NEUTRON MODERATION IN A ROTATING DISC

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ABSTRACT

The aim of this project was to find out if a rotating moderator disc can be used for the focusing of neutron beams. This could be a cheap way to increase the yield of a neutron source. Another advantage could be that the source can have hotter neutrons if the beam tube is in the direction of the spinning disc and cooler if the beam tube is in the opposite direction.

A Monte Carlo code has been written to investigate this problem. The total neutron yield and the neutron yield for a single beam tube were measured for different spinning speeds of the rotating moderator disc. It turned out that the yield per tube was up to 30 times higher with the rotating disc than without. The yield started to increase from where the edge of the disc had approximately the speed of thermal neutrons. The increase stopped at the point where 95% of the disc was above the speed of thermal neutrons.

The energy of the neutrons increased as well. This can be problematic because thermal neutrons are most useful. The average energy increase can be overcome by making a trade off between the extra yield and the higher average energy.

The second phenomenon investigated was the differentiation in energy of the neutrons. The more energetic neutrons are expected to leave the disc in the direction of the spinning, where less energetic neutrons are expected in the opposite direction. This was seen at the higher spinning speeds, but the neutrons leaving the disc against the spinning direction still had more energy than when disc did not spin. The angle dependence of the neutron energy became clearer at the point where even the slow neutrons had more energy than thermal neutrons. The relatively slow neutrons also showed no significant increase in yield. An application of the effect could be that the average energy of the neutrons can be easily influenced by shifting the angle of the beam tube.

Finally an interesting phenomenon occurred. At high rotation speeds a decrease in average neutron energy occurred at the angle with the maximum neutron yield. This was not expected, but this effect might be used to reduce the average energy increase.

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1. INTRODUCTION

The aim of this bachelor project is to research a method to create a higher yield from a neutron source, by focusing the neutron beam. A neutron beam is guided away from the source by a neutron beam tube. A beam tube can accept only a small angle of incoming neutrons, because it is a long and small vacuum pipe as seen in figure 1.1. If a neutron enters such a beam tube at an angle that is too large, it will scatter and it will be absorbed at the side of the tube and most likely not reach the target. Neutrons that enter the beam tube at a small angle can reach the end more easily. Most neutrons generated by a source are normally lost because they do not arrive at the beam tube at the right angle, but when the beam is focused this loss can be reduced.

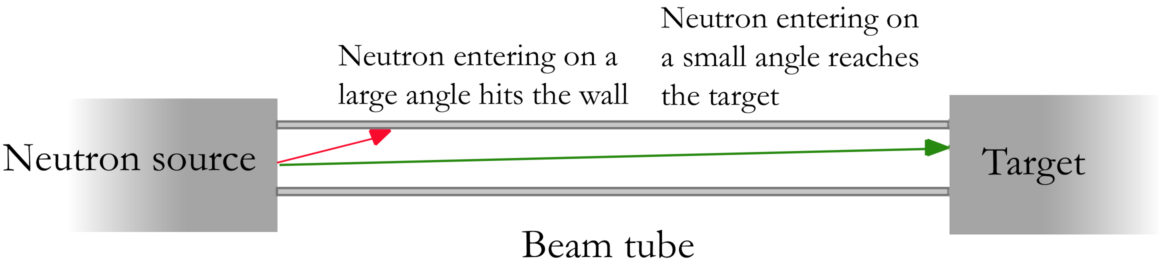

Figure 1.1 Layout of a beam tube

Neutron beams are used in many research fields like material research, biology, physics, and engineering. For most research it is better if the neutron flux is as high as possible, since the pictures made with neutron spectroscopy are better and materials can be examined quicker. Therefore a lot of investigation is done to increase the neutron flux of neutron sources.

Most investigation focuses on increasing the output of the neutron source. For that reason the sources are continuously made bigger, like the Swiss Spallation Neutron Source (SINQ) at PSI in Switzerland or the Intense Pulsed Neutron Source (IPNS) at Argonne in Chicago. The newest largest neutron source is the Spallation Neutron Source in Oak Ridge.

The present project however aims at losing fewer neutrons. Therefore it could be used in addition to most neutron sources. High intensity neutron sources are very large devices and cost hundreds of millions of Euros, therefore an increase in yield with a relatively cheap mechanism would be a great asset.

In figure 1.2 a schematic picture is shown of what such a setup could look like. The outer box represents the boundary of the setup. It may contain moderating material like water. The blue box is the core where the neutrons are created. In this core, or next to, is the rotating disc with one or more beam tubes attached.

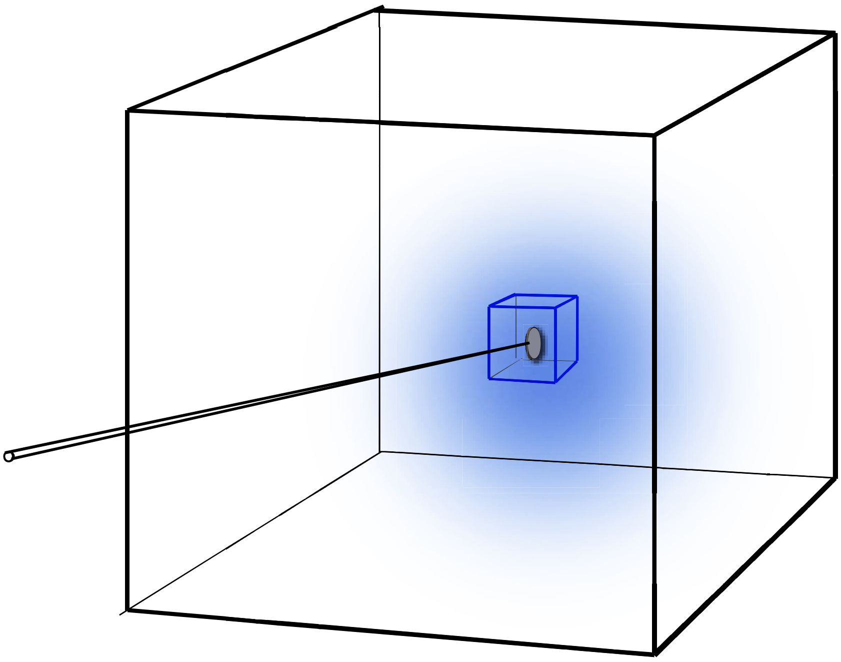

Figure 1.2 Schematic picture of the implementation of a rotating disc in a neutron source

The idea is to create a fast rotating moderator, which centrifuges the neutrons in towards the plane perpendicular to the rotation axis. The expectation of dr. F.M. Mulder is that this mechanism will force the neutrons from a 180 degree angle to an 18 degree angle, which would increase the output of neutrons by a factor 10. This would be a cheap way to gain neutron yield.

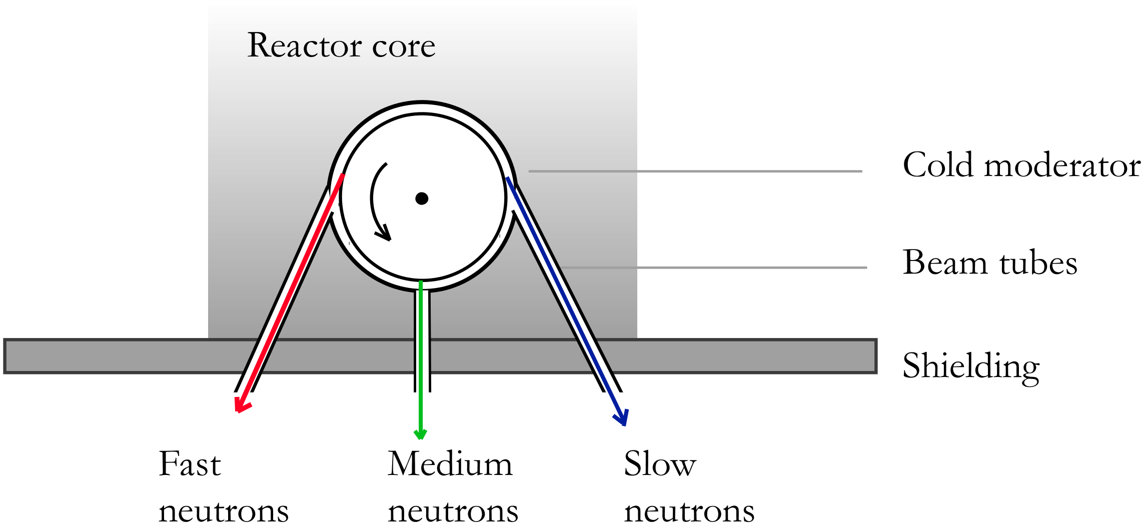

Figure 1.3 Layout of the spinning moderator

Another good feature of this setup could be that the average energy of the neutron beam can be dependent of the angle of the neutron beam guide. The neutrons will gain velocity in the plane of the disc. If this is the direction of the beam tube, the neutrons will be hotter, if the extra speed is away from the beam tube, the neutrons are cooler.

This bachelor project investigates if such gains are likely and what the important properties of such a system for a high neutron yield would be.

A Monte Carlo simulation is used to simulate the neutrons in a rotating moderator. Different spinning speeds are used and the angle of the outgoing neutron beam is compared with the average neutron yield.

2. THEORY

2.1 Monte Carlo simulation

Monte Carlo simulation is a method to evaluate integrals and can be used to solve integrals that are not analytically solvable. To do a Monte Carlo simulation a lot of calculating power is needed, but with the new computers it is becoming more and more popular. The main advantage of a Monte Carlo simulation is that the calculating doesn't become more complicated when an integral becomes more difficult. This way it is a bit longwinded for simple calculations, but for complex integrals it is an easy way to approximate the solution.

The main aspect of Monte Carlo simulation is that it uses probability instead of analytical solutions. The answers are therefore never exact, but can be really accurate using statistical analysis.

