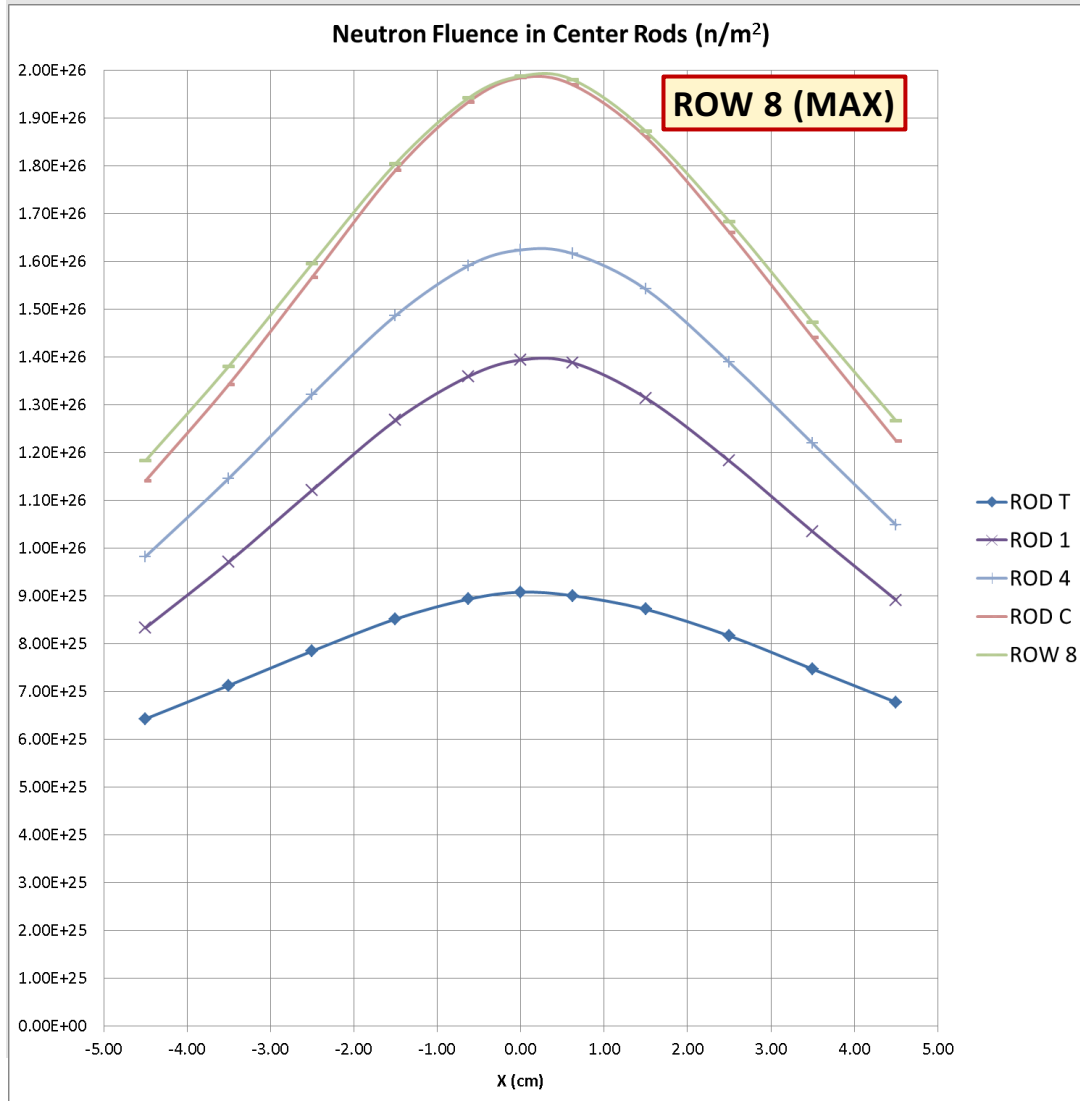
Geometrical position (center)
 Fluence: Rod 1 > Rod A&B
 Fluence: Rod 4 > Rod 2&3

Upper part of the target



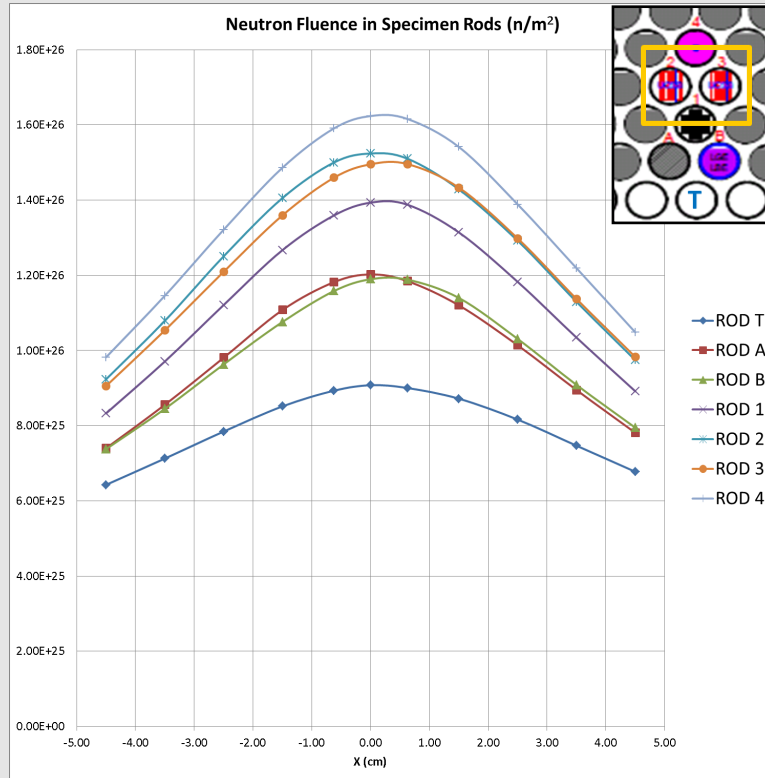
Geometrical position (center)
 Fluence: Rod 8 > Rod 7&9
 Fluence: Rod 10&11 > Rod 7&9
 Fluence: Rod 13 > Rod 12&14

