The neutron halos for 2 different x-y aspect ratios, for the initial energy between 10 MeV and 260 MeV, and for the initial energy above 260 MeV

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Abstract

The results of earlier calculations reported in reference 1, here called report FEB2003, were extended to lower energies. Only case 1 and case 3 were considered. Inelastic scattering in the spoiler and in collimators COL0 and COL1 was ignored to drastically cut down on computer time. The calculations were done separately for the energy region between 10 MeV and 262 MeV, and for the region between 262 MeV and 1,400 MeV.

1 Introduction and summary

Recently, in reference 1, hereafter called report FEB2003, calculations were done for four x-y aspect ratios for momenta above 750 MeV/c, or 262 MeV. An anomaly was found when the calculations were extended to lower energies, as reported in reference 2, report APRIL2003. Below the pion production threshold of 245.77 MeV/c the angular distribution of inelastic neutrons is very much shifted to larger angles. The reason for that is not clear, but it is no cause for alarm, since inelastic neutrons contribute only marginally to the halo.

In FEB2003 it became clear that the transmission of inelastic neutrons to the decay region was very small for the spoiler, and for collimators COL0 and COL1, see table 12 of that report. Furthermore, the vertical halo caused by neutrons with a last scattering in those collimators is still quite close to the axis, see figure 5 of that report. This suggests a way to drastically reduce the computer time. Most neutrons from the production target are stopped in the first collimators which determine the acceptance. There, a lot of time is spent following the many inelastic neutrons which cascade down in energy to below the chosen threshold energy. A calculation which allowed neutrons to go to even lower energy than 262 MeV would therefore take a prohibitive amount of time. However, no big error is made if the calculation is restricted to elastic scattering up till COL1, and if only for COL2 until COL4 the inelastic neutrons are taken into account.

Therefore, the calculations of FEB2003 were repeated following this new procedure, but with the threshold energy of the final neutrons set at 10 MeV. Initial neutrons had energies above 262 MeV. It took only 8 hours to do a calculation for 50 million initial neutrons. A separate calculation was made for initial energies between 10 MeV and 262 MeV following again the same procedure. That calculation took 16 hours for 50 million initial neutrons. Both types of calculations were done for cases 1 and 3 of FEB2003. Case 1 has a vertical acceptance angle of 2.6 mr, and case 3 has 3.8 mr.

There are two reasons for splitting the calculations for the two regions, instead of doing one calculation from 10 MeV until 1,400 MeV. Firstly, the behaviour of the inelastic cross section is very different below the pion production threshold. Therefore, it makes sense to make that behaviour explicit. Secondly, according to figure 16, page 141, of the original proposal the slope of the cross section at 46.5 degrees changes very much below 260 MeV. One linear slope is taken in the calculations below 260 MeV, and an other slope above 260 MeV. Below 260 MeV the formula is $N = 10000 * 10^{-3.25E}$, and above 260 MeV it is $N = 3000 * 10^{-1.36E}$.

2 Results

The results are given in table 1 for case 1, and in table 2 for case 3. Distributions are given in figures 1 to 3.

2.1 The tables

Calculations were done for 50 million initial neutrons. The tables give the number of neutrons that reach 14 m, after the last scattering in the indicated elements. The spoiler is 7 cm thick Lead, at 50 cm from the target. Take table 1. The left part shows the results for the low energy calculation, and the right part is for the high energy calculation. The total number is given, the number of elastic and inelastic scatterings, and the number of inelastic events with a final momentum below 750 MeV/c. Of course, for the low energy calculation all neutrons have a momentum below 750 MeV/c.

Inelastic processes are only taken into account for COL2, COL3 and COL4. A number of remarks can be made.

- The number of final neutrons directly from the target without any scattering is much lower for the low energy calculation than for the high energy calculation. In the latter case about 50 percent of the neutrons within the 500 μsr acceptance area pass the spoiler, but in the former case it is less than 40 percent.

- The fraction of neutrons from the more downstream elements decreases very rapidly in the low energy case, compared to the high energy case. The reason is that elastic scattering at low energies gives a larger scattering angle than at higher energies. If neutrons are scattered at low energy, they will then have a reduced possibility of passing subsequent elements.

- The number of inelastic neutrons is very small in the low energy case for the reasons given in report APRIL2003.