The best way to explain the Monte Carlo method is by giving a simple example. If it is needed to solve the following equation:

$$\int_b^a f(x)dx \tag{2.1}$$

The Monte Carlo method to solve this equation would be to rewrite the equation of (2.1) into

$$(b-a)\overline{f}(x) \tag{2.2}$$

Where $\overline{f}(x)$ is the average of *f(x)* on the interval [a,b]. Then N uniformly distributed random numbers are taken from the interval [a,b] and $\overline{f}(x)$ is calculated using

$$\overline{f}(x) = \frac{1}{N}\sum_{n=1}^{N} f(x_n) \tag{2.3}$$

The error in $\overline{f}(x)$ can be estimated by

$$\sigma^2 = \frac{\overline{f^2}(x) - \overline{f}^2(x)}{N} \tag{2.4}$$

To calculate a multiple integral (b-a) can be replaced by an n-dimensional volume, from which N uniform distributed numbers are taken. Then x becomes an n-dimensional vector **x**.

$$\iiint_V f(\mathbf{x})dV = \frac{1}{V}\overline{f}(\mathbf{x}) \tag{2.5}$$

$$\overline{f}(\mathbf{x}) = \frac{1}{N}\sum_{n=1}^{N} f(\mathbf{x}_n) \tag{2.6}$$

The Monte Carlo calculation doesn't become a lot more complicated, where the analytical solution becomes a lot more difficult.

This is just one of the examples how Monte Carlo can be used to solve complicated calculations, but there are lots of other techniques used in different fields. The main aspect is that the solutions are approximated by simulating with a huge amount of random numbers.

2.2 Random walk simulation

To simulate the neutron transport in the rotating disc, the random walk technique is used. A particle is generated at a random point, with a random impulse and a random direction. All these random properties are not really random, but according to a certain distribution. This can be a uniform distribution, but also more complicated distributions. Also all the interactions are decided randomly according to a distribution.

Then the path of the particle is calculated and its interactions with the environment are simulated, until its path is somehow terminated. When this process is repeated many times, one can see what happens on average.

The difficult part is to create the right distributions for the different properties and events. This is very important because the behaviour of the entire system depends on the right events.

The code also has to be fast enough, so the millions of trajectories can be made in a reasonable calculation time. This large amount of simulations is needed to be able to obtain reliable statistics on the results. The code follows these steps:

A particle is generated somewhere at a uniformly distributed position in the core, with a random direction and an energy is chosen to be 1 eV. Next the distance to a collision with a moderating nucleus is calculated. The particle goes to that point, and has an interaction there. The new properties after the interaction are calculated. The particle gets a new speed, and direction. It then flies toward its next interaction point.

Every step the particle has a probability to end its journey. It can be absorbed, fly out of the core, or hit the detector. The particle flies out of the core if the path crosses the boundary, this is easily checked by looking at the particle location. The particle hits the detector, if it hits the location of the detector in the right direction. The absorbing process is a random process; it can happen at any step.

When a particle is terminated a new particle is created at a random place and the process then starts from the beginning. This must be repeated until the statistics are considered reliable.

2.3 Neutron transport in stationary media

To describe a neutron there are 4 important properties: its location, its direction, the length of the path until the next collision and its speed. With these 4 properties and the interaction distributions it is possible to calculate its entire trajectory.

The location is straightforward, plain Cartesian coordinates are used. It’s the starting point of the particle. That is known from its last step, or it is created at that point.

The direction changes only if the particle collides with a moderator nucleus. In this project the collision can be approached as a classical elastic collision and the new direction is assumed to be uniformly distributed over all angles in the centre of mass frame.

The path length is determined by the total cross section of the moderator Σ_T. This is a parameter that determines the likelihood of an interaction between the neutron and the material it is travelling through. The unit of a cross section is m^{-1} but the more commonly used unit is cm^{-1}. The cross section is dependent on the energy of the neutron and the properties of the moderating material. It is the probability a particle will interact with the material. It has not necessarily to do with the geometrical cross section of a nucleus.

There are different types of cross sections for every type of interaction. For example the Σ_a is for the absorption cross section, the Σ_s for the scattering cross section, Σ_T for the total interaction cross section. For the path length the total cross section is important, but to figure out if a particle is absorbed the absorption cross section is used.

The path length is Poisson distributed. An easy way to generate a Poisson distribution is to calculate it from a uniform distribution. Generating a uniform distribution is an intrinsic function of FORTRAN. That calculation starts from the following relation:

$$P(x \leq \rho) = P(y \leq s) \tag{2.7}$$

This means that the chance that x is smaller or equal to uniformly distributed number ρ must be equal to the chance y is smaller or equal to another distributed number s. This can also be written as

$$\int_{-\infty}^{\rho} g(x)dx = \int_{-\infty}^{s} f(y)dy \tag{2.8}$$

Here g is the uniform distribution and f the other distribution. They are both 0 for negative values, so the integrals start at 0. The uniform part is just

$$\int_{0}^{\rho} g(x)dx = \rho \tag{2.9}$$

Where ρ is in the interval of the uniform distribution is taken between 0 and 1. If f(y) is the Poisson distribution, with k = 1, the second part becomes:

$$\int_{-\infty}^{s} f(y)dy = \int_{0}^{s} \sigma e^{-\sigma y} dy \tag{2.10}$$

Graphically it means that the grey part for the left graph in figure 2.1 should be as large as the grey part on the right side.

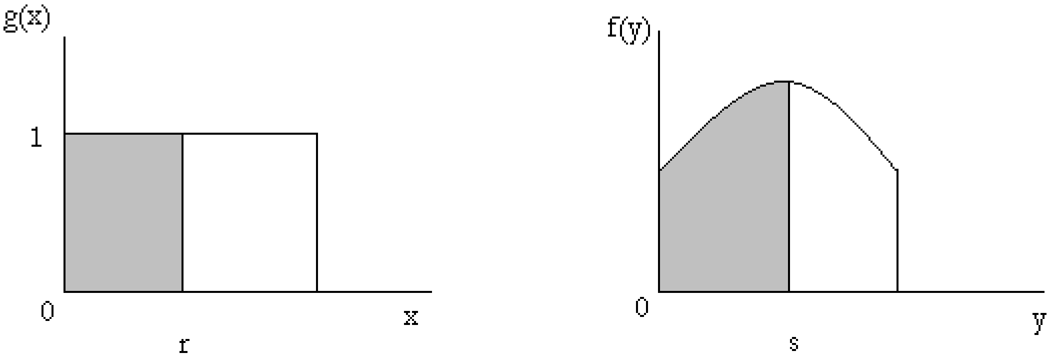

Figure 2.1 Calculating a distribution function from a uniform distribution

Then a relation between the uniformly distributed ρ and the Poisson distributed s is easily calculated combining equation (2.8) with equation (2.9) and equation (2.10).

$$\rho = 1 - e^{-\sigma s} \rightarrow s = -\frac{\ln(1-\rho)}{\sigma} \tag{2.11}$$

The energy of a neutron changes at every collision with a particle. We assume only elastic scattering, so there is conservation of energy. Applying the conservation laws of energy and momentum, the ratio between the initial energy E and the final energy E' becomes:

$$\left(\frac{E'}{E}\right) = \frac{A^2 + 1 + 2A\cos(\theta)}{(A+1)^2} \tag{2.12}$$

A is the mass of the moderator nucleus in neutron masses. θ is the angle between the neutron and the target in the centre of mass frame. E and E' are both in the lab frame. If θ is 0, there is almost no collision and E'= E, if $\theta = \pi$, there is a head on collision and E' is minimal, as it should behave.

The scattering is assumed to be isotropic. Therefore the new direction of the particle is uniformly distributed in the centre of mass frame.

2.4 Neutron transport in moving media

A method to calculate the transport of neutrons in moving media has been suggested by Wilson, Scott and Pomraning[2]. To calculate the trajectory of a neutron in moving media, the properties of the neutron are transformed to the centre of mass system. The centre of mass means centre of mass of all the moderator nuclei, so the velocity of this frame compared to the lab frame is the average speed of the moving moderator nuclei, which is just the speed of the disc. The new neutron velocity then becomes:

$$\vec{v}'_n = \vec{v}_n - \vec{u}_D \tag{2.13}$$

The primed frame is the centre of mass frame; v_n is the neutron speed, either in the lab frame or in the primed frame. u_D is the speed of the disc in the lab frame. In figure 2.2 the situation of the colliding particle and nucleus in the centre of mass frame is given.

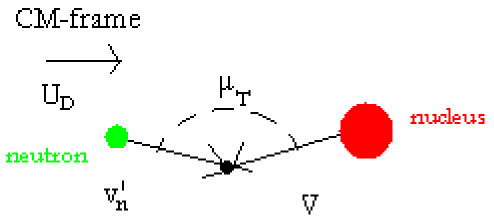

Figure 2.2 Angles and velocities in the centre of mass frame

The direction cosines, A'_b, B'_b, C'_b, which respectively give the angle with the x, y and z axis before the collision become:

$$\begin{aligned} A'_b &= v'_{nx} / \left|\vec{v}_n - \vec{u}_D\right| \\ B'_b &= v'_{ny} / \left|\vec{v}_n - \vec{u}_D\right| \\ C'_b &= v'_{nz} / \left|\vec{v}_n - \vec{u}_D\right| \end{aligned} \tag{2.14}$$

The subscript b implies before scattering and the subscript x, y or z means the x, y or z component. The energy is in the moving frame:

$$E'_b = \frac{1}{2} m \left|v'_n\right|^2 \tag{2.15}$$

In the primed frame the nuclei velocities have a Maxwellian distribution. This is because the centre of mass frame is the rest frame of the moderator. The velocities of distinguishable particles are then Maxwellian distributed according to the kinetic theory. V is the speed of a moderator nucleus.

$$\begin{aligned} P(V) &= \frac{2}{\pi^{1/2}} \beta^3 V^2 e^{-\beta^2 V^2} \\ \beta &= \left(\frac{A}{2kT}\right)^{1/2} \end{aligned} \tag{2.16}$$

The effective scattering cross section becomes

$$\sigma_s^{eff}\left(E'_b\right) = \frac{1}{v'_n} \iint \sigma_s\left(v_{rel}\right) v_{rel} P(V)\, dV d\mu_t \tag{2.17}$$

Here

$$v_{rel} = \left(v'^{2}_{n} + V^{2} - 2\mathrm{v}'_{n} V \mu_{t} \right)^{1/2}$$
$$\mu_{t} = \frac{\vec{v}'_{n}}{\left| \vec{v}'_{n} \right|} \cdot \frac{\vec{V}}{\left| \vec{V} \right|} \tag{2.18}$$

v_{rel} is the relative speed between the neutron and the nucleus it is going to collide with. μ_T is the cosine angle between the neutron and its target. We assume that the cross section is independent of v_{rel} so $\sigma_s(v_{rel}) = \sigma_s^0$

The technique to sample the integral has been developed by Carter and Cashwell[1]. See figure 2.3. First the cosine angle μ_T is calculated using a rejection technique. Then the target's direction is calculated, it is uniformly distributed on the cone that is determined by μ_T.