- NEUTRON FLUENCE DISTRIBUTION OF CENTER RODS

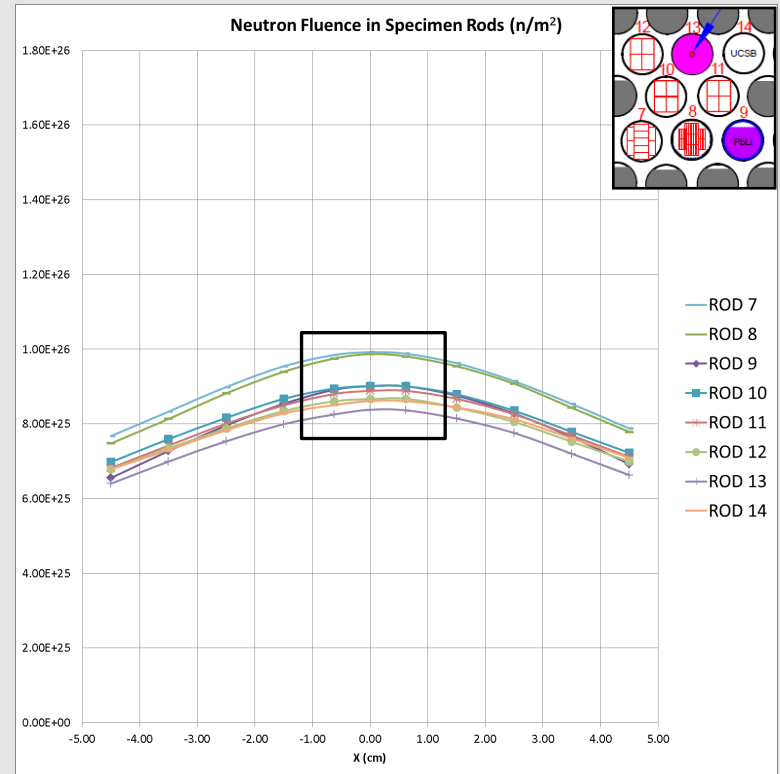


- NEUTRON FLUENCE DISTRIBUTION OF SPECIMEN RODS

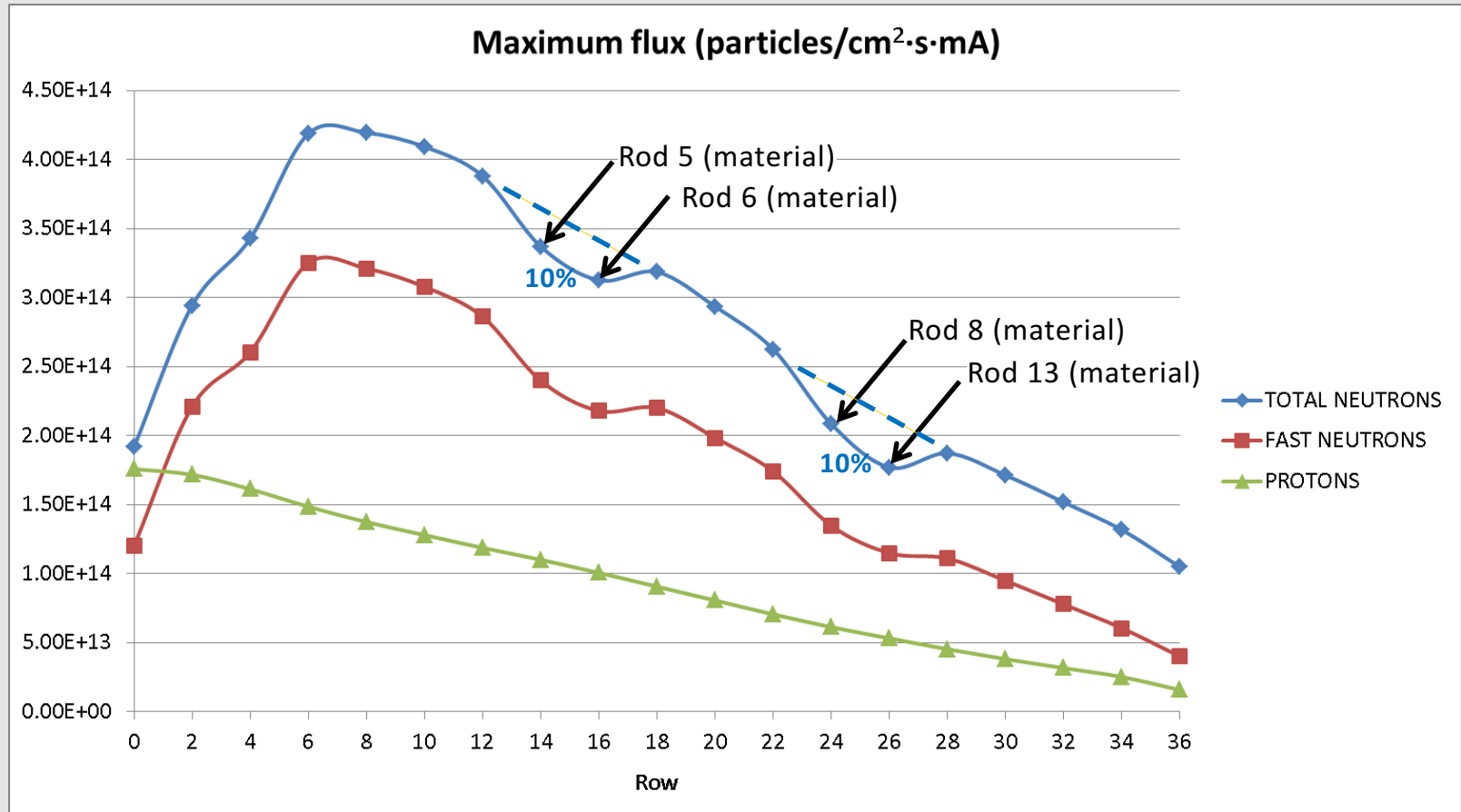
Lower part of the target



Upper part of the target

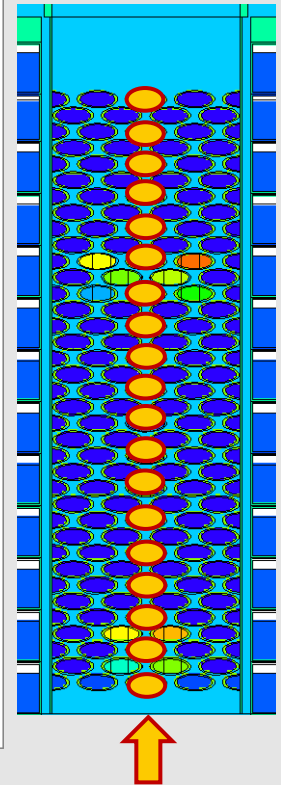
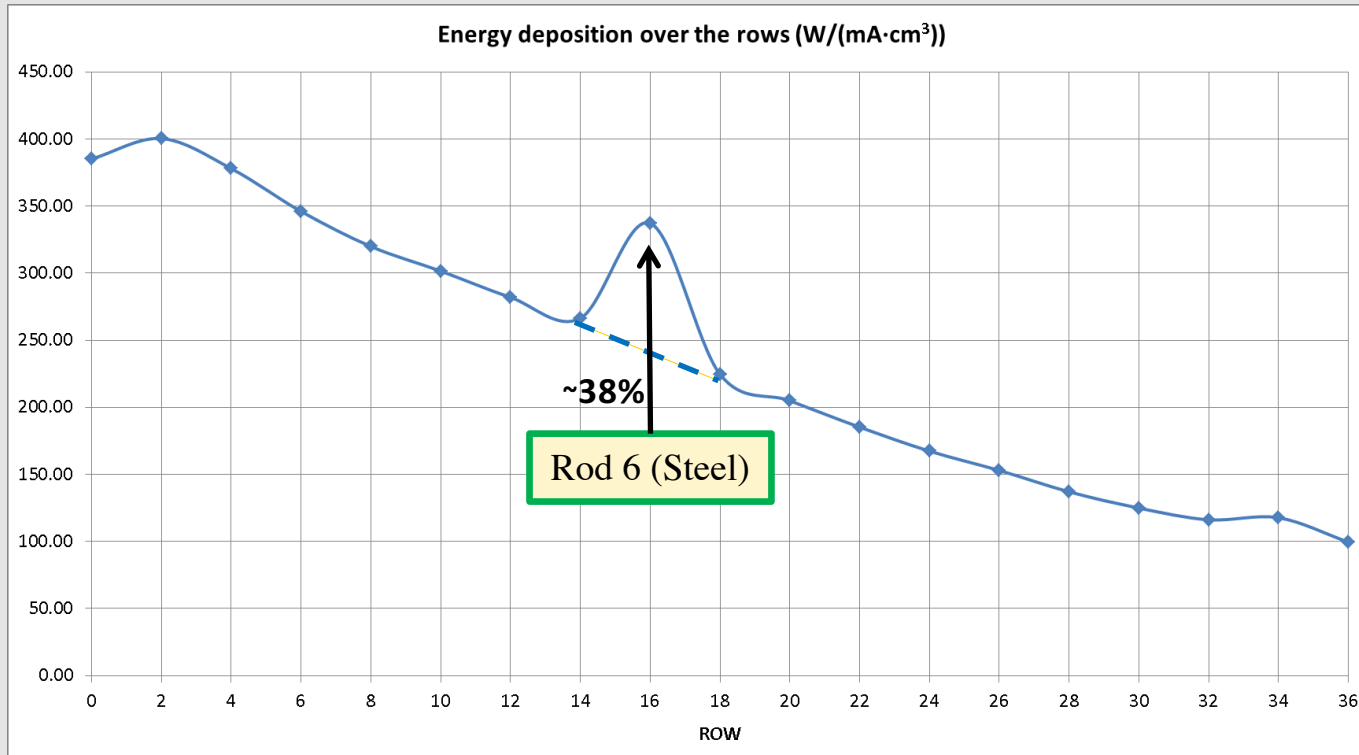


- MAXIMUM PROTON AND NEUTRON FLUX



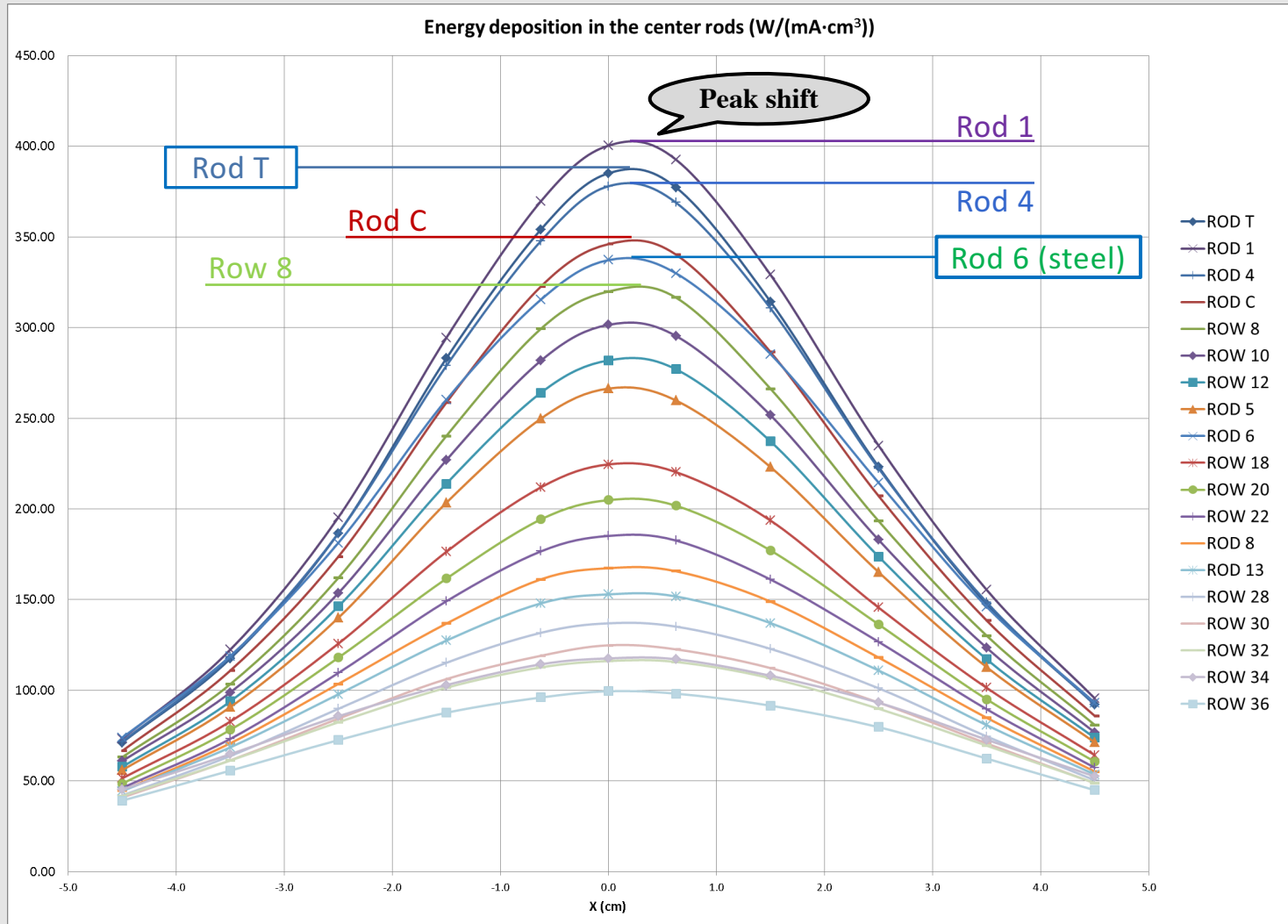
ENERGY DEPOSITION IN **CLADDING TUBES** OF CENTRAL RODS

Maximum energy deposition in the center rods

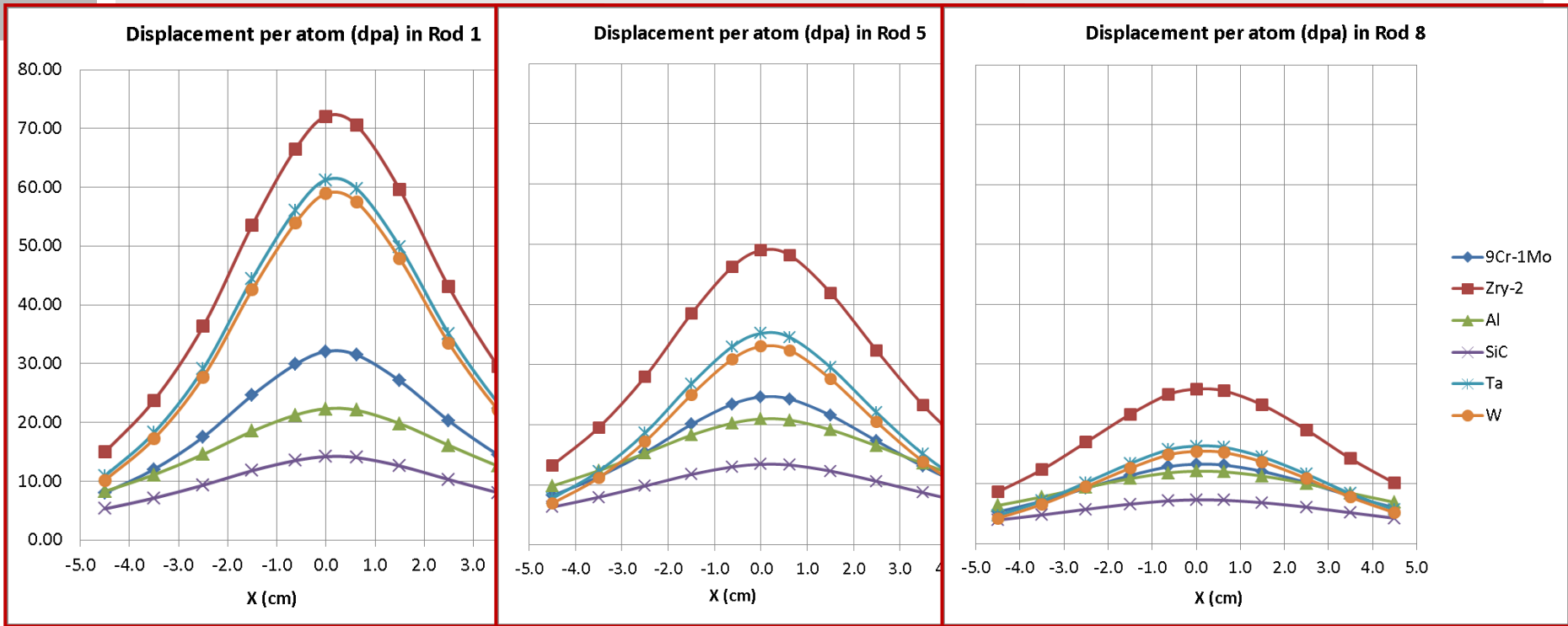


Center Rods

- ENERGY DEPOSITION IN THE **CLADDING TUBES** OF CENTER RODS



- DISPLACEMENT DAMAGE (ROD 1, ROD 5, ROD 8)