- The number of inelastic neutrons below 750 MeV/c from the high energy calculation is for each collimator comparable to the number of elastic neutrons from the low energy calculation. However, it has to be taken into account that the production cross section for the lower energies is about a factor 2 to 2.5 higher than for the high energy case. More about that in section 3.

- The numbers for the high energy case are close to the numbers in report FEB2003, but slightly different, since firstly the calculation is extended to lower final energies, and secondly inelastic processes in the initial stages have been ignored.

- The trends in the results for case 3 are similar. As in FEB2003 the scattering from the later collimators is more important for case 3 than for case 1.

2.2 The figures

Figure 1 shows the horizontal and vertical x and y distributions, normalized to 1.0 in the center. The low and high energy cases have been normalized independently. The blue curves are for the high energy case, and the red curves are for the low energy case. Both case 1 and case 3 are shown in the same plots. In general, the red and blue curves have the same trend but, as expected from the tables, the low energy y distribution falls off more steeply. The reason is that fewer neutrons reach the downstream collimators from which they can get to higher y.

Figure 2 shows the fraction of neutrons with x or y larger than the values indicated on the horizontal axes. Again, the low energy curves fall off steeper than the high energy curves.

Contours are shown in figure 3. The blue curves are for the high energy case as it was calculated in FEB2003 with a low momentum cutoff of 750 MeV/c. The difference between the low and high energy case is not much for the 10 percent and the 1 percent contours. This is to be expected, since those contours are determined by a last scattering from the upstream collimators. For the other contours the difference becomes noticeable in the vertical direction. It is larger for case 3 than for case 1.

3 Normalization

According to table 4, page 141, of the proposal, the neutron yield above 10 MeV is 1.11 10^{-6} per proton per μsr at 46.5 degrees. Above 100 MeV it is 1.04 10^{-6}, and according to a private communication from Littenberg it is 0.53 as much, or 0.55 10^{-6}, above 262 MeV. Therefore, the yield for low energy neutrons between 10 MeV and 262 MeV is 1.11 10^{-6}, and the yield for high energy neutrons above 262 MeV is 0.55 10^{-6}. Therefore, for a comparison of the halos, the low energy rates have to be multiplied by a factor 2. On the other hand, during the generation of the neutron energies in the subroutine gukine, I used the straight lines on a logarithmic scale indicated in the introduction. Integrating those curves, and comparing the two energy regions, gave a factor 2.5 higher rates for the low energy case. I could easily have drawn the lines, guided by the all too human eye, a little bit different. In that case the result would have been a factor 2.25.

For now, I take implicitly a factor 2.0 by using the yields stated in the beginning of this section for the calculation of the absolute intensities in subsection 3.1.

According to section 7.1 of FEB2003, in the high energy case, there were 80,000 neutrons per bin in the central 5 two dimensional bins of 1 cm in y by 5 cm in x each. They cover an area of 25 cm^2. This gives 16,000 per cm^2. As in that report, the absolute values of x and y were taken for the binning, so that this number is the sum for 4 quadrants. In the real world, there are then 4,000 neutrons per cm^2.

In the low energy case, the transmission of neutrons through the spoiler is much less, and there are only 60,000 neutrons per bin in the center. This gives then in the real world 3,000 neutrons per cm^2.

3.1 Absolute intensities

To obtain the absolute intensities, a slightly different reasoning is followed as in section 7.2 of FEB2003. 50 Million neutrons were generated in a large solid angle of 3360 μsr. According to tables 1 and 2 roughly 4 Million neutrons went through for the high energy case and 3 Million in the low energy case. Using the yields stated above, and 10^{14} protons per pulse, there are then 22.4 10^9 neutrons in the low energy case, and 14.8 10^9 in the high energy case.

The above 3,000 per cm^2 and 4,000 per cm^2 correspond then to 22 10^6 and 15 10^6 neutrons per cm^2 in the low, respectively the high energy case. The 10 percent contour corresponds then to 2.2 million and 1.5 million neutrons per cm^2. The 1 percent contour corresponds to 220,000 and 150,000. The 0.2 percent contour corresponds to 44,000 and 30,000. The 0.02 percent contour correspond to 4,400 and 3,000 neutrons per cm^2.