Then a new direction is generated. This new direction is uniformly distributed, because isotropic scattering is assumed. Finally the new properties of the particle are calculated from its new direction, its starting direction and the mass of the moderator nucleus.

Now we only need to transform the particle back to the lab frame, to let it continue its trajectory. The neutron velocities become:

$$\begin{aligned} v^{n}_{ax} &= \frac{\sqrt{2E'_{a}}}{m} A'_{a} + u_{Dx} \\ v^{n}_{ay} &= \frac{\sqrt{2E'_{a}}}{m} B'_{a} + u_{Dy} \\ v^{n}_{az} &= \frac{\sqrt{2E'_{a}}}{m} C'_{a} + u_{Dz} \end{aligned} \tag{2.19}$$

and the energy and the direction cosines after collision become:

$$\begin{aligned} E_{a} &= \frac{1}{2} m \left[\left(v^{n}_{ax} \right)^{2} + \left(v^{n}_{ay} \right)^{2} + \left(v^{n}_{az} \right)^{2} \right] \\ A_{a} &= \beta v^{n}_{ax} \\ B_{a} &= \beta v^{n}_{ay} \\ C_{a} &= \beta v^{n}_{az} \end{aligned} \tag{2.20}$$

where $\beta = \frac{1}{\sqrt{2E_{a} / m}}$

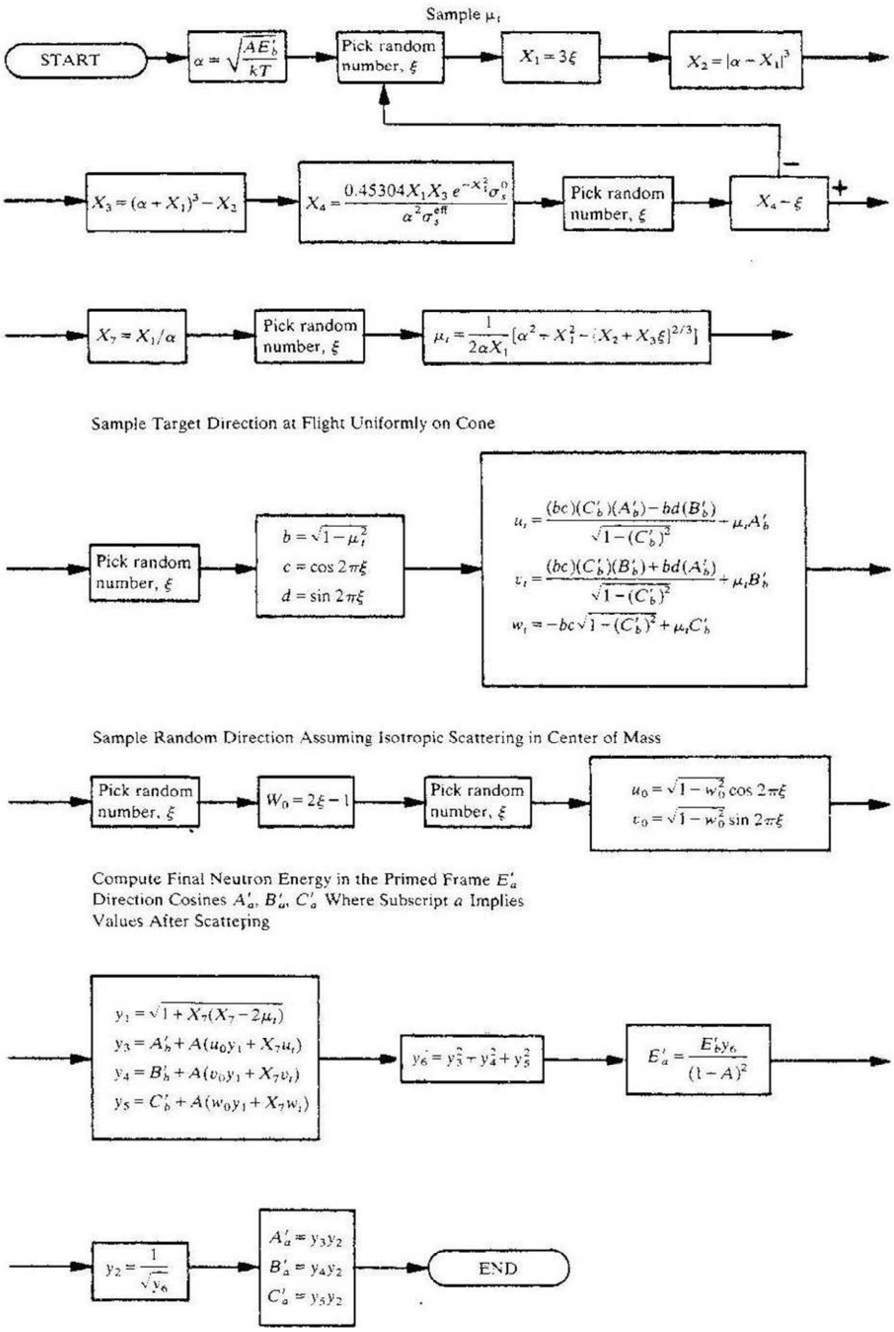

Figure 2.3 Flow diagram for sampling the integral of equation (2.17) First the angle cosine μ_T is generated, then the nucleus direction on the cone of μ_T, next the particle's direction after collision, finally the new properties of the particle are calculated.

3. SETUP OF SIMULATION

The Monte Carlo code especially written for this system is split in two parts. The first part generates a particle at a certain point, with a certain direction and energy. Then, it calls the next part which calculates the actual path of the particle. This second part returns if the detector was hit, and if so what the properties of the particle were at that point.

There can be as many particles created as needed. The properties of all the hits are stored and can be used for postprocessing.

Next the neutron properties are transferred to the centre of mass frame of the moderator at that point. In the centre of mass frame the integral of equation (2.17) is sampled using the technique developed by Carter and Cashwell. The steps of this technique are shown in figure 2.3.

3.1 Generating the effective cross section

The particles' speed and direction after the collision are transferred back to the lab frame. In the lab frame, the new path length is calculated using equation (2.11). If the particle is outside the moving disc, this is straightforward. However if the particle is inside the rotating disc a correction has to be made for the speed of the moderator. The cross section that the particle sees is not the normal cross section, but because of the speed of the disc more moderator nuclei come past the neutron and it has a higher probability to interact with one of the moderator nuclei. An effective scattering cross section must be calculated. Carter and Cashwell[1] suggest the following method:

$$\sigma_{eff} = \sigma \frac{v_{cm}}{v_l} f\left(a,v\right) \tag{3.1}$$

where

$$\begin{gathered} f\left(a,v\right) = \frac{1}{v_{cm}\sqrt{\pi a}} e^{-av_{cm}^2} + \left(2 + \frac{1}{av_{cm}^2}\right) erf\left(v_{cm}\sqrt{2\mathrm{a}}\right) \\ erf\left(x\right) = \frac{1}{\sqrt{2\pi}} \int e^{-t^2/2} dt \end{gathered} \tag{3.2}$$

and

$$a = 5.18\left(10^{-13}\right)\frac{M}{kT} \tag{3.3}$$

v_{cm} is the relative speed between the particle and the moderator. v_l is the speed of the particle in the lab frame. M is the mass of a moderator nucleus in amu; kT is the material temperature in eV.

If a particle's path runs from inside the disc to outside, or vice versa, the effective cross section changes dramatically. The velocity of the centre of mass frame is equal to the speed of the disc at that point. At the radial edge of the disc it is the highest. Outside the disc it is zero. In this case the path until the edge of the disc is calculated with the first effective cross section and then from the edge onward the path is calculated with the new effective cross section.

The program then checks if the particle has hit the detector or the edge of core. If that is the case, the run of the particle ends. If the detector is hit, all the properties of the particle are returned, otherwise, a new particle is created at a random location, with a random direction, and the calculations start over again.

If nothing is hit, the final step is to check if the particle is absorbed. If so the run also ends, if not it loops to the beginning of the program and calculates the speed of the moderator at that point.

In this simulation the disc and the rest of the moderating material were both consisting of water. This can however be easily changed.

One thermal group cross sections have been used. This can be justified, because the neutrons are during most simulations at thermal energy. This is where the neutrons feel the effect of the rotating disc and this is the interesting part.

3.2 Processing hits

In a real setup the detectors would be beam tubes, from where the neutrons are guided out of the core, and transported to place where they are needed. In this simulation the beam tubes are replaced by detectors. If a neutron hits this detector, its direction is recorded.

In the postprocessing it can be determined if the neutron would have entered the beam tube. The beam tube accepts only neutrons that are within 1 degree of the direction of the tube. In figure 1.1 it is shown that if the particle enters with a larger angle it will hit the wall and not reach the end of the tube.

During the postprocessing an angle is given to the beam tube, and then the number of neutrons that would enter the beam tube in that direction is counted. The big advantage of storing all hits and postprocess it later is that the best angle of the beam tube can easily be determined.

Also the relation between the angle of the beam tube and the average energy of the neutrons can be measured. As seen in figure 3.1 the angle of the beam tube can be shifted from $-\pi$ to π. Since the beam tubes accept neutrons within 2 degree radius, 90 bins have been made, this way at all angles there is exactly one tube and all detector hits enter exactly one tube. Now a plot can be made where every bin represents a tube.

The radius of the disc is chosen to be 10 cm; it has to be large enough so that the neutrons can interact with the disc and can be influenced by its speed. Therefore the neutrons must have a few steps inside the disc, which means that the mean free path of the neutrons must be small enough compared to the disc. In the case of this simulation the mean free path is around 0,3 cm. The rotating speed is varied, to see the relation between the spinning speed and the neutron yield.