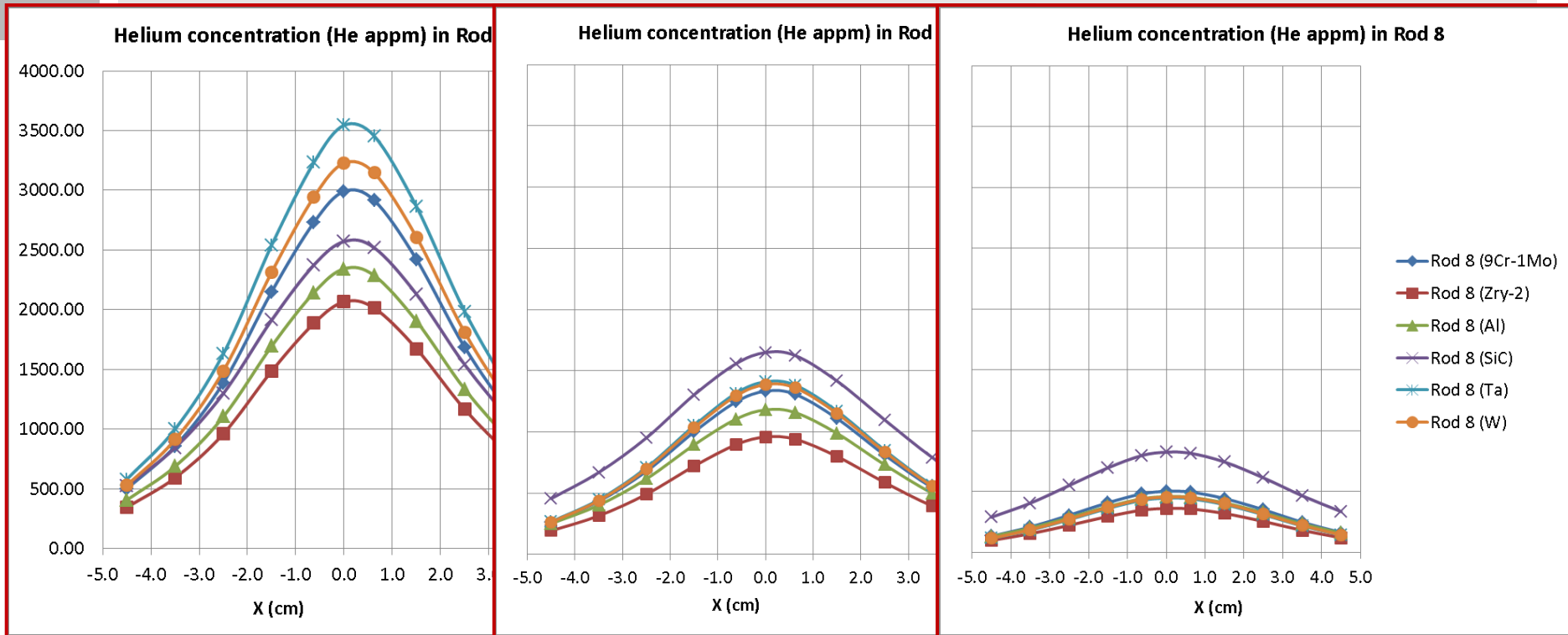


ROD 1

ROD 5

ROD 8

- **HELIUM CONCENTRATION (ROD 1, ROD 5 AND ROD 8)**

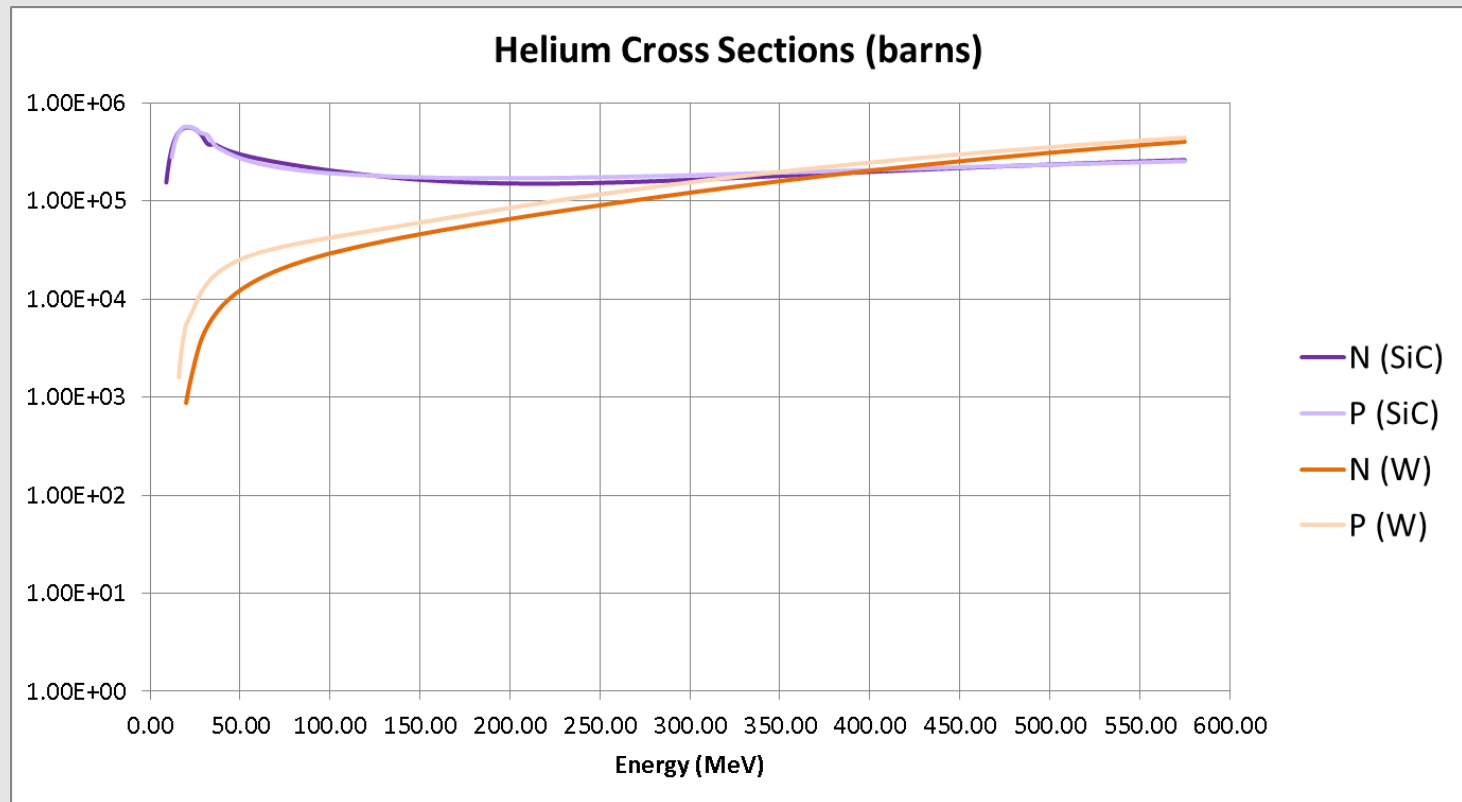


ROD 1

ROD 5

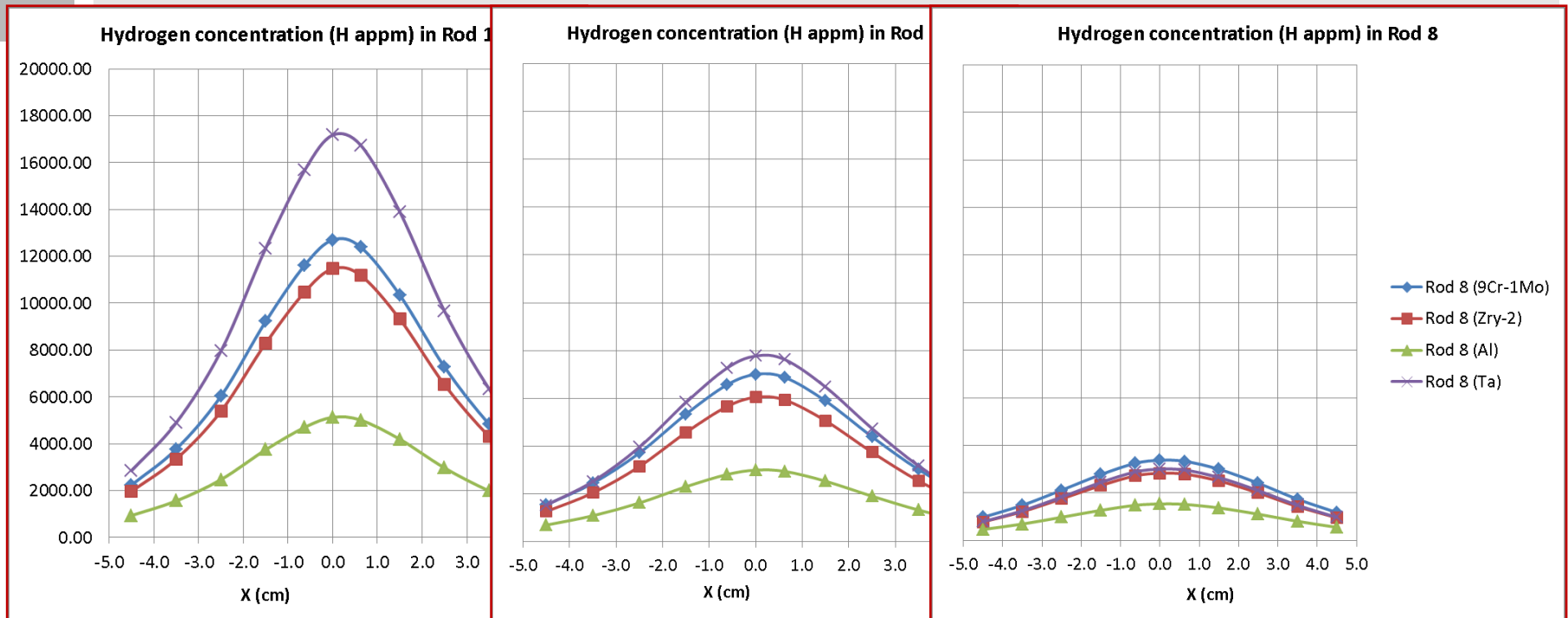
ROD 8

- **HELIUM CROSS SECTION**



Data source: W. Lu

- **HYDROGEN CONCENTRATION (ROD 1, ROD 5 AND ROD 8)**



ROD 1

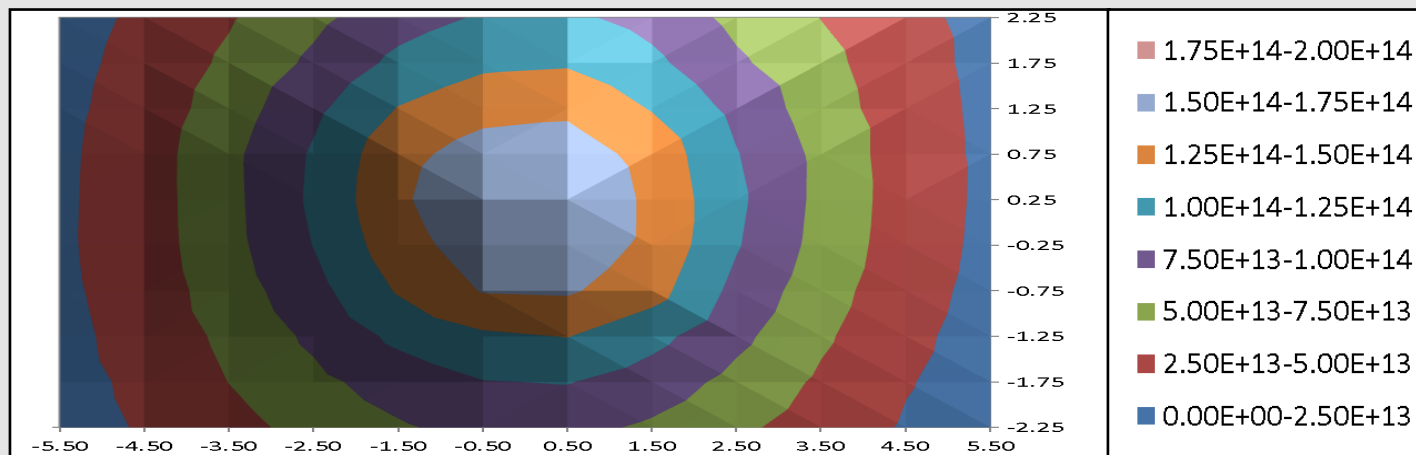
ROD 5

ROD 8

- CALOTTE. PROTON FLUX

Proton flux ($p/(cm^2 \cdot s \cdot mA)$) vs XY plane (cm)

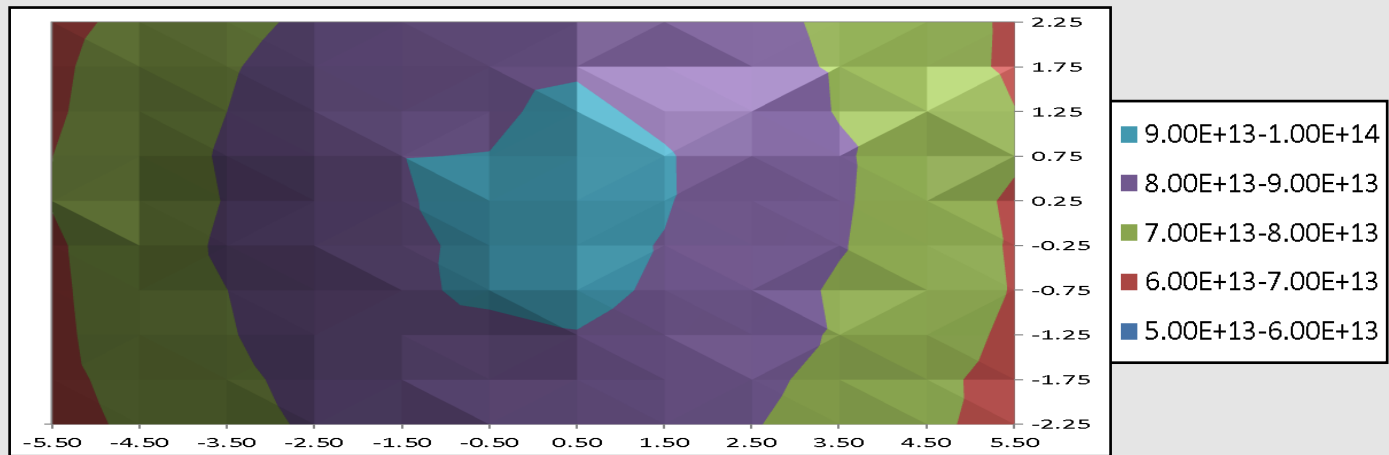
Y \ X	-5.50	-4.50	-3.50	-2.50	-1.50	-0.50	0.50	1.50	2.50	3.50	4.50	5.50
2.25	1.57E+13	2.93E+13	4.76E+13	6.90E+13	8.98E+13	1.02E+14	1.04E+14	9.18E+13	6.84E+13	4.94E+13	3.11E+13	1.79E+13
1.75	1.78E+13	3.25E+13	5.46E+13	7.99E+13	1.06E+14	1.20E+14	1.22E+14	1.05E+14	7.89E+13	5.73E+13	3.42E+13	1.83E+13
1.25	1.94E+13	3.53E+13	6.21E+13	9.44E+13	1.26E+14	1.41E+14	1.45E+14	1.23E+14	9.33E+13	6.20E+13	3.62E+13	1.93E+13
0.75	2.06E+13	3.79E+13	6.88E+13	1.03E+14	1.42E+14	1.61E+14	1.63E+14	1.41E+14	1.01E+14	6.87E+13	3.63E+13	2.03E+13
0.25	2.11E+13	3.82E+13	6.82E+13	1.04E+14	1.46E+14	1.71E+14	1.73E+14	1.45E+14	1.05E+14	6.85E+13	3.80E+13	1.99E+13
-0.25	2.13E+13	3.79E+13	6.71E+13	1.01E+14	1.40E+14	1.63E+14	1.65E+14	1.45E+14	1.02E+14	6.65E+13	3.69E+13	1.92E+13
-0.75	2.04E+13	3.58E+13	6.25E+13	9.16E+13	1.27E+14	1.51E+14	1.53E+14	1.35E+14	9.27E+13	6.06E+13	3.40E+13	1.77E+13
-1.25	1.83E+13	3.40E+13	5.55E+13	8.00E+13	1.06E+14	1.21E+14	1.26E+14	1.08E+14	8.12E+13	5.40E+13	3.04E+13	1.57E+13
-1.75	1.71E+13	2.99E+13	5.03E+13	6.88E+13	8.60E+13	9.91E+13	1.01E+14	8.84E+13	6.77E+13	4.60E+13	2.65E+13	1.41E+13