References

[1] Comparison of the neutron halos for 4 different x-y aspect ratios, for momenta above 750 MeV/c, February 14 ,2003 http://www.triumf.ca/people/doornbos/halocomp.ps

[2] Anomaly in neutron scattering and reactions at 745.77 MeV/c, April 2 ,2003. http://www.triumf.ca/people/doornbos/anomaly.ps

Table 1: Number of neutrons directly from target, or with last scattering in spoiler or indicated collimator. This is case 1. el means elastic, in means inelastic.

case	start P below 750 MeV/c			start P above 750 MeV/c			
	total	el	in	total	el	in all	in below 750
target	2,809,760			3,771,120			
spoiler	38,532			106,280			
COL0	6,130			20,804			
COL1	2,057			5,087			
COL2	387	365	22	1,409	1,065	344	160
COL3	22	20	2	166	115	51	28
COL4	19	16	3	73	33	40	21

Table 2: Number of neutrons directly from target, or with last scattering in spoiler or indicated collimator. This is case 3. el means elastic, in means inelastic.

case	start P below 750 MeV/c			start P above 750 MeV/c			
	total	el	in	total	el	in all	in below 750
target	2,839,520			3,828,880			
spoiler	46,680			138,324			
COL0	7,262			28,728			
COL1	3,389			9,470			
COL2	749	725	24	2,675	2,105	570	266
COL3	62	54	8	320	215	105	50
COL4	39	33	6	177	55	122	75