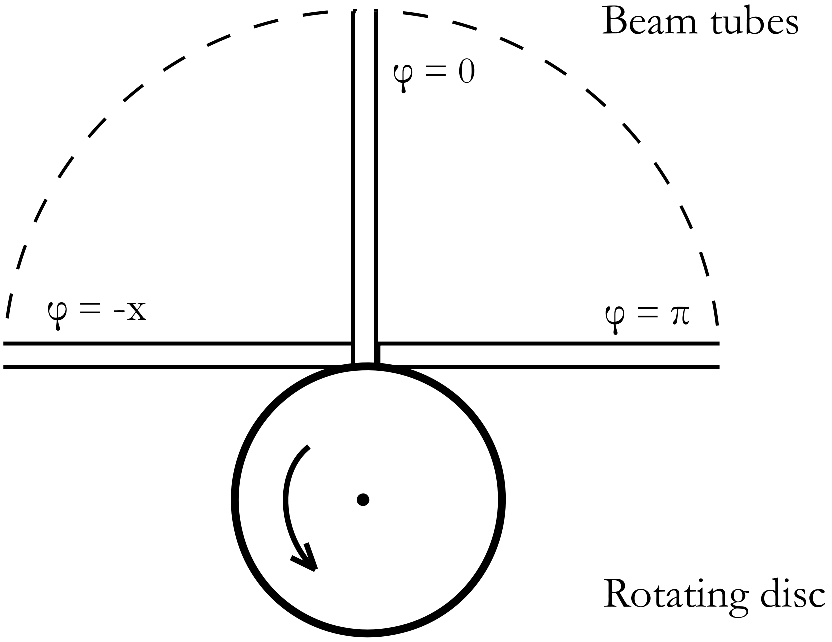

Figure 3.1 The possible directions of the beam tubes at the point of the detector

3.3 The behaviour of a neutron without a moving disc

In order to see if the program worked properly some tests were done. First the paths of a few particles were plotted, some with a rotating disc and some without. It was clear that a particle that did not enter a rotating disc had a random path as expected. This is shown in figure 3.2, the starting energy of the neutrons was 1 eV, and in a few steps that became below 0.1 eV. This was done to see if the system still had moderating properties.

The energy of a neutron does reduce to about thermal as can be seen in figure 3.3. This was the neutron of the trajectory of figure 3.2. It starts at 1 eV at a uniformly distributed location in the core and since there is no spinning disc it doesn't matter if it enters the disc or not.

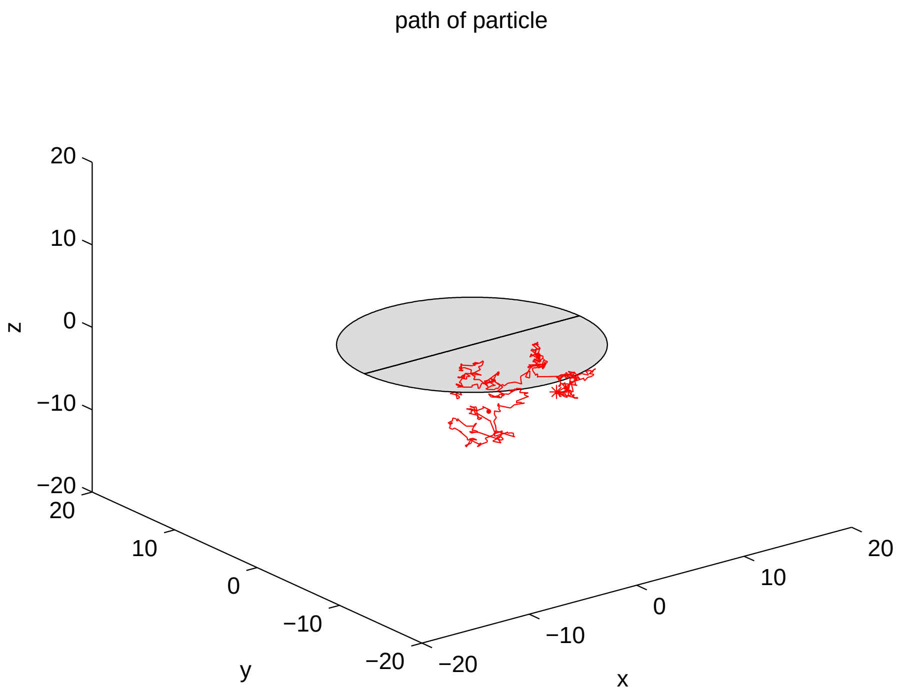

Figure 3.2 A typical neutron trajectory if the disc is stationary

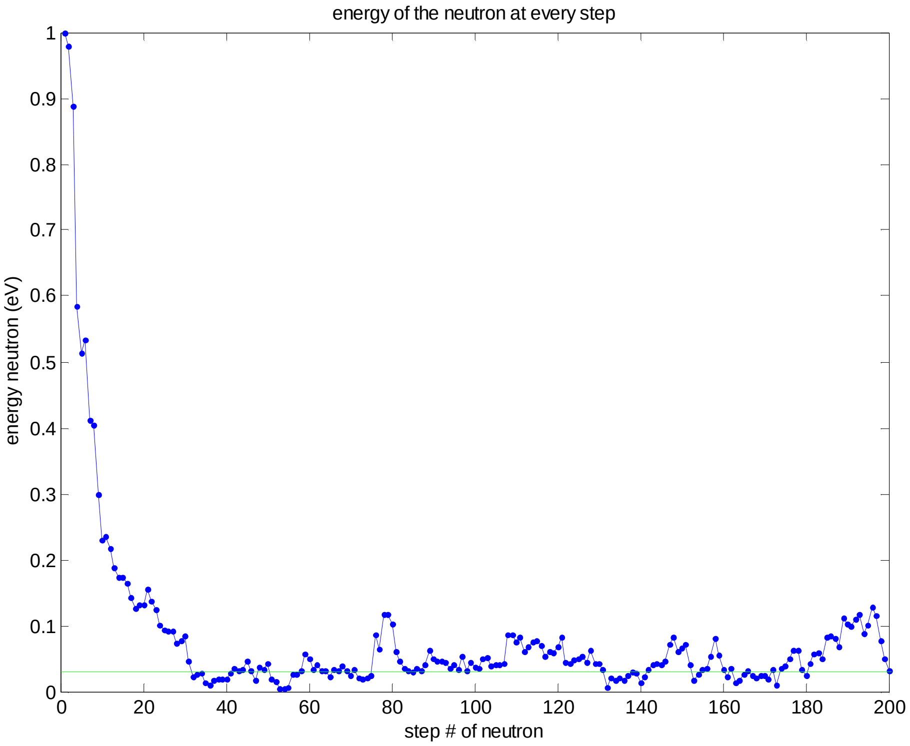

Figure 3.3 The energy of a neutron at every step of its trajectory through a core with a stationary disc, the green line indicates thermal energy

3.4 The interaction of a neutron with the spinning disc

In the situation were the disc had a high rotation speed, the particle is clearly pulled along with the rotation of the disc as shown in figure 3.4. The particle starts at the dot and ends its path at the cross, so it clearly spirals outward. Also the particle stays more or less in a 2D plane. This is expected, because of the speed it gets in the direction parallel to the plane. This is exactly the behaviour that the system should have.

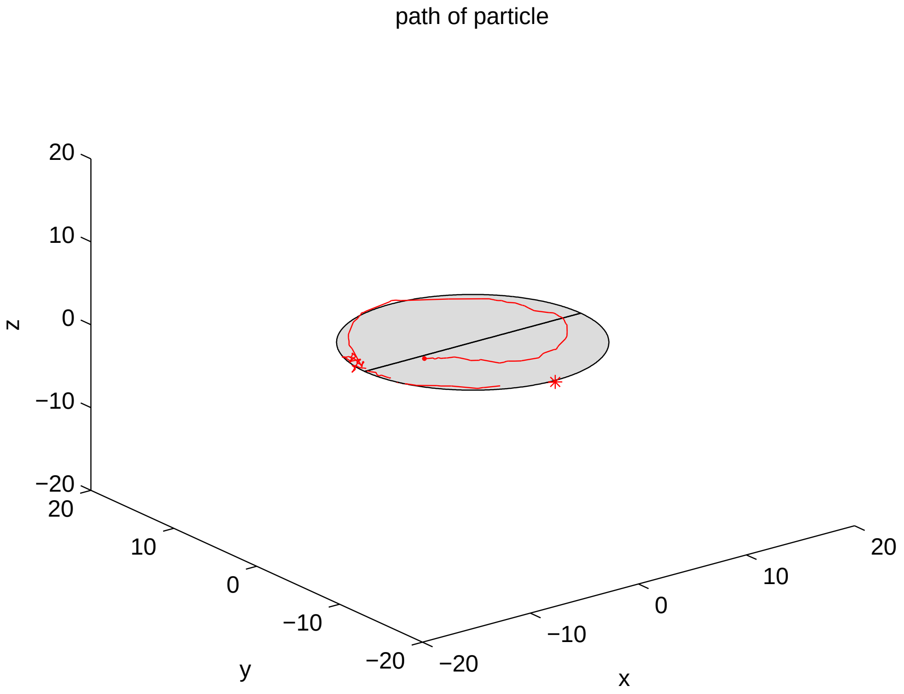

Figure 3.4 A typical neutron trajectory with a spinning disc

The neutrons in a system without a spinning disc cool down to the energy of thermal neutrons. This is the way the system should behave. In systems with a spinning disc, the energy is higher than without a disc. This is expected, because the particle has its thermal speed, but that is for the centre of mass frame. For the lab frame the average speed will be higher, because the speed of the disc has to be added to the speed in the centre of mass frame. On average the velocity and the energy of the neutrons will be higher.

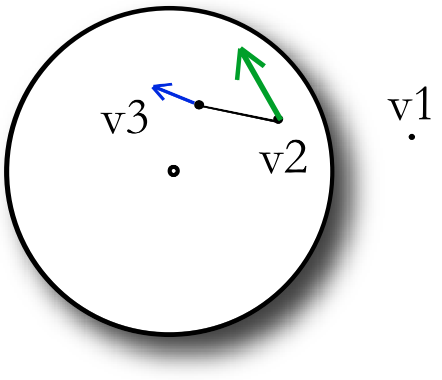

Figure 3.5 Disc speed differences along a path of a neutron

The velocity of the moderator is assumed to be constant along a step length of a neutron. This is allowed, although the total cross section and therefore likelihood that a particle scatters is dependent on the speed of the disc at the location of the particle.

This is demonstrated in figure 3.5. At v1 there is no velocity; at v2 there is the largest velocity. The velocity at v3 is slightly less and in another direction than at v2 but still comparable.