-2.25	1.59E+13	2.70E+13	4.13E+13	5.86E+13	7.23E+13	8.30E+13	8.19E+13	7.12E+13	5.50E+13	3.82E+13	2.27E+13	1.26E+13



- CALOTTE. NEUTRON FLUX**

Neutron flux (p/(cm²·s·mA)) vs XY plane (cm)

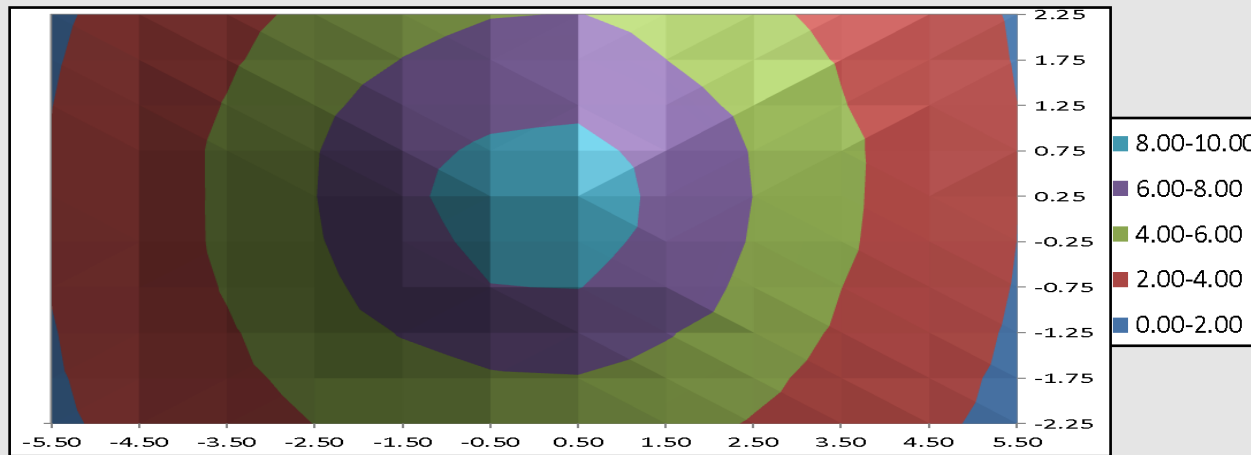
Y \ X	-5.50	-4.50	-3.50	-2.50	-1.50	-0.50	0.50	1.50	2.50	3.50	4.50	5.50
2.25	6.79E+13	7.19E+13	7.73E+13	8.18E+13	8.48E+13	8.67E+13	8.84E+13	8.65E+13	8.21E+13	7.85E+13	7.26E+13	6.91E+13
1.75	6.87E+13	7.35E+13	7.92E+13	8.40E+13	8.64E+13	8.87E+13	8.94E+13	8.61E+13	8.28E+13	7.92E+13	7.27E+13	6.90E+13
1.25	6.91E+13	7.39E+13	8.00E+13	8.52E+13	8.76E+13	8.93E+13	9.12E+13	8.87E+13	8.56E+13	7.94E+13	7.49E+13	7.01E+13
0.75	6.99E+13	7.46E+13	8.11E+13	8.64E+13	8.99E+13	9.01E+13	9.18E+13	9.05E+13	8.68E+13	8.14E+13	7.40E+13	7.10E+13
0.25	7.03E+13	7.39E+13	8.05E+13	8.61E+13	8.97E+13	9.14E+13	9.24E+13	9.05E+13	8.58E+13	8.11E+13	7.45E+13	6.88E+13
-0.25	6.89E+13	7.47E+13	8.15E+13	8.60E+13	8.89E+13	9.13E+13	9.19E+13	8.97E+13	8.50E+13	8.06E+13	7.41E+13	6.93E+13
-0.75	6.86E+13	7.44E+13	7.99E+13	8.46E+13	8.87E+13	9.15E+13	9.20E+13	8.89E+13	8.45E+13	7.87E+13	7.40E+13	6.96E+13
-1.25	6.83E+13	7.41E+13	7.94E+13	8.42E+13	8.70E+13	8.80E+13	8.97E+13	8.71E+13	8.30E+13	7.93E+13	7.35E+13	6.85E+13
-1.75	6.79E+13	7.28E+13	7.81E+13	8.24E+13	8.51E+13	8.64E+13	8.73E+13	8.55E+13	8.25E+13	7.67E+13	7.18E+13	6.75E+13
-2.25	6.67E+13	7.18E+13	7.64E+13	8.14E+13	8.36E+13	8.63E+13	8.54E+13	8.39E+13	8.07E+13	7.52E+13	7.13E+13	6.76E+13



- **CALOTTE. DISPLACEMENT DAMAGE**

Displacement per Atom (dpa) vs XY plane (cm)