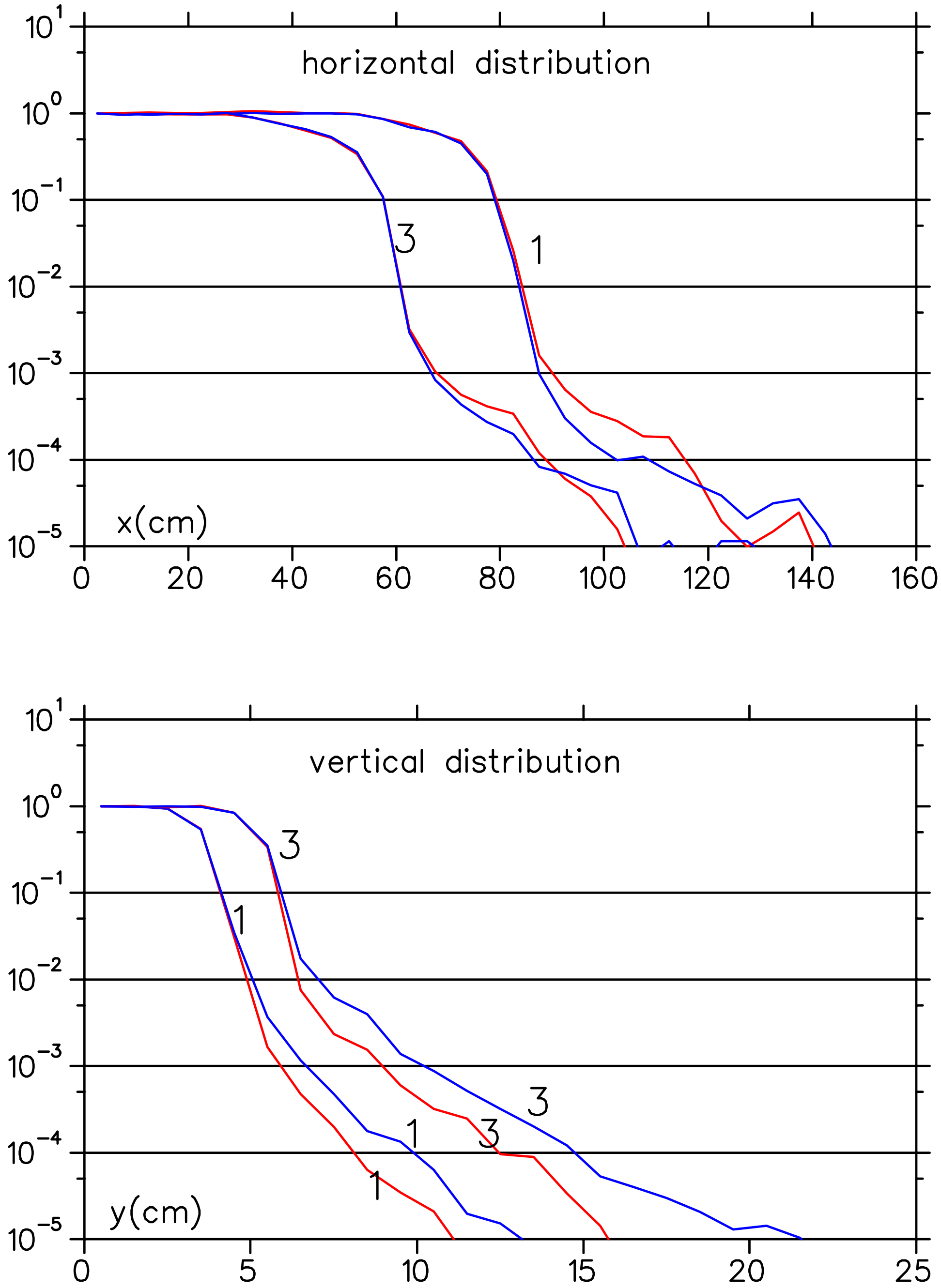

Figure 1: Normalized horizontal and vertical beam profiles at 14 m for the low energy calculation in red and for the high energy calculation on blue. Both case 1 and case 3 are indicated