The step length is directly related to the probability a particle has to scatter. However the difference in effective cross section at the beginning of a step and at the end of a step differ not a lot as explained in section 3.1. This influences the step length very little except at the border between the disc and the normal moderator. The Poisson distribution of equation (2.11) allows that the program can stop the particle at the edge of the disc and then generate a new path length from there.

3.5 Properties of the physical system

In reality there is no detector but a beam tube that will guide the neutrons out of the core. A beam tube only accepts neutrons typically within 1 degree. The neutrons exit the disc at a certain angle and to get a yield as high as possible it is needed to find out at what angle the most neutrons exit. Then the beam tube can be made in that direction. This is the maximum exit angle.

For the disc a radius of 10 cm has been chosen and a thickness of 2 cm. The mean free path is 0.3 cm so this gives the neutrons enough time to feel the movement of the disc.

The material of the moderator and the moderating disc where both water, the total cross section used is 3.26482 cm^{-1} and the scattering cross section is 3.24598 cm^{-1}. Here the neutrons are assumed to be only in the thermal energy group.

For the temperature of the moderator 300 K was used. This is equal to an energy of 0.026 eV.

The particles where generated near the spinning disc, at a random place in a box of 20 x 20 x 20 cm around the disc. The size of the core was an almost infinitely large sphere, with a diameter of 40 m.

3.6 The yield increasing mechanisms

The following mechanisms to increase the yield are separately discussed in chapter 4. The first is the effect that due to the centrifugal effect more neutrons will spin out of the disc. This will increase the total amount of hits at the detector.

The second effect follows directly from the first. Because the neutrons remain in the plane of the spinning disc the direction of the neutrons will also be more in the plane of the spinning disc, as already demonstrated in figure 3.4. Therefore the direction of the neutron will have on average a smaller angle with the plane of the disc. In the case of this simulation that is the x-y plane.

The third effect is that neutrons will be forced to leave the disc at an angle. This is the maximum exit angle seen in figure 3.1. This happens because the neutrons have their own speed but also get a speed from the rotating disc. As this speed increases, it forces the neutrons into one angle. From the total number of hits, 90 bins are made. Each bin is 2 degrees wide, which maker every bin equal to a fictional beam tube that has no z-angle dependency. The number of hits in a bin would mean that a tube at that point would have that number of neutrons entering.

At the end all these effects are put together and the total increase in yield will be examined. Here every bin can be translated as a beam tube. The number of hits in a bin is the number of hits a beam tube in that direction would generate.

The effects are first split up and then at the end combined because if both angles are taken into account the statistics become less reliable. The number of hits is too small. It does give a good indication of what can happen.

4. RESULTS

4.1 Number of detector hits

The first aspect which is tallied is the total amount of hits that is generated. The speed of the rotating disc is slowly increased from 0 to 10^6 rad/s, which is 160.000 revolutions per second. As can be seen in figure 4.1 at first the yield doesn't increase significantly. Then around 10^4 rad/s the number of neutrons starts to increase. After 10^5 the amount of hits doesn't increase significantly. The yield at the maximal spinning speed is 3,5 times higher than without a spinning disc.

A green line has been put into the figure to indicate the moment where the edge of the disc reaches the speed of thermal neutrons. As expected, the neutrons start to feel the influence of the disc from around the moment the disc reaches that speed.

Close to the centre of the disc the speed due to the rotation is of course lower. At the red line 95% of the disc is above the thermal velocity.

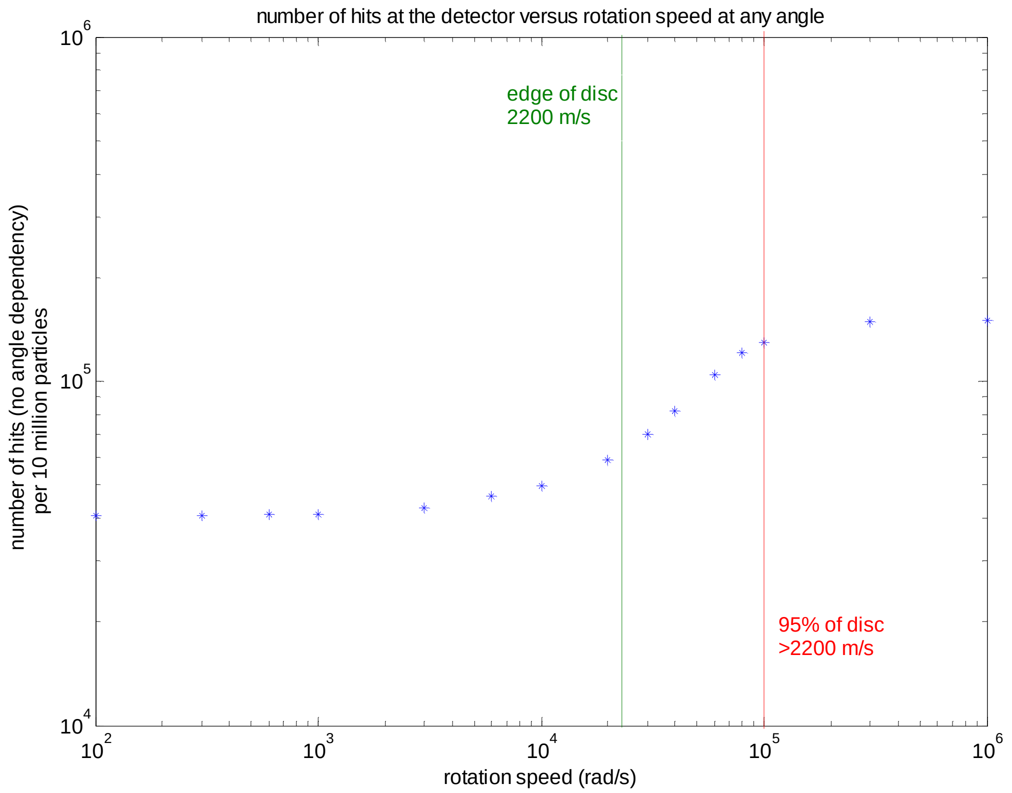

Figure 4.1 Total amount of hits on the detector versus rotation speed of disc

4.2 Number of hits in plane

Now the fact that a beam tube can't accept all incoming particles is taken into account. Here the z-angle dependence is taken into account. The total of hits is now lower but the increase is higher.

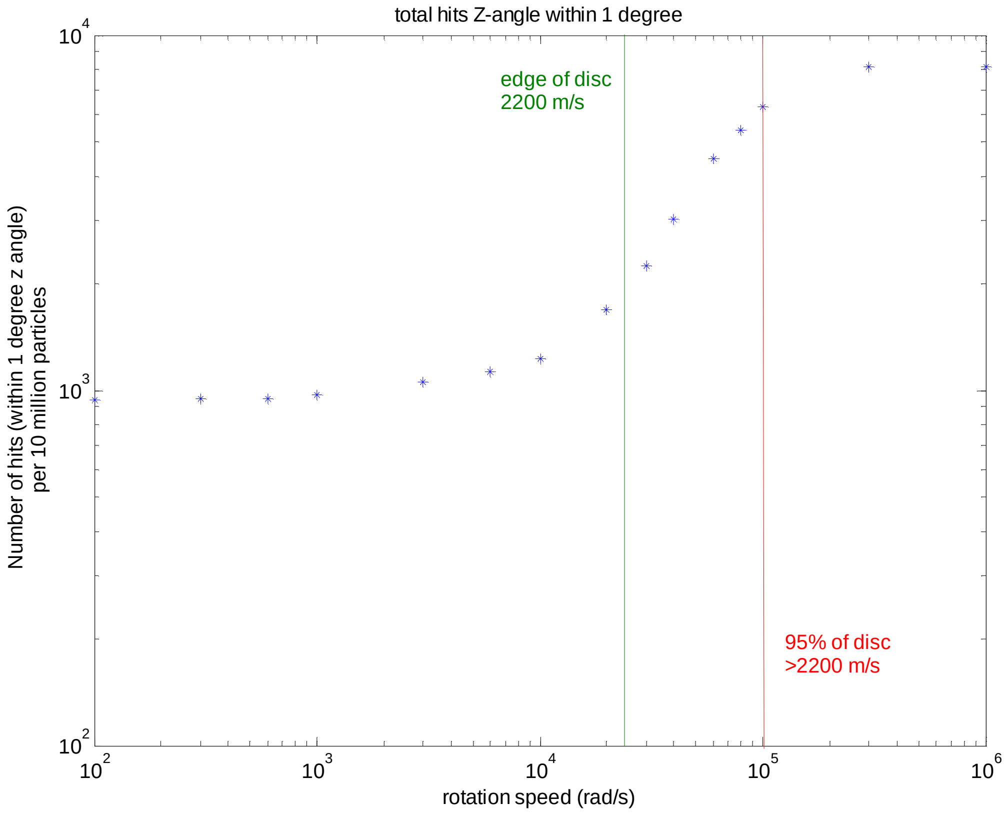

Figure 4.2 The number of neutrons hitting the detector within 1 degree of the x-y plane

Figure 4.2 shows the yield when a beam tube only accepts neutrons within 1 degree in the z-direction. The fact that the spinning disc forces the neutrons in a plane, means that the neutron paths will have less angle with that plane and therefore with a spinning disc relatively more neutrons will enter the tube. The total yield is of course less than if all neutrons are taken in account, but the increase is now up to 8,5 times more than without the spinning moderator

4.3 Neutrons at the maximum exit angle

4.3.1 Yield at the maximum exit angle

Next the direction of the neutrons that hit the detector is taken into account. Due to the speed of the rotating disc, the direction is highly influenced. This is because the velocity of the neutrons consists of two parts. The velocity the neutrons have compared to the centre of mass frame and the velocity of the centre of mass frame has compared to the lab frame of the detector. This second part adds a bias to the average angle.