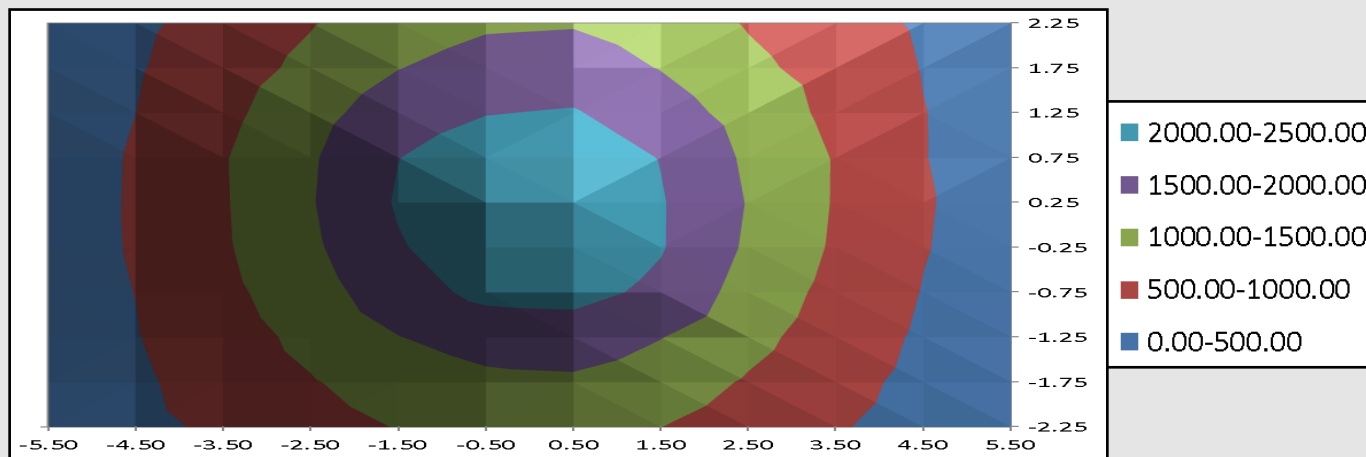
Y \ X	-5.50	-4.50	-3.50	-2.50	-1.50	-0.50	0.50	1.50	2.50	3.50	4.50	5.50
2.25	1.78	2.51	3.42	4.43	5.34	5.92	6.04	5.48	4.42	3.52	2.58	1.88
1.75	1.89	2.67	3.76	4.95	6.04	6.69	6.78	6.01	4.87	3.87	2.72	1.93
1.25	1.98	2.81	4.09	5.54	6.88	7.53	7.73	6.79	5.52	4.08	2.86	2.00
0.75	2.06	2.95	4.35	5.90	7.53	8.27	8.40	7.54	5.88	4.41	2.88	2.07
0.25	2.10	2.95	4.35	5.96	7.69	8.69	8.80	7.67	5.97	4.37	2.93	2.01
-0.25	2.07	2.96	4.33	5.81	7.43	8.39	8.46	7.61	5.83	4.29	2.90	1.99
-0.75	2.04	2.87	4.12	5.45	6.97	7.96	8.04	7.22	5.46	4.01	2.78	1.93
-1.25	1.94	2.75	3.82	4.98	6.11	6.71	6.93	6.14	4.96	3.76	2.62	1.83
-1.75	1.87	2.56	3.57	4.49	5.26	5.84	5.92	5.35	4.43	3.37	2.41	1.73
-2.25	1.76	2.39	3.17	4.02	4.66	5.19	5.11	4.63	3.88	3.01	2.22	1.64



- **CALOTTE. HELIUM CONCENTRATION**

Helium concentration (appm He) vs XY plane (cm)

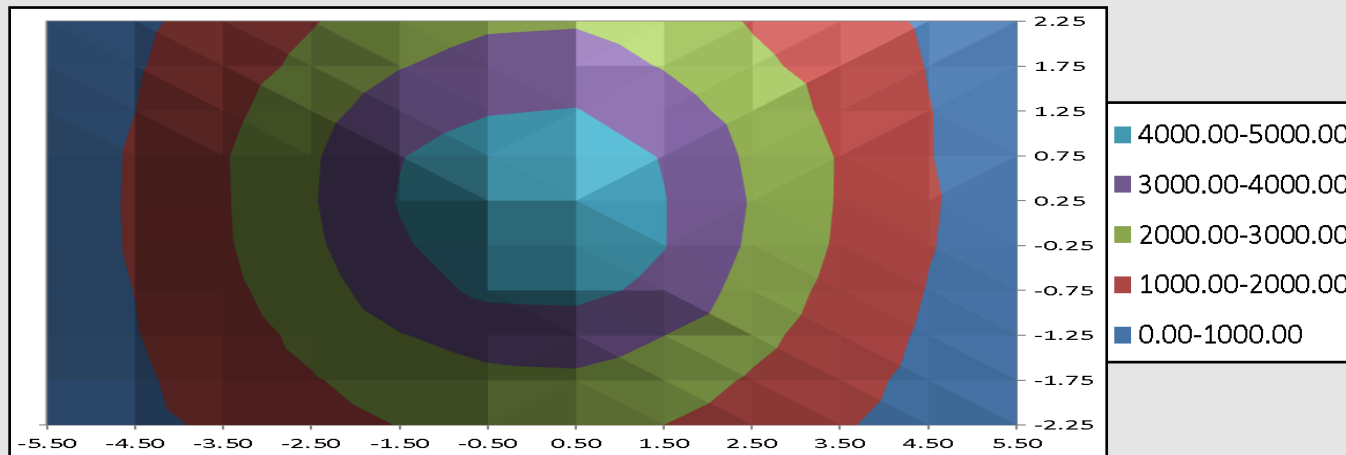
Y \ X	-5.50	-4.50	-3.50	-2.50	-1.50	-0.50	0.50	1.50	2.50	3.50	4.50	5.50
2.25	223.16	414.79	671.07	970.96	1261.91	1437.99	1466.51	1290.89	963.05	696.04	439.86	254.60
1.75	253.07	458.85	768.59	1123.11	1487.96	1685.21	1717.41	1481.30	1109.81	806.70	482.19	259.84
1.25	275.18	498.06	874.01	1325.30	1769.04	1982.28	2036.57	1733.34	1310.24	871.98	510.96	274.51
0.75	292.20	535.49	968.08	1445.66	1992.24	2261.07	2282.27	1982.25	1419.95	966.56	512.06	287.70
0.25	298.78	539.58	959.18	1467.06	2045.65	2394.30	2419.39	2032.51	1473.79	963.14	535.98	282.56
-0.25	302.69	534.57	944.07	1413.49	1958.69	2286.39	2310.66	2030.56	1430.38	936.19	521.02	272.32
-0.75	290.06	505.45	879.12	1288.15	1785.89	2124.50	2147.78	1893.98	1301.80	853.30	481.08	251.86
-1.25	260.23	479.87	781.72	1125.10	1486.21	1695.81	1763.47	1513.01	1142.28	759.64	429.43	223.27
-1.75	243.08	423.35	709.39	968.51	1209.63	1392.04	1420.23	1242.66	952.77	648.17	375.57	201.18
-2.25	225.64	381.90	582.53	826.37	1016.91	1168.33	1151.41	1002.08	774.56	539.48	321.96	179.87



- CALOTTE. HYDROGEN CONCENTRATION**

Hydrogen concentration (appm H) vs XY plane (cm)

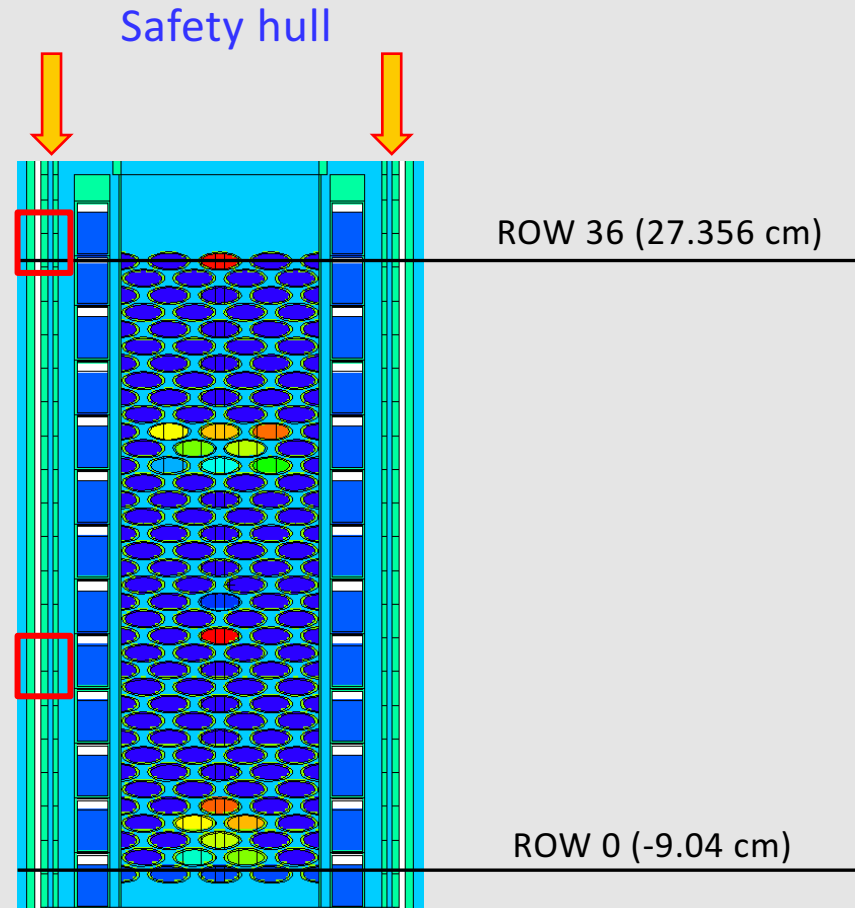
Y \ X	-5.50	-4.50	-3.50	-2.50	-1.50	-0.50	0.50	1.50	2.50	3.50	4.50	5.50
2.25	449.29	830.11	1338.55	1933.53	2509.77	2857.60	2915.82	2566.72	1917.68	1387.97	880.40	510.65
1.75	508.16	918.56	1532.42	2235.64	2956.31	3347.02	3410.66	2943.18	2208.19	1608.16	964.71	522.73
1.25	552.62	995.55	1742.30	2635.94	3513.44	3937.14	4043.10	3443.72	2605.93	1737.44	1021.45	551.25
0.75	586.28	1069.96	1926.14	2874.60	3955.80	4486.33	4529.36	3935.52	2823.86	1925.08	1024.05	577.06
0.25	599.00	1077.10	1909.91	2914.82	4059.73	4747.41	4799.78	4034.22	2928.64	1917.24	1071.28	567.41
-0.25	606.65	1067.84	1881.10	2809.36	3888.40	4533.57	4582.88	4028.81	2842.31	1864.23	1041.41	547.38
-0.75	582.14	1010.93	1752.08	2561.05	3546.70	4216.52	4261.83	3759.34	2588.15	1700.73	962.38	506.26
-1.25	523.44	959.09	1559.20	2239.13	2954.26	3368.94	3501.46	3005.34	2272.11	1516.23	860.28	449.79
-1.75	488.99	847.18	1415.55	1929.80	2403.81	2767.72	2822.58	2472.04	1896.63	1294.74	752.53	405.85
-2.25	454.23	764.24	1164.29	1647.01	2024.38	2325.14	2290.54	1995.27	1545.14	1078.78	646.04	363.84



CALOTTE AND SAFETY HULL

- **SAFETY HULL. PROTON & NEUTRON FLUX** (particles/(cm²·s·mA))