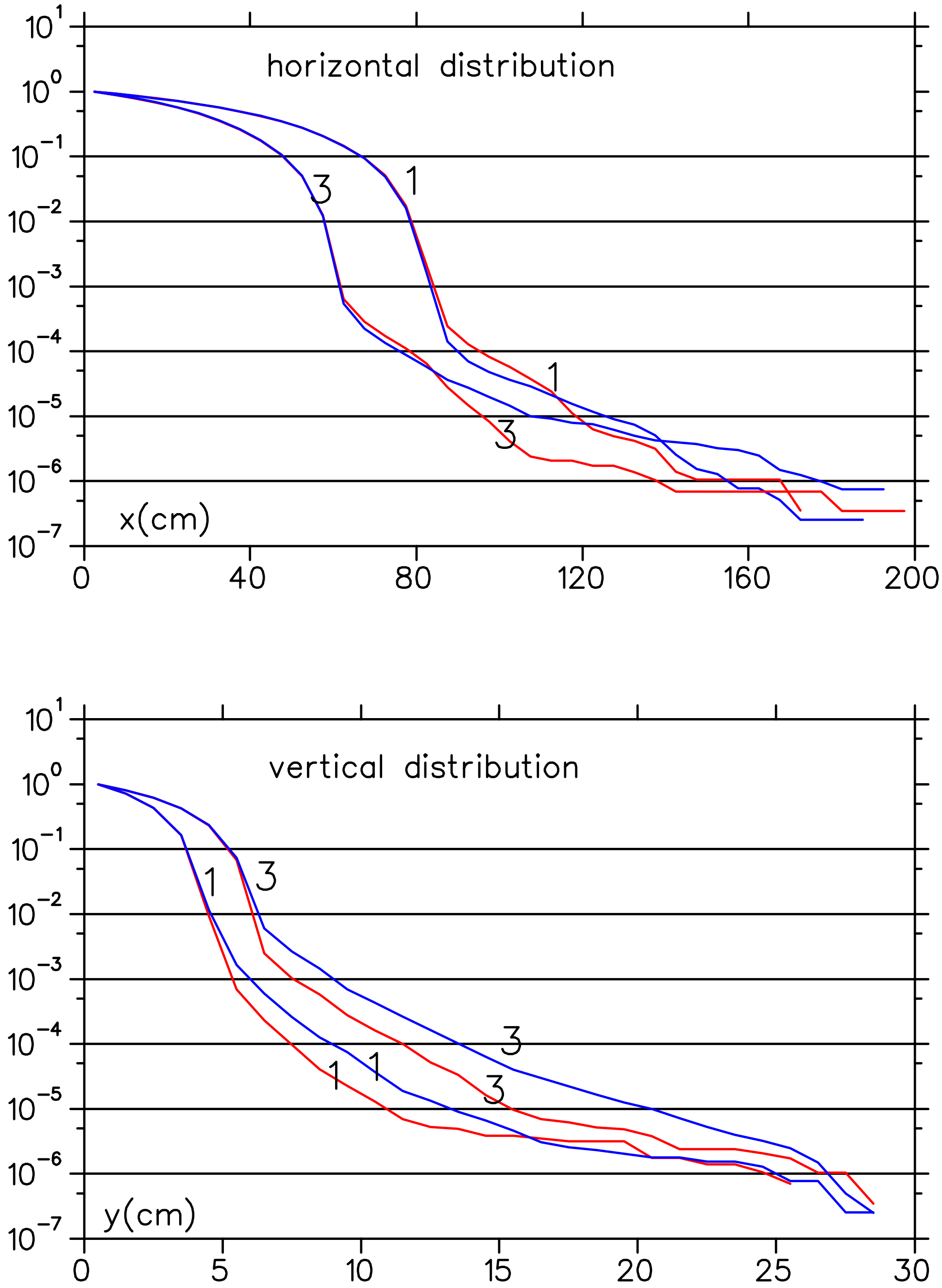

Figure 2: Fraction of beam outside the areas, indicated on the horizontal axis

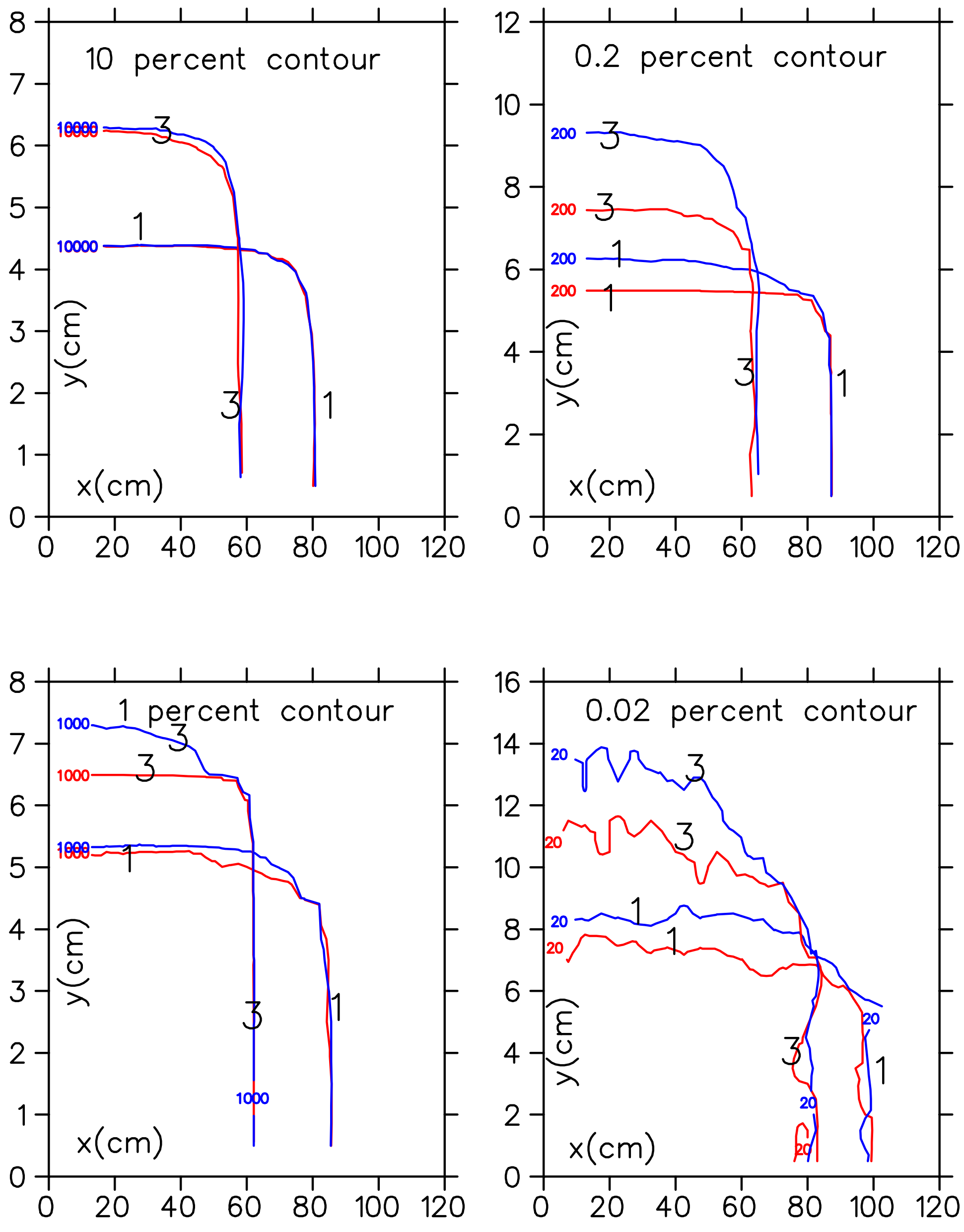

Figure 3: Contour plots at 14 m. Blue is for the high energy calculation of report EB2003 and red for the low energy calculation