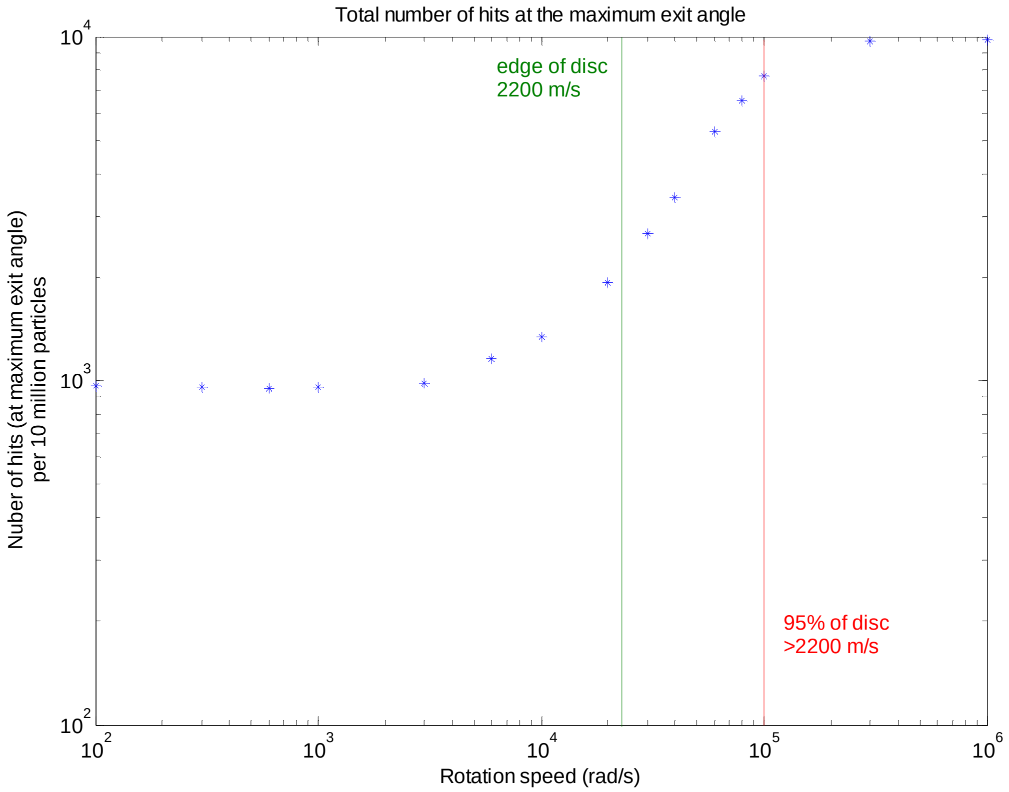

Figure 4.3 The number of neutrons hitting the detector at the maximum exit angle

As seen in figure 4.3 the yield at the maximum exit angle also increases with the rotation speed. The location of the maximum exit angle changes as will be discussed in section 4.3.2, but as long as that location is known a lot higher yield can be realized. At the maximum rotation speed the yield is 10 times higher than with no disc.

The increase seems to start a little bit earlier than for the increase due to the previous two mechanisms. However this can also be, because this mechanism has a larger effect on the yield.

4.3.2 Dependency of the energy on the exit angle

The energy is also expected to be dependent of the direction of the neutron. If a neutron comes out in the direction of the rotating movement, it is expected that the neutrons are relatively hot. If they are in the opposite direction they are expected to be relatively cold.

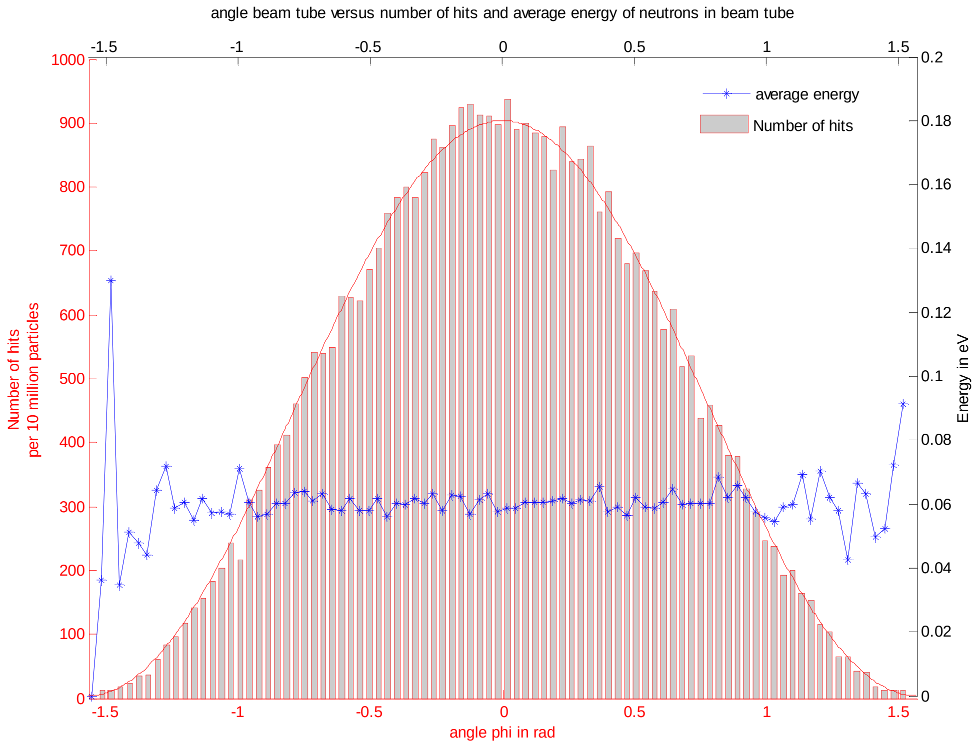

Figure 4.4 Number of hits and average energy of the neutrons versus beam tube angle at a rotation speed of 0 rad/s

The first situation is when the disc is not moving. The results are plotted in figure 4.4. The distribution of hits has no preference for left or right. It is also more likely that a neutron flies straight out of the disc, then at a large angle. That is also logical, because there is no moving disc yet. The average energy of the neutrons is approximately the speed of thermal neutron. That is what is expected. This looks exactly like a cosine distribution as can be seen from the plot. The thin red line is the exact cosine distribution.

At the maximum exit angle approximately 1000 neutrons enter the beam tube. That number is used to compare the gain at the higher rotation speeds.

A beam tube can accept only neutrons that differ 1 degree from the beam tube angle, so a beam tube that is at 0 degree, accepts only neutrons from -1 degree to 1 degree.

At the edges of the plot the graph starts to oscillate. This is due to the fact that there are very few hits at the borders, so the statistics are not reliable in that region. The regions with just a few hits are not important, so this effect can be neglected.

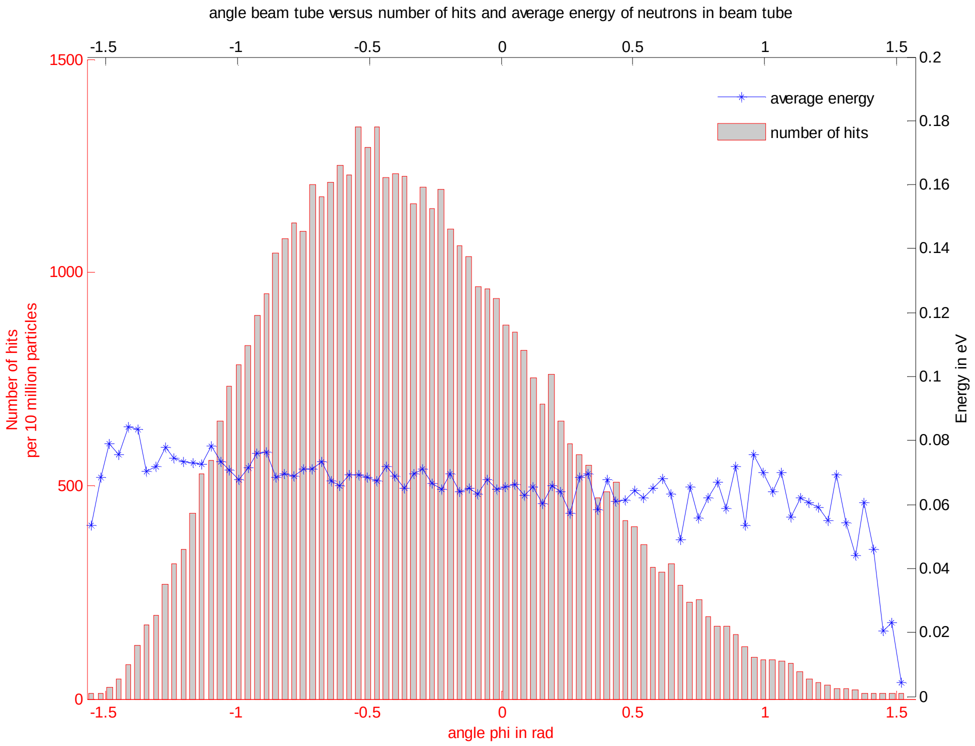

Figure 4.5 Number of hits and average energy of the neutrons versus beam tube angle at a rotation speed of 10^4 rad/s

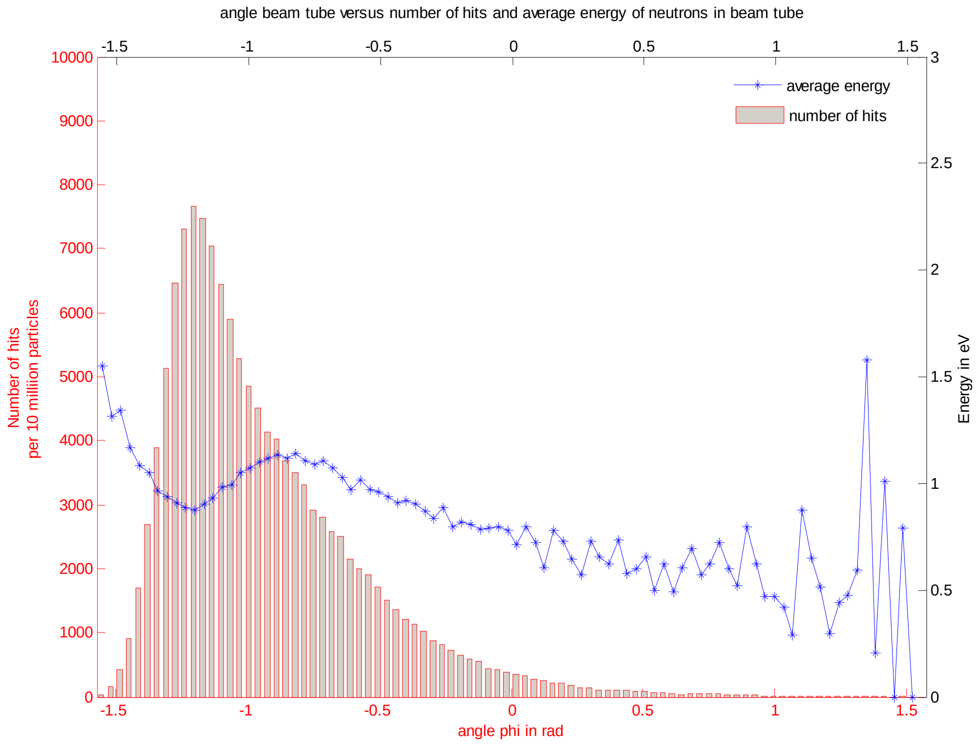

Figure 4.6 Number of hits and average energy of the neutrons versus beam tube angle at a rotation speed of 10^5 rad/s

At a speed of 10^4 rad/s the first shift is seen. As shown in figure 4.5, the maximum isn't exactly at 0 degree, and a small average energy increase is seen at a lower angle, which is an angle that is in the direction of the rotation. The average energy has increased slightly. The yield of a single beam tube has increased to nearly 50% more than with no speed, where the number of neutrons that hit the detector only increased around 25%. This trend is seen at higher rotation speeds. The maximum exit angle increases and the neutron yield increases.