FLUX POSITION	PROTON		NEUTRON	
	OUTER	INNER	OUTER	INNER
31.725	4.13E+11	4.42E+11	6.54E+13	6.65E+13
29.325	4.70E+11	5.99E+11	7.22E+13	7.37E+13
26.225	4.29E+11	5.80E+11	8.17E+13	8.40E+13
23.125	4.04E+11	5.18E+11	9.13E+13	9.43E+13
19.875	4.08E+11	5.09E+11	1.01E+14	1.05E+14
16.625	4.20E+11	5.14E+11	1.10E+14	1.15E+14
13.375	4.24E+11	5.22E+11	1.19E+14	1.24E+14
10.125	4.04E+11	5.07E+11	1.26E+14	1.32E+14
6.875	3.69E+11	4.61E+11	1.30E+14	1.37E+14
3.625	3.14E+11	4.00E+11	1.31E+14	1.39E+14
0.375	2.41E+11	3.14E+11	1.28E+14	1.36E+14
-2.875	1.63E+11	2.17E+11	1.19E+14	1.27E+14
-6.125	9.08E+10	1.25E+11	1.05E+14	1.11E+14
-9.375	3.21E+10	4.58E+10	8.71E+13	9.09E+13



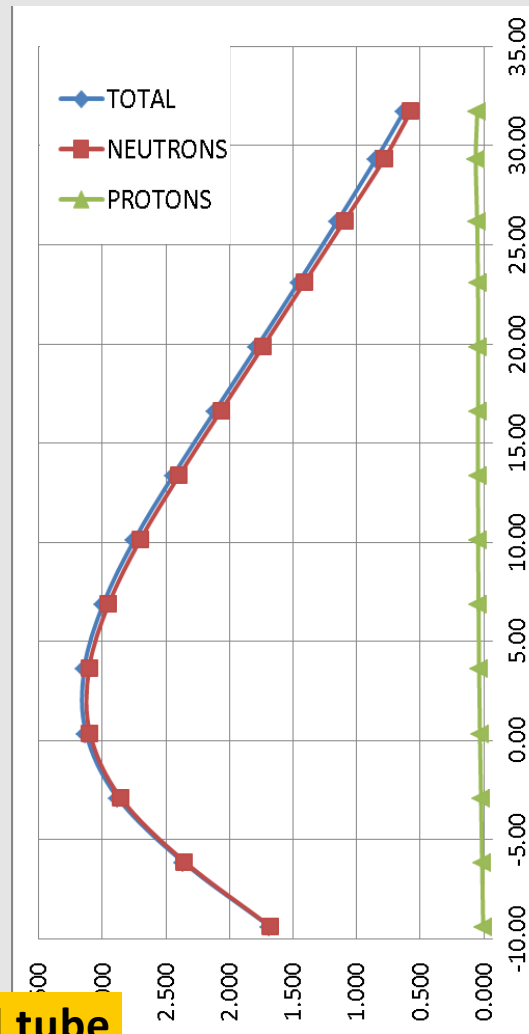
- SAFETY HULL. DISPLACEMENT DAMAGE

SAFETY HULL. INNER WALL

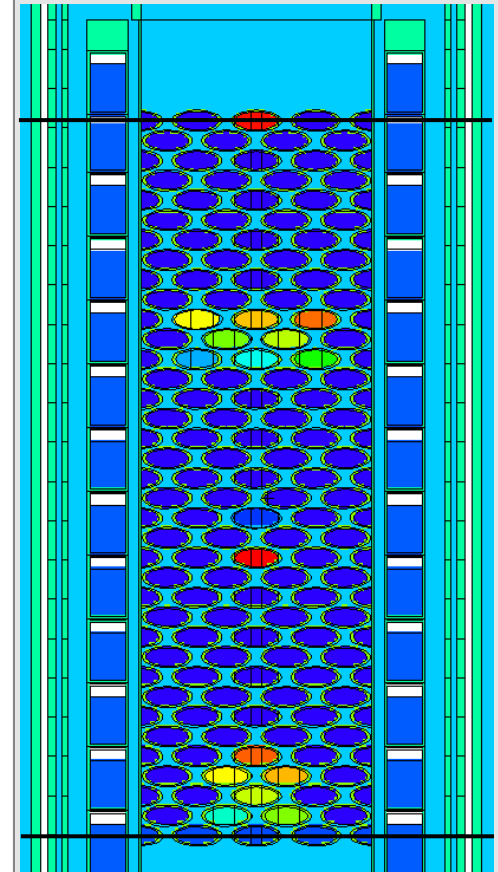
POSITION	TOTAL	NEUTRONS	PROTONS
31.725	0.627	0.575	0.052
29.325	0.847	0.783	0.064
26.225	1.147	1.094	0.053
23.125	1.454	1.407	0.047
19.875	1.782	1.736	0.046
16.625	2.114	2.068	0.046
13.375	2.442	2.395	0.047
10.125	2.747	2.702	0.046
6.875	2.994	2.951	0.042
3.625	3.143	3.105	0.038
0.375	3.130	3.099	0.031
-2.875	2.883	2.860	0.023
-6.125	2.369	2.354	0.015
-9.375	1.688	1.682	0.006

→ 0.23 dpa / Ah

→ **21 dpa in total in central tube**



ROW 36 (-27.36 cm)



ROW 0 (-9.04 cm)

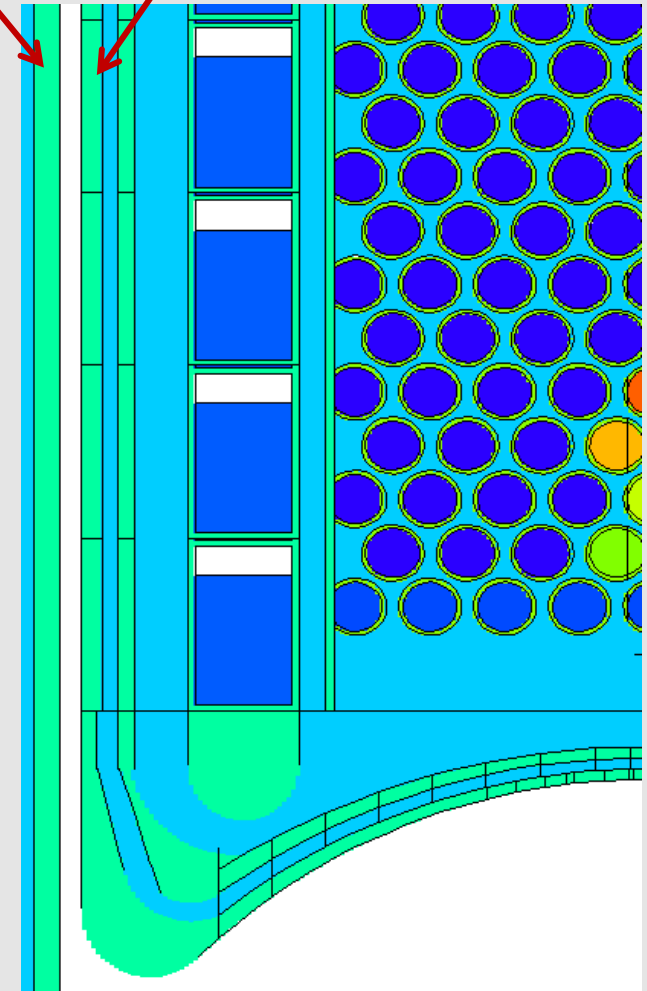
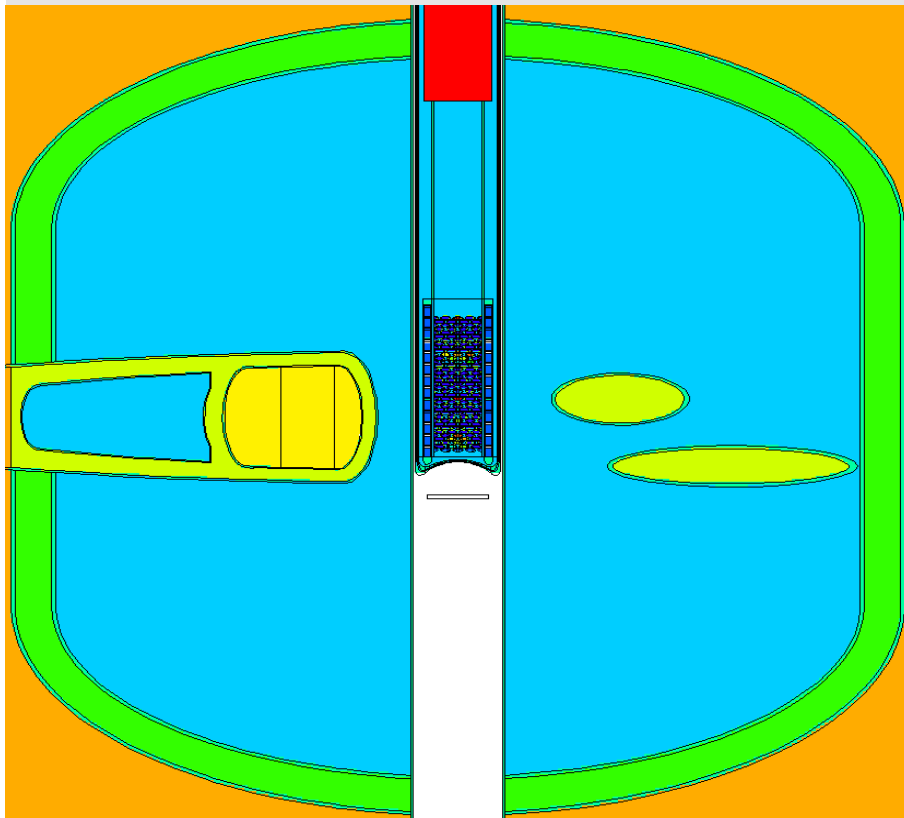
CALOTTE AND SAFETY HULL

- **CENTRAL TUBE DISPLACEMENT DAMAGE**

→ 0.23 dpa / Ah

→ **21 dpa in total in central tube**

Central tube Safety hull

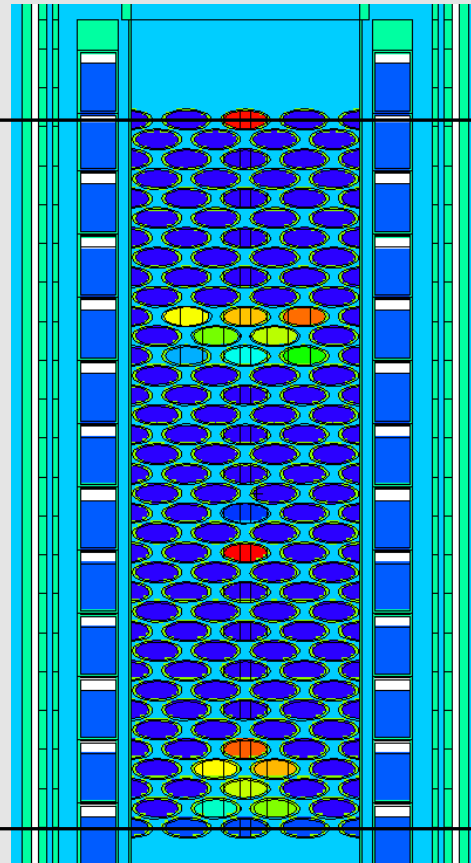


Thank you!



