Measurements of the packing factor for the COMPASS polarized target
summer student report

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Contents

1 Introduction

In the COMPASS experiment, target material ^{6}LiD is filled in two cells to be irradiated by muon beam, in order to study the spin structure of nucleons.

The distribution of the ^{6}LiD grains inside the cells and the material content are needed to understand the geometrical cuts used in asymmetry analysis and also to determine the dilution factor for the data analyzes. However, since there is space between the ^{6}LiD 2-4 mm crystals, the amount of ^{6}LiD filled in the cells is not obvious, even though we know the precise size of the target cells.

I measured the volume of the dummy particles filled into the cells, and then simulated the filling of particles in a cylinder.

2 Measurements of the packing factor

2.1 Preparation for the measurement

The target cell is divided into two cells as in Fig. 1. The target materials in the two cells are polarized in the opposite direction to each other to cancel the false asymmetry due to time-dependent variations in the beam intensity.

Each of the cells, referred to as upstream and downstream cell, has a cylinder shape and the size is approximately 600 mm long and 30 mm in diameter. The calculated volume for the cells is 424 cm^3.

The packing factor of the target cell is defined as the ratio between the volume of the materials loaded into the cell and volume of the cell

$$PF = \frac{V_{\rm mat}}{V_{\rm cell}}. \tag{1}$$

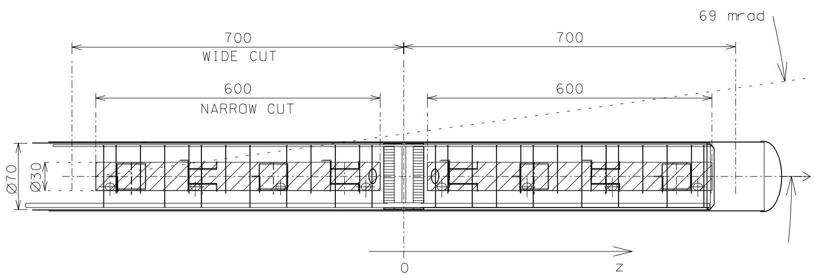

Figure 1: A brief picture of the target cells. The two cells are referred to as upstream and downstream cells. Each cell has a cylinder shape and the size is approximately 600 mm long and 30 mm in diameter. The calculated volume for the cells is 424 cm^3. The upstream and downstream target cells are hatched for clarity.

The volume of the ^{6}LiD material can be known by dividing the total weight of the unloaded material by the density of ^{6}LiD. The total weight was already measured before, and the density is also known to a good accuracy. So the only value which is needed in order to determine the packing factor is the volume of the cell. In the COMPASS experiment, ^{6}LiD was kept in LN_2 at 77 K and was loaded into the cell. The shrinking of the cells (made of epoxy impregnated polyamide mesh reinforced with kevlar thread) in low temperature should be taken into account. Hence, even though we know the exterior size of the cells, we still have to measure the volume of the cells.

In order to measure the target cell volume, the cells were cooled inside LN_2 bath and filled with dummy particles whose thermal shrinking is negligibly small, and then after unloading the dummy particles, the volume of the dummy particles were measured with a measuring glass tube. A similar measurement was carried out in room temperature, using two different kinds of dummy particles.

The two dummy particles were quartz grit and plastic beads. They are shown in Fig. 2. The shape and size of each quartz grit had a wide variety, but the typical diameter was 3 mm and the length was 6 mm. Compared to this, plastic beads were quite uniform and the shape was close to a sphere. Also, the plastic beads were slippery.

Since there is space between particles in the measuring cylinder, the packing factor of the measuring cylinder had to be determined first in order to know the amount of particles which was filled in the cells. Therefore, after filling the measuring cylinder with particles up to a certain scale, water was poured to fill the space between particles. By comparing the weight of the whole measuring cylinder before and after pouring water, the volume of the water poured was determined and hence the packing factor of the cylinder and also the density of the dummy particles could be known. The results are summerized in Table 1. Since the plastic beads were slippery, they seemed to slip into space easier compared to quartz grit, and this led to a higher packing factor.