At a speed of 10^5 rad/s something interesting happens. This can be seen in figure 4.6. Here the average energy of the neutrons has a local minimum at the maximum exit angle. Compared to lower rotation speeds the average neutron energy still increases, but it isn't monotonous increasing at greater angles. The yield is here 8 times the yield of the same system with no spinning disc.

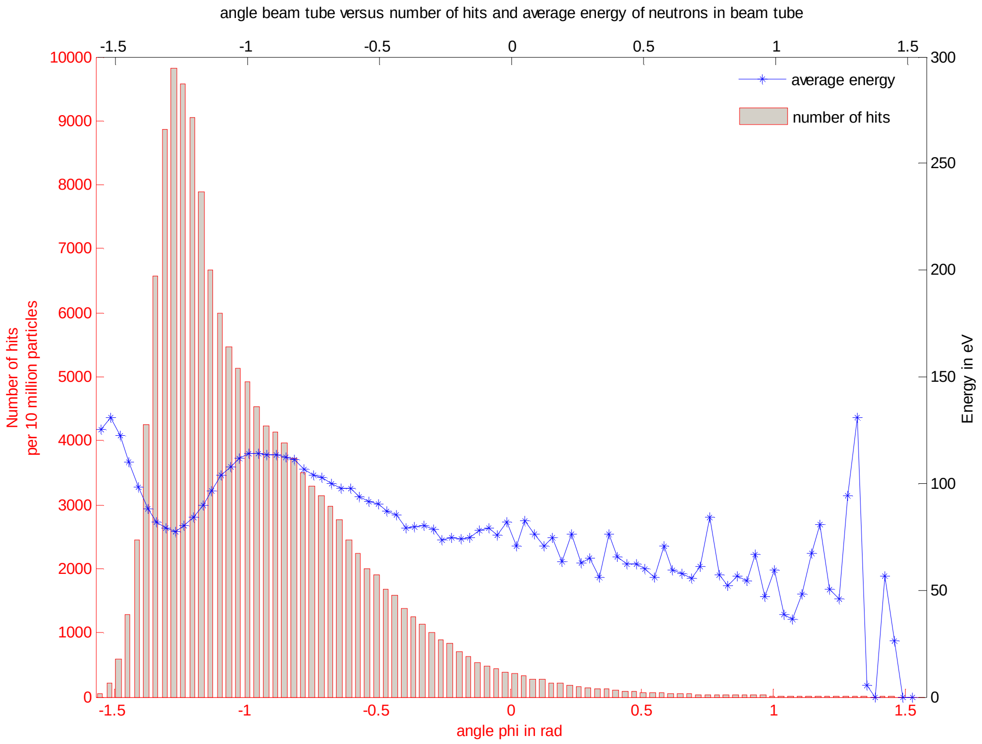

Figure 4.7 Number of hits and average energy of the neutrons versus beam tube angle at a rotation speed of 10^6 rad/s

At the highest measured speed, 10^6 rad/s this effect is even more obvious, as seen in figure 4.7. The average energy of the neutrons is higher than with the lower rotation speeds, but it does decrease around the maximum exit angle compared to the smaller exit angles. The yield at the maximum is 10 times higher than without rotation. The total yield of all beam tubes together is increased only by 350%.

Finally in figure 4.8 the angle that is the maximum exit angle is plotted against the rotation speed. Here it is shown that the maximum yield moves to a greater angle. This happens at the same moment where in figure 4.3 the yield starts to increase. As the yield and the angle do not increase a lot any more after the disc hits 10^5 rad/s, this seems to be related.

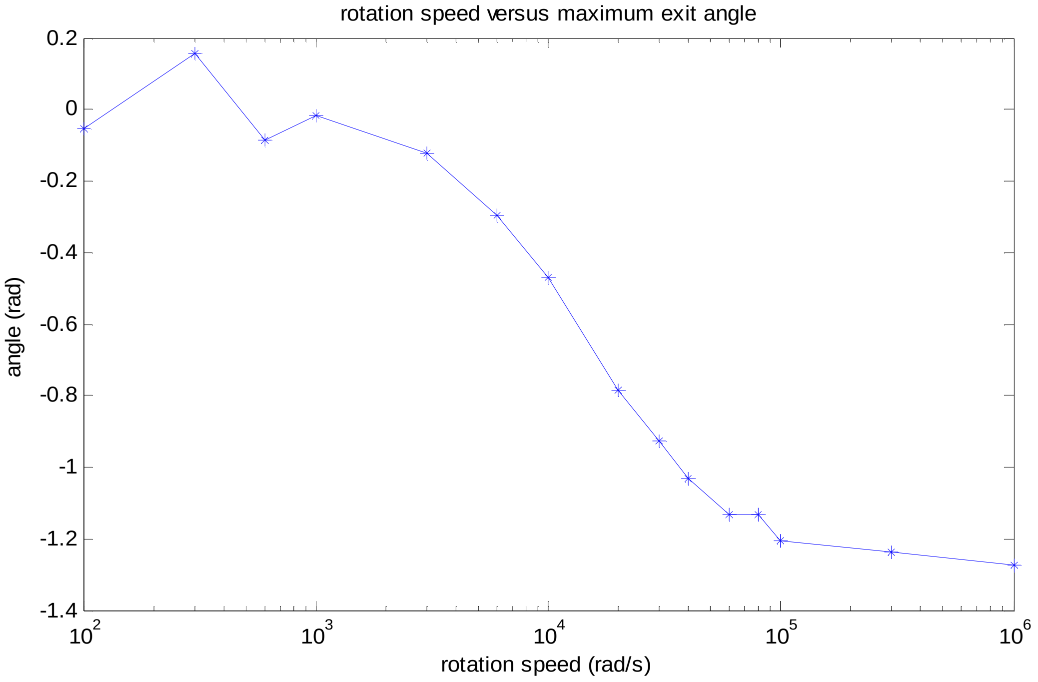

Figure 4.8 The angle of the maximum exit angle versus the rotation speed

4.4 The energy gain

With the increase in rotational speed the average energy of the neutrons that exit the disc also increases. In figure 4.9, the average energy of the exiting neutrons is plotted together with the energy a neutron with the speed of the edge of the disc would have. The velocity of the neutrons is at first just above thermal velocity. When the discs edge reaches thermal velocity the energy of the neutrons increases together with that of the disc.

To main fact is that whereas the yield doesn't increase anymore after 95% of the disc reaches thermal speed, the energy keeps on increasing.

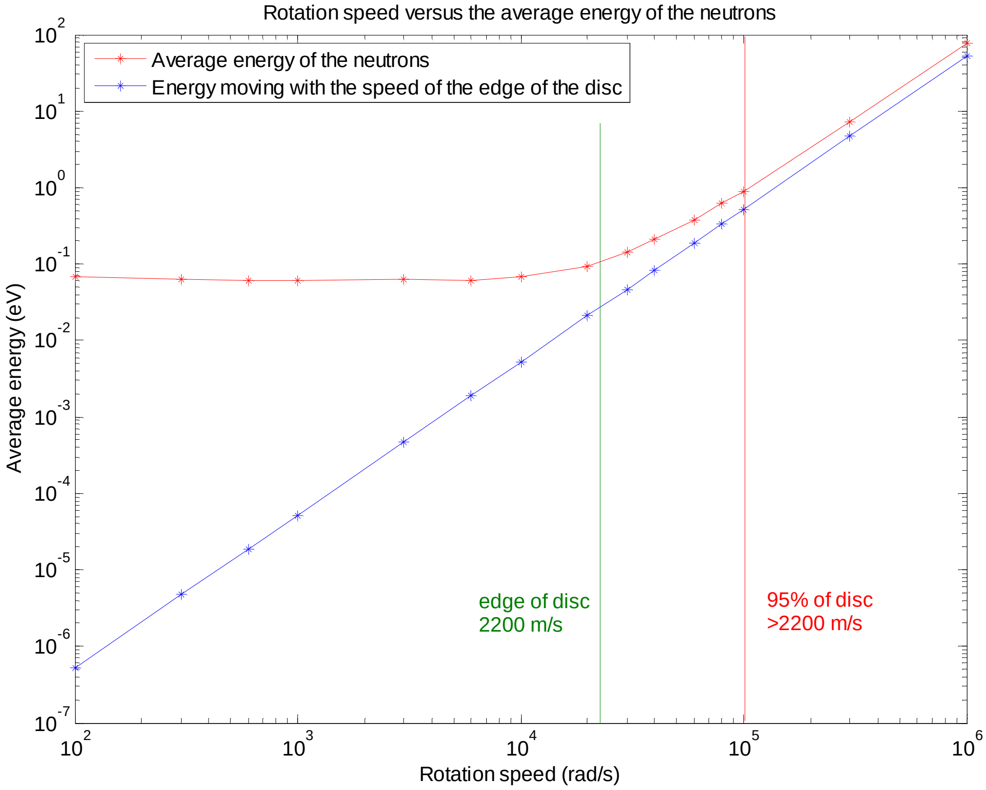

Figure 4.9 The average energy of the neutrons that hit the detector

4.5 Total possible extra yield

Of the final case where all angle dependencies are incorporated the results can be seen in figure 4.10. The increase gets up to 30 times the amount of neutrons that enters a beam tube without a spinning moderator disc. Although this result is promising the number of hits is very low and the statistics aren't very reliable anymore. However this postprocessing does resemble the reality of the beam tubes the best.