SAFETY HULL. ENERGY DEPOSITION ($W/(mA \cdot cm^3)$)

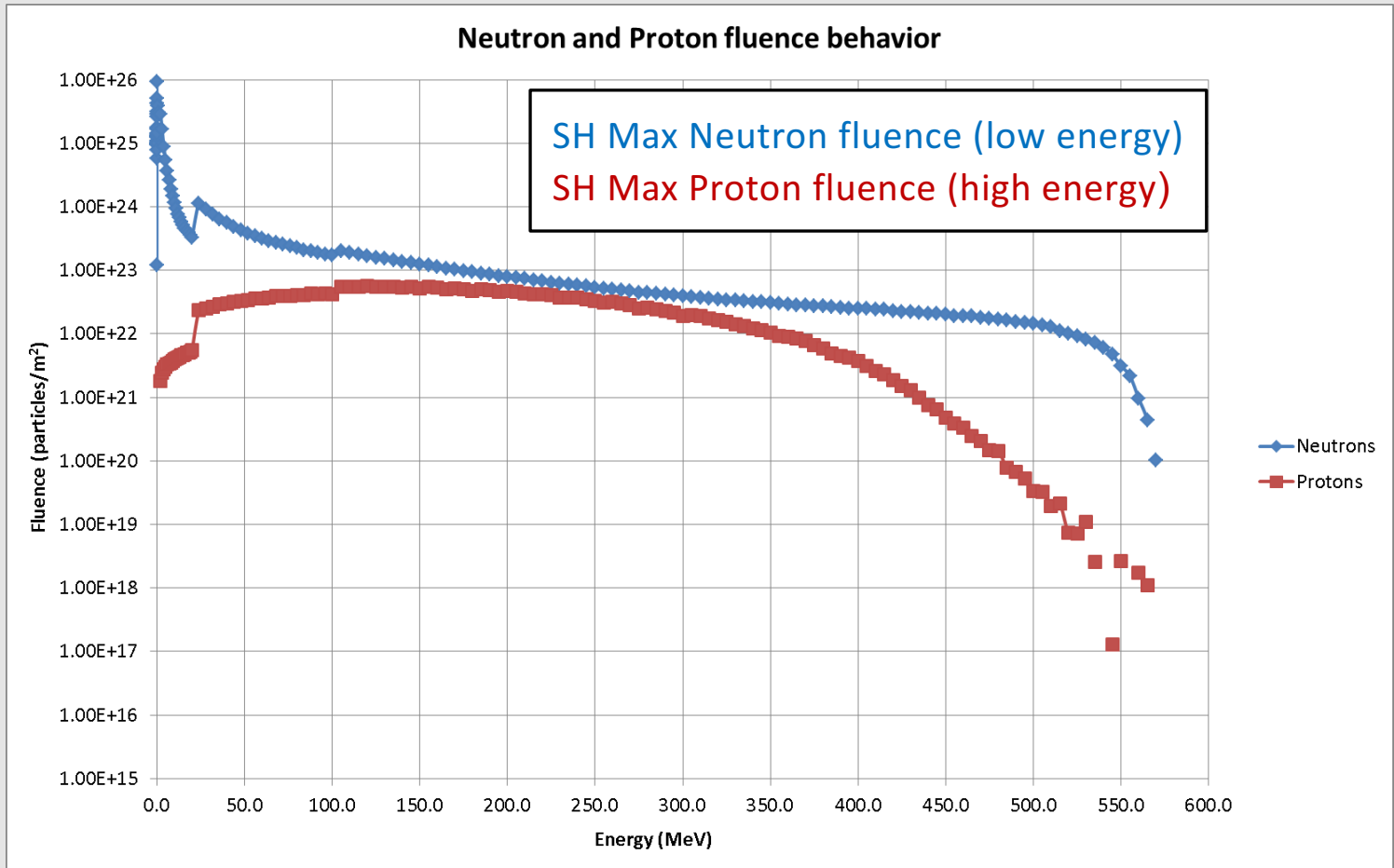
POSITION	OUTER	INNER
31.725	1.45	1.61
29.325	1.47	1.90
26.225	1.28	1.64
23.125	1.27	1.51
19.875	1.31	1.54
16.625	1.36	1.58
13.375	1.40	1.63
10.125	1.39	1.64
6.875	1.34	1.56
3.625	1.23	1.46
0.375	1.06	1.27
-2.875	0.85	1.02
-6.125	0.61	0.74
-9.375	0.38	0.44



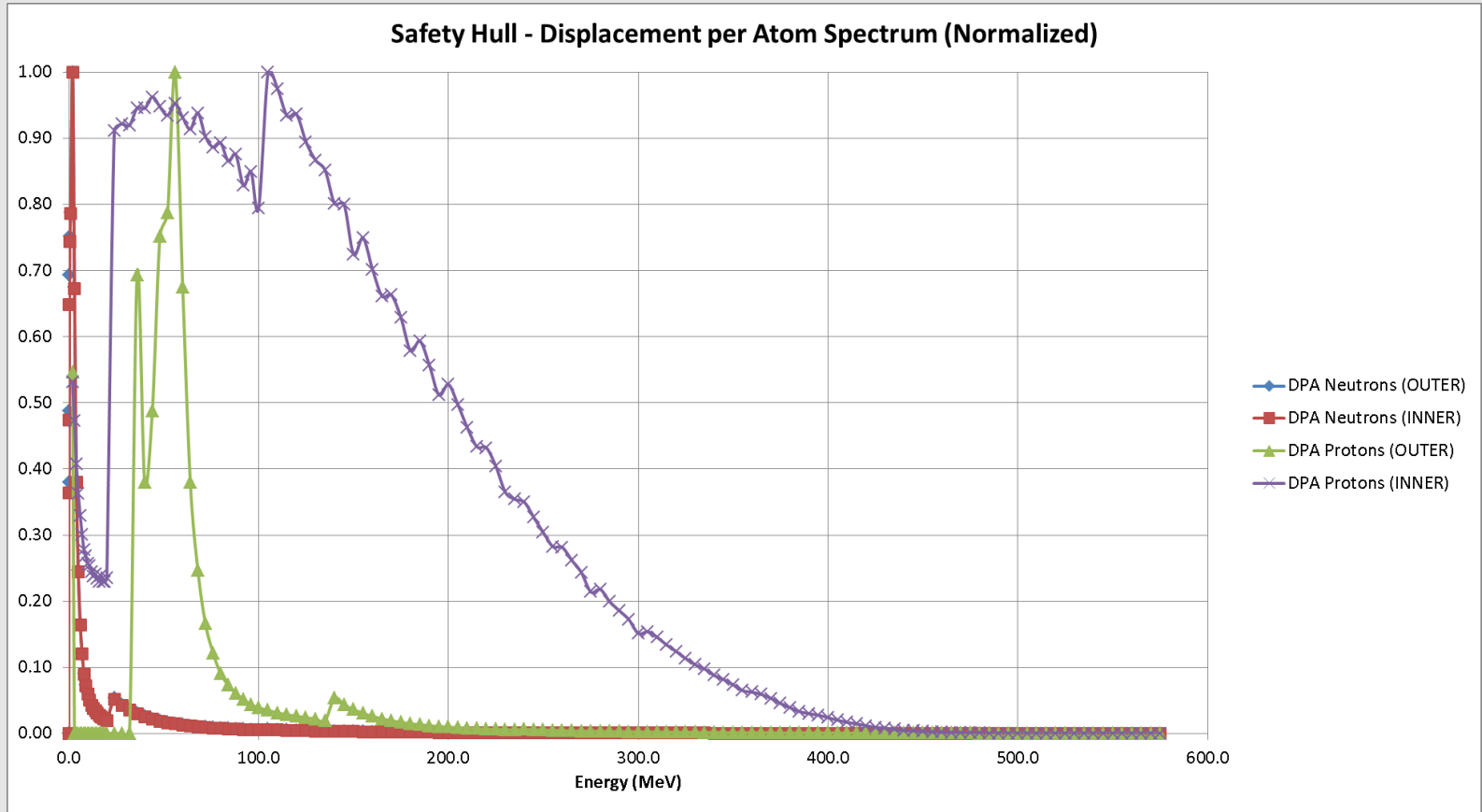
ROW 36 (27.356 cm)

ROW 0 (-9.04 cm)