The uncertainty of the above measurement is due to the loading process. If the cylinder is well shaken the beads slip more easily into volume and the packing factor increases. The loading of measuring cylinder should be carried out similarly each time to get same the packing factor.

	PF for measuring cylinders	density [g/cm^3]
quartz grit	0.64 ± 0.01	2.79 ± 0.02
plastic beads	0.66 ± 0.01	0.86 ± 0.01

Table 1: The packing factor and density of dummy particles.

Using the above values, the volume and packing factor of the target cells in room temperature were measured. First, the cells were filled with dummy beads and then unloaded. The volume of the dummy beads were measured by a measuring cylinder. If the packing factor of the target cells and the measuring cylinder were the same, then this volume could be interpreted as the actual interior volume of the cells.

Figure 2: Left: Quartz grit. Right: Plastic beads.

The packing factor in the measuring cylinder is used to determine the volume of the beads. The packing factors in the target cells were determined by dividing the volume of the dummy material by the calculated volume 424 cm^3. The interior volume of the cells doesn't necessarily coincide with the calculated volume, but the calculated volume is a good approximation.The results are summerized in Table 2.

Comparing the PF of the cells obtained in this way to the PF of the measuring cylinder in Table 1, the cells and cylinder seem to have similar packing factors.

quartz grit	downstream	upstream
measured volume of the unloaded beads [cm^3]	395 ± 4	407 ± 3
volume of the dummy material [cm^3]	253 ± 7	261 ± 7
PF of the target cell	0.60 ± 0.02	0.62 ± 0.02
plastic beads	downstream	upstream
measured volume of the unloaded beads [cm^3]	415 ± 5	420 ± 5
volume of the dummy material [cm^3]	274 ± 8	277 ± 8
PF of the target cell	0.65 ± 0.02	0.65 ± 0.02

Table 2: Values for the downstream and upstream cells measured using two different kinds of dummy material, quartz grit and plastic beads.

The volume of the dummy material can also be determined by measuring the weight of the beads by their density determined above. In this way, the actual volume of the quartz grit was 252 ± 2 cm^3 for downstream and 261 ± 2 cm^3 for upstream cell. For the plastic beads, it was 273 ± 4 cm^3 for downstream and 277 ± 4 cm^3 for upstream cell.

2.2 Measurement of the cell volume inside LN_2

Each of the target cells was filled with quartz grit inside a LN_2 bath. The reason why quartz grit was used was because its thermal shrinking in low temperature is small, and also because the shape of cryastals is quite similar to the ^{6}LiD grains used as the target material in the experiment.

Quartz grit was unloaded and the volume was measured with a measuring cylinder, and this value was interpreted as the interior volume of the cells in low temperature. The results were 400 ± 5 cm^3 for downstream and 400 ± 4 cm^3 for upstream cell. Here the packing factor of the target cells and the measuring cylinder were assumed to be the same. This assumption seems to be pretty realistic on first glance since the cells and the measuring cylinder has similar pillar shape and diamiter, and also from the result obtained in the last section. However, it should not be forgotten that the method used in the last section had a certain problem, and also since the cells and cylinder are made from different materials, the accuracy of this assumption remains as a big question.

There was also another problem. While the cells were loaded, they were always observed carefully with a flashlight whether or not there was a large space yet to be filled. In this way, first the downstream cell was filled and then the upstream cell was filled. However, after the upstream cell had been filled, a pretty large space was found in the downstream end of the downstream cell. Some of the possible interpretations are — the particles in the downstream cell was packed while the upstream cell was loaded and hence space was made, the downstream cell expanded because it was no longer inside the LN_2 bath, or the filling of the downstream cell was simply insufficient.

Using the value above, the packing factor for the ^{6}LiD target material of run 2004 was calculated.