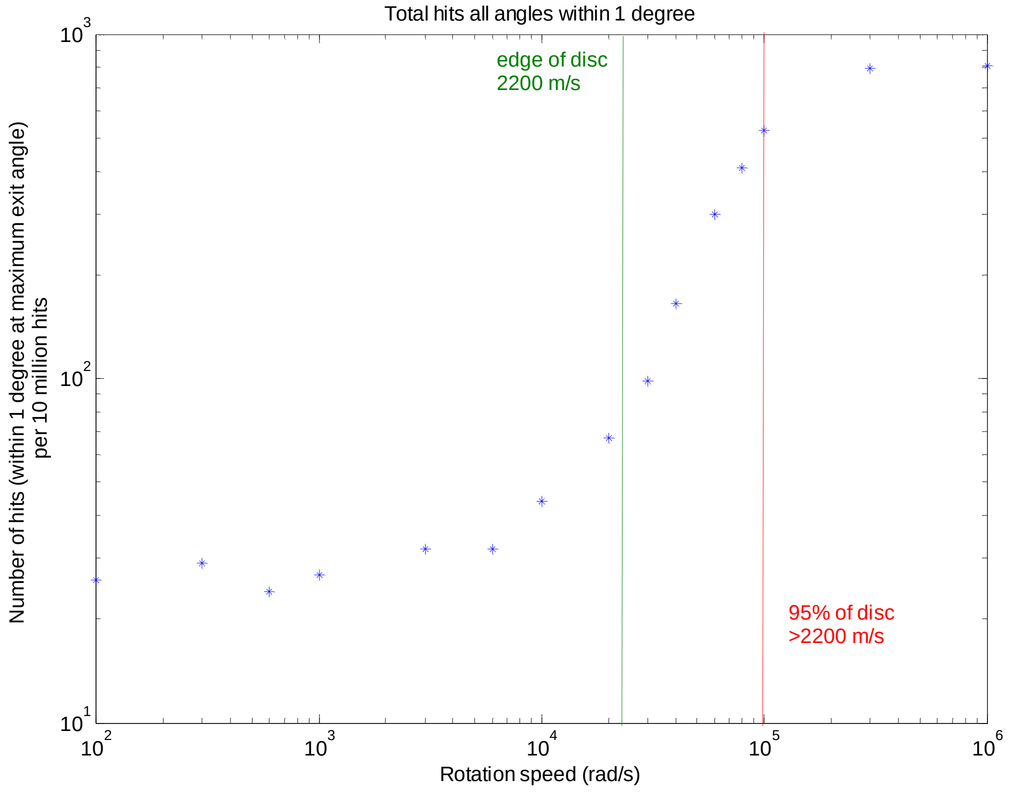

Figure 4.10 Total number of neutrons that enter a beam tube at the maximum exit angle

5. DISCUSSION

5.1 Assumptions

For this simulation the assumption has been made that the neutrons are mostly in the thermal group. As seen in figure 4.9, this is valid for the lower rotation speeds, but for the higher rotation speeds, this is not the case. The results from that region are therefore less reliable. However the conclusion, that the neutrons become more energetic holds. From a rotation speed of 10^5 rad/s and upward, the average neutron energy becomes epithermal.

The neutrons are set to start at an energy of 1 eV. This is done to see if the neutrons cool down as they are supposed to do. This is the case. It happens in just a few steps and therefore the fact that the starting energy is slightly high will not influence the outcome significantly.

In reality the energy of the entering neutrons depends on the setup of the system. If the disc is placed in the middle of a core, the energy of the neutrons can be a lot higher. If the disc is placed outside the core and there is already some moderating material in between the neutrons can already been moderated to thermal neutrons.

In this simulation the neutrons start at a uniform distributed place in the moderator. In a real life situation the starting position and direction are not as uniform as in this code. It is likely that the spinning disc is on one side attached to the neutron source. The neutrons then will enter the disc from one side with a non-uniform distributed direction. The layout of the disc and the neutron source may influence the outcome of the experiment.

To investigate the average energy of the neutrons that are not in the main direction, a lot more simulations must be done. There the yield is very low, so there can't be anything said about the average energy.

It is also assumed that the speed of the moderator is constant along the length of a path. This is especially important for the effective cross section and therefore the path length of a particle. A look at the difference in effective cross section at the beginning and the end of a particles path showed that only where the particle crosses the boundary of the disc the difference is significant.

Also in this code the beam tubes are replaced by detectors. This increases the efficiency of the program significantly, since it can now calculate the yield for all possible beam tubes in one run, but this might introduce uncertainties. The behaviour of a beam tube is different from that of a detector, especially neutrons that haven't got the right angle for the beam tube, but hit the beam tube, might scatter in the right direction for the beam tube. With detectors this is not possible. This will only affect a small number of neutrons.

5.2 Choices in the program

To simulate the trajectories of the neutrons a Monte Carlo code was written, this is done because it is very hard, if not impossible, to calculate the neutron transport in moving media with ordinary transport equations. For the Monte Carlo code, it didn't become a lot more complicated. The only extra step was to transfer the neutron from one frame to another. Of course this is done many times, so the calculation time does increase, but the complexity doesn't increase that much.

The computer code has been written in FORTRAN, because this kind of repetitive calculating is fast in FORTRAN. This was necessary because the calculating time was more than 160 hours for all the simulations on a 2.0 GHz pentium.

However the graphics are more easily done with Matlab, this is why the program was split in a calculating part and a part with the postprocessing and graphical output.

5.3 Discussion of the results

The graphs of the average energy in section 4.3.2 are rough side regions of the graph. This can partly be explained by the fact that there aren't a lot of hits at those angles. That influences the statistics. However the fluctuations are larger then one would expect.

It also seems that for the higher rotation speeds the fluctuations on the left are smaller than on the right. This can be because the energy the neutrons gain from the disc are not as random as the energy they get from thermal collisions. However this can also be merely an optical illusion, because there are fewer bins on the left side than on the right side.

The energy of the neutrons in a system without a spinning disc is not exactly 0.025 eV but a little bit higher as seen in figure 3.3 and figure 4.9. This is not a very big influence on the behaviour of the particles, but it is an inaccuracy that must be further investigated.

5.4 Interpretation of the results

The decrease in average energy seen in figure 4.6 and figure 4.7 for the maximum exit angle can also be a result of the assumption that there are only thermal neutrons. In fact, when the dip in average energy occurs, the neutrons should become above thermal. This means that the effect could be just the effect of reaching the boundaries of the assumptions made.

There are some problems in the practical use of the simulation. One of the problems is that the spinning moderator increases the average energy of the neutrons. Even worse, the higher the gain, the higher the average energy increase is. This way the effect of moderating becomes undone. There is no use in a higher yield if this means that the neutrons become useless.

A solution can be to make a trade off between the gain and the average energy. The rotation speed can be adjusted to the energy needed. One cannot get the maximum gain, but the neutrons are still very useful.

Another solution can be the properties of the moderator. In this case water is used, but maybe with a material with different moderator properties, there can be a little bit lower average energy. This probably cannot help much though, because the average energy increase is due to the fact that the neutrons are pulled along with the rotating disc and that disc is spinning at a higher speed than that of thermal neutrons.

Another option could be the phenomenon that is seen at the rotation speeds above 10^5 rad/s. As seen in figure 4.6 and figure 4.7 the energy of the neutrons decreases if the beam tube is put at an angle where the maximum yield is. It is unknown what causes this phenomenon, but maybe the effect can be used to decrease the energy of neutrons that enter the beam tube. To study this region, more neutron energy groups must be used.

It will also be difficult to create a disc with the spinning speeds of the simulation. The rotational speed record of a man made artefact is $2.1\text{x}10^6$ rad/s, but this is only a steel ball with a diameter of 0.8 mm, this was done by Jesse Beams in 1946 [6]. A microfabricated gas turbine can reach a rotational speed of the magnitude 10^5 rad/s, see L. X. Liu et al [7]. An ultracentrifuge is an object that has approximately the same dimensions as the moderator disc in this setup and has a rotational speed of the order 10^4 rad/s as seen on the site of Beckmann Coulter [8]. It will be a challenge to produce a rotating disc with a velocity of 10^4 rad/s or even faster.

6. CONCLUSION

The aim of this research was to see if a rotating moderator disc could enhance the neutron yield. This seems to be the case. The neutrons however are heated by the spinning moderator.

The total amount of neutrons that hit the beam tube increases from the moment the moderator spins with a speed, larger than 10^3 rad/s. This continues until the disc hits 10^5 rad/s then a maximum is reached and the yield doesn't increase significantly. This is a very promising result.

Figure 4.10 shows the total number of neutrons that enter the beam tube in this simulation. Although the number of neutrons entering a beam tube is not high enough for reliable statistics is does show that taking all three effects into account the yield increases quite a lot.

Altogether this technology could be very useful to boast neutron production in neutron sources around the globe. A significantly increase in neutron yield can be achieved. More research is needed to see what materials could be used best and what would be the optimal dimensions of the system.

It is also unknown why there is a reduction in average neutron energy at the maximum exit angle at high rotation speeds. This phenomenon should be further investigated.

Another aspect that hasn't been looked into is the feasibility of the rotation speeds used in this simulation. The speeds needed for influencing the neutron trajectories are very high, and it will be hard to create a rotating object with such speeds. Also the properties of the materials inside will be influenced by such rotations.

Another property that could be an interesting aspect of the rotating disc is that if the beam tube is aimed differently the average energy of the neutrons can be varied. This seems to be true for higher rotation speeds.

However if looked more closely, the relative cool neutrons are still more energetic than thermal neutrons. Also the yield is very low. This makes the rotating moderator not very suitable for creating cooler neutrons. In practice it might be interesting to be able to change the average energy of the neutron beam simply by adjusting the direction of the beam tube.

In this study only one type of disc is used. It is possible that different discs give other results. For example the size and the material of the disc can be changed, that might give lower energies for the neutrons that hit the detector or lower spinning speeds.

For more calculations the adjoint Monte Carlo method might be used to speed up calculations and to get better statistics. Now a typical simulation using 10^7 particles took approximately 10 hours on a 2.0 GHz Pentium computer. This is per rotation speed. If you want to run more simulations, with bigger numbers, to see what the other variables influence the behaviour of the system and gaining better statistics, this must be a lot faster.

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