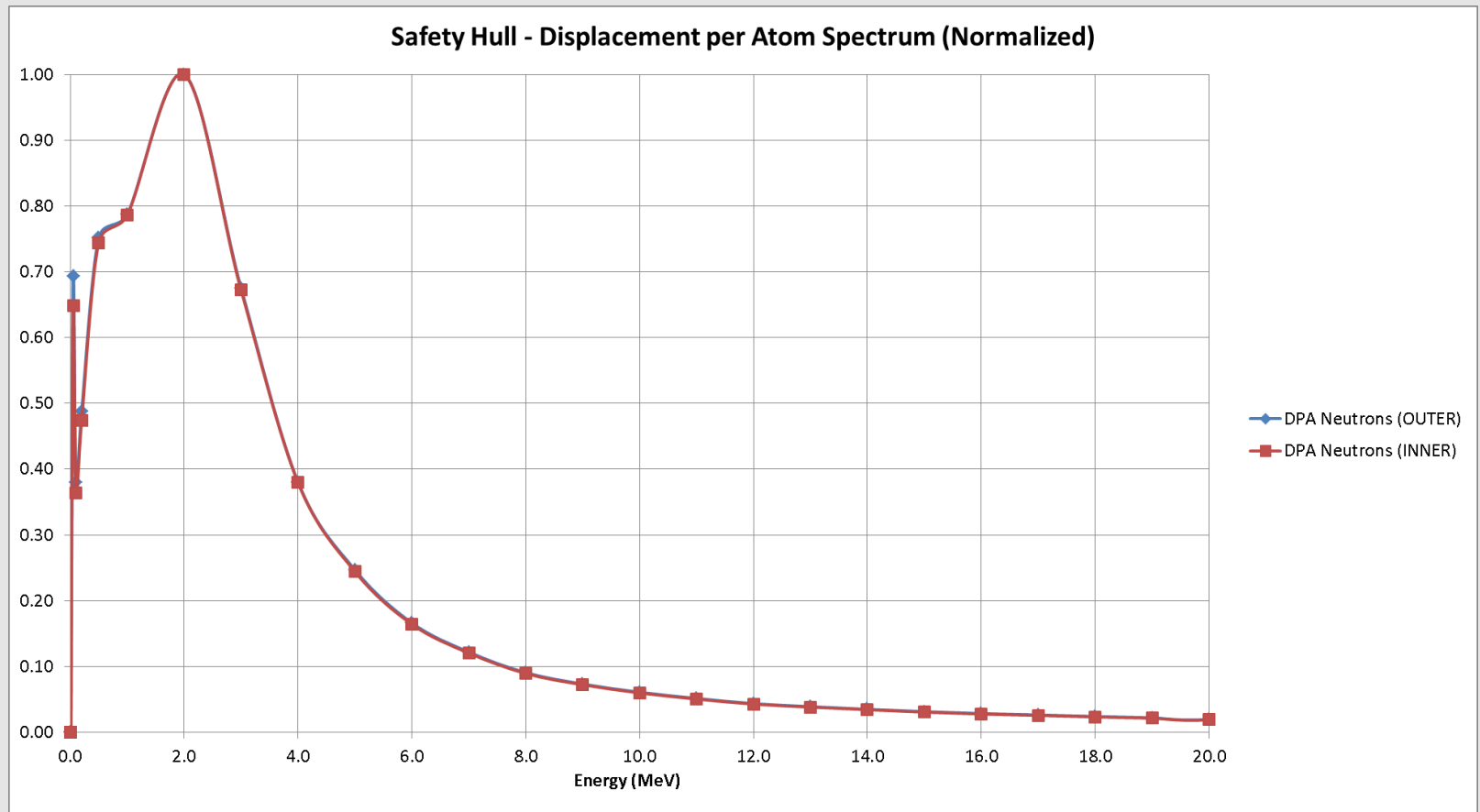
SAFETY HULL. NEUTRON AND PROTON FLUENCE



SAFETY HULL. DISPLACEMENT PER ATOM

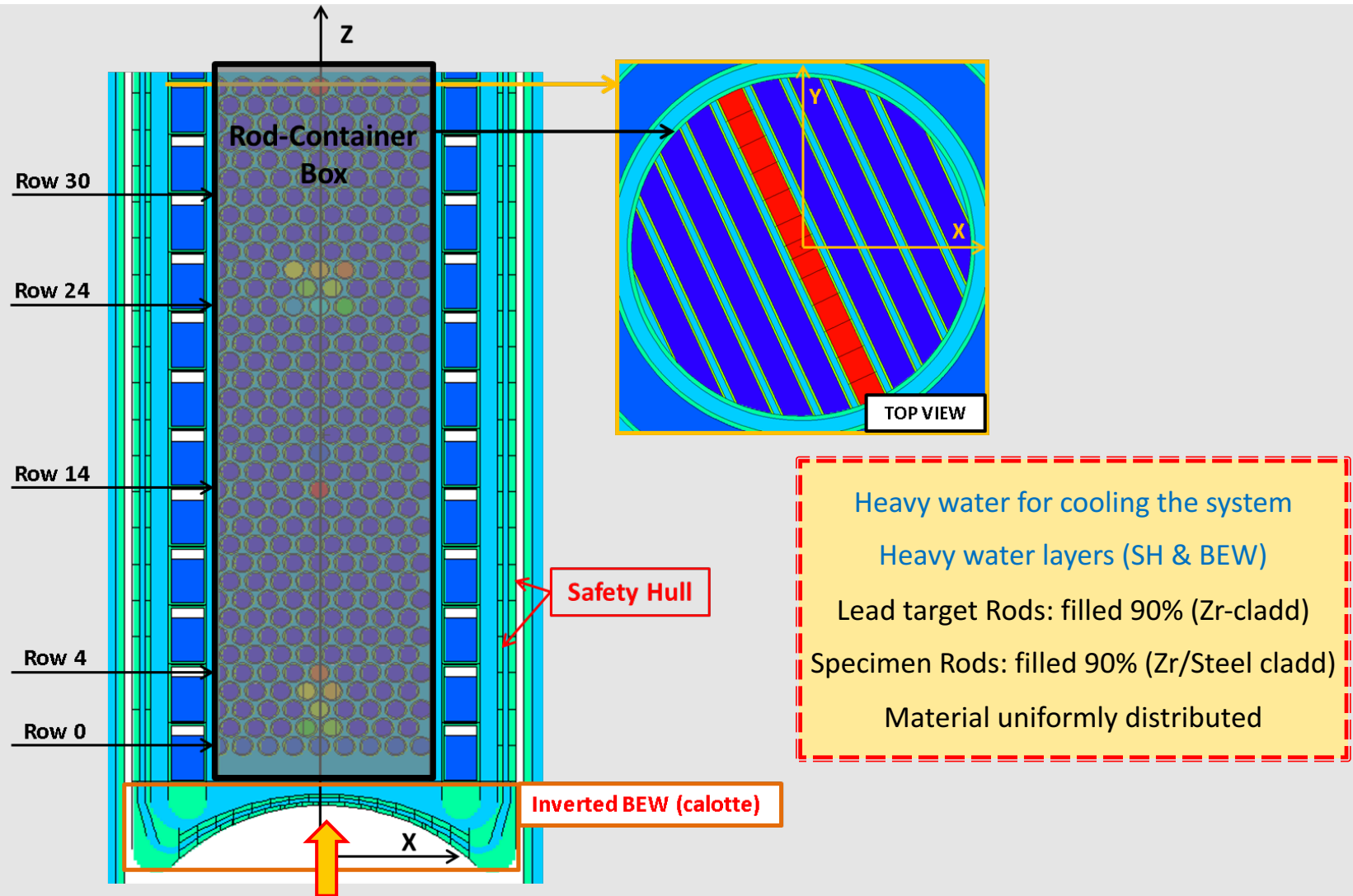


SAFETY HULL. DISPLACEMENT PER ATOM



STIP VI – TARGET 9. IMPLEMENTATION IN MCNPX

2



STIP VI – TARGET 9. GAMMA – MAPPING

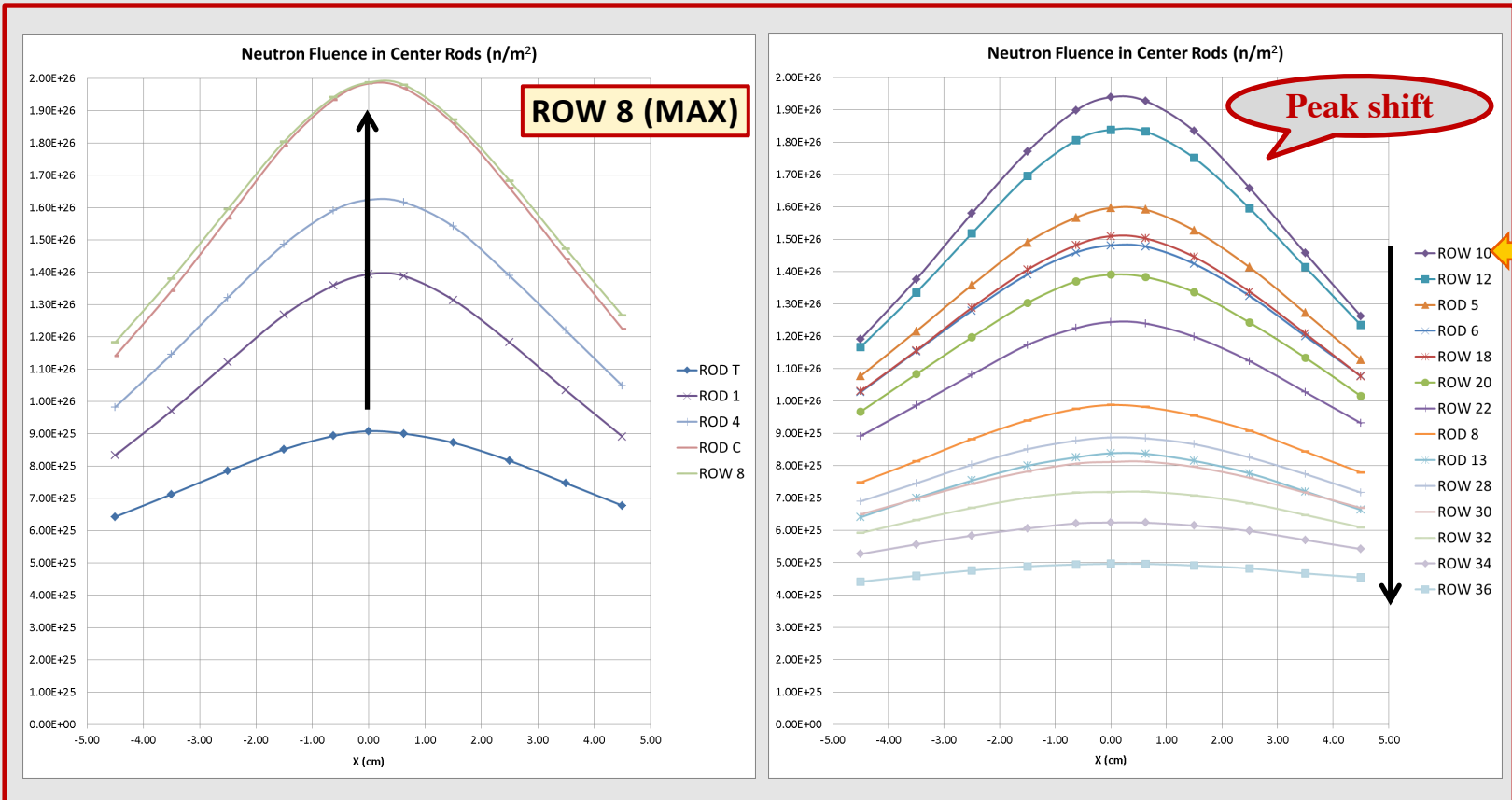
2

Proton fluence (p/m²) of the g-mapping in XY plane (cm)

Y \ X	-4.60	-3.40	-2.20	-1.00	-0.20	0.20	1.00	2.20	3.40	4.60
-5.20	0.00E+00	6.22E+24	7.94E+24	1.00E+25	1.04E+25	9.49E+24	9.75E+24	7.07E+24	4.78E+24	0.00E+00
-4.40	0.00E+00	8.72E+24	1.33E+25	1.59E+25	1.68E+25	1.71E+25	1.67E+25	1.29E+25	7.11E+24	3.85E+24
-3.60	5.04E+24	1.19E+25	1.85E+25	2.53E+25	2.59E+25	2.82E+25	2.48E+25	1.98E+25	1.13E+25	5.97E+24
-2.80	7.76E+24	1.64E+25	2.55E+25	3.30E+25	3.61E+25	4.05E+25	3.74E+25	2.58E+25	1.65E+25	9.87E+24
-2.00	9.54E+24	1.96E+25	3.31E+25	4.70E+25	5.61E+25	5.35E+25	5.01E+25	3.60E+25	2.03E+25	1.13E+25
-1.20	1.20E+25	2.18E+25	3.85E+25	5.99E+25	6.87E+25	7.08E+25	6.14E+25	4.04E+25	2.45E+25	1.24E+25
-0.40	1.21E+25	2.67E+25	4.26E+25	6.98E+25	7.99E+25	8.18E+25	6.85E+25	4.47E+25	2.60E+25	1.35E+25
0.00	1.26E+25	2.67E+25	4.40E+25	7.20E+25	8.59E+25	8.25E+25	7.13E+25	4.80E+25	2.66E+25	1.41E+25
0.40	1.42E+25	2.54E+25	4.35E+25	7.20E+25	8.17E+25	8.58E+25	7.12E+25	4.62E+25	2.74E+25	1.18E+25
1.20	1.31E+25	2.63E+25	3.96E+25	6.70E+25	7.90E+25	7.61E+25	6.60E+25	4.20E+25	2.46E+25	1.25E+25
2.00	1.04E+25	2.19E+25	3.32E+25	5.81E+25	6.10E+25	6.40E+25	5.69E+25	3.70E+25	2.22E+25	9.54E+24
2.80	8.46E+24	1.64E+25	2.69E+25	4.39E+25	4.60E+25	5.00E+25	4.40E+25	2.94E+25	1.88E+25	7.34E+24
3.60	6.37E+24	1.20E+25	2.02E+25	3.09E+25	3.13E+25	3.61E+25	2.87E+25	2.25E+25	1.42E+25	4.83E+24
4.40	4.68E+24	9.10E+24	1.35E+25	1.85E+25	2.19E+25	2.26E+25	1.97E+25	1.50E+25	9.82E+24	0.00E+00
5.20	0.00E+00	5.25E+24	8.51E+24	1.10E+25	1.30E+25	1.32E+25	1.27E+25	1.05E+25	6.58E+24	0.00E+00

Proton Beam shift 2-3 mm in Y+

- NEUTRON FLUENCE ANALYSIS. CENTER RODS



F. ENERGY DEPOSITION IN THE RODS. SPECIMEN RODS (CLADDING)

3F