PF could be expressed by the following equation

$$PF = \frac{V_{\rm mat}}{V_{\rm cell}} = \frac{m}{\rho \cdot V_{\rm cell}} \tag{2}$$

where m is the mass of the target material in the cell and ρ is the density of material. ρ is known to a good accuracy, and also m had been already measured before. Using the value of $V_{\rm cell}$ measured above, the packing factor was calculated to be 0.534 ± 0.026 for downstream and 0.516 ± 0.025 for upstream cell. Just for reference, the hexagonal close packed structure is the state that gives the largest packing factor for filling uniform-sized spheres into an infinite 3 dimensional space, and the packing factor is $\pi/3\sqrt{2} \simeq 0.74$.

3 Target material 2004

Besides the packing factor, the element composition of the target material and the amount of ^{3}He and ^{4}He in different geometrical cuts were determined for the run 2004. I avoided using the packing factor calculated above in order to calculate these values, since the method used above to determine the packing factor didn't seem to be so reliable. Details about these values are summerized in Ref. [1].

4 Simulation of the filling

The filling of target cells was simulated. The original program was written by Jaakko Koivuniemi, and details about the simulation carried out before with the program is summerized in Ref. [2].

Here the target material grains is approximated with random sized spheres for simplicity and also for saving computing time. The spheres are loaded one by one into a 3 cm diameter cylinder. The procedure is demonstrated in Fig. 3.

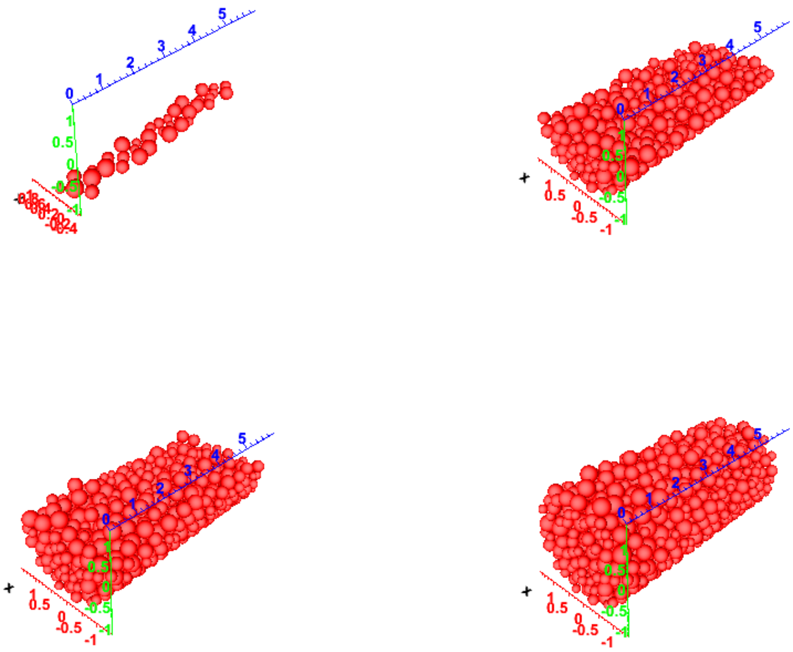

Figure 3: Procedure for target filling.

Random sized beads (2-4 mm diameter) are loaded one by one. For each new bead, an initial position inside the cylinder is given randomly. Then from the initial position, the bead is dragged down vertically (to the -y direction) until it crashes into already loaded beads or the cylinder wall. This operation which consists of giving an initial position and then dragging down is tried for a certain number of times, and then the position in xz plane with smallest y coordinate is chosen. Then a new bead is created and the same set of operations are repeated.

There are two slightly different simulation programs, *pfsim6cm* and *filltrg*. *Filltrg* writes the filling into a file for 3D visualization. *Pfsim6cm* fills the target cell several times and calculates the PF of each filling. Also, they differ in the way the beads are dragged down, which is explained below.

4.1 Dependence of the packing factor on the target length

The packing factor is expected to increase toward a certain asymptotic value as the target length increases, since the effect of the upstream and downstream walls become smaller. For the 60 cm cells of the COMPASS experiment, the effect of the walls is probably negligibly small. However, due to long computing time needed, 6 cm long cylinder was used for simulations.

The simulation program was run for different target lengths in order to see the target length dependence on the packing factor. The result is shown in Fig. 4. As shown in the graph, running the program with a

6 cm long cell seems to be sufficient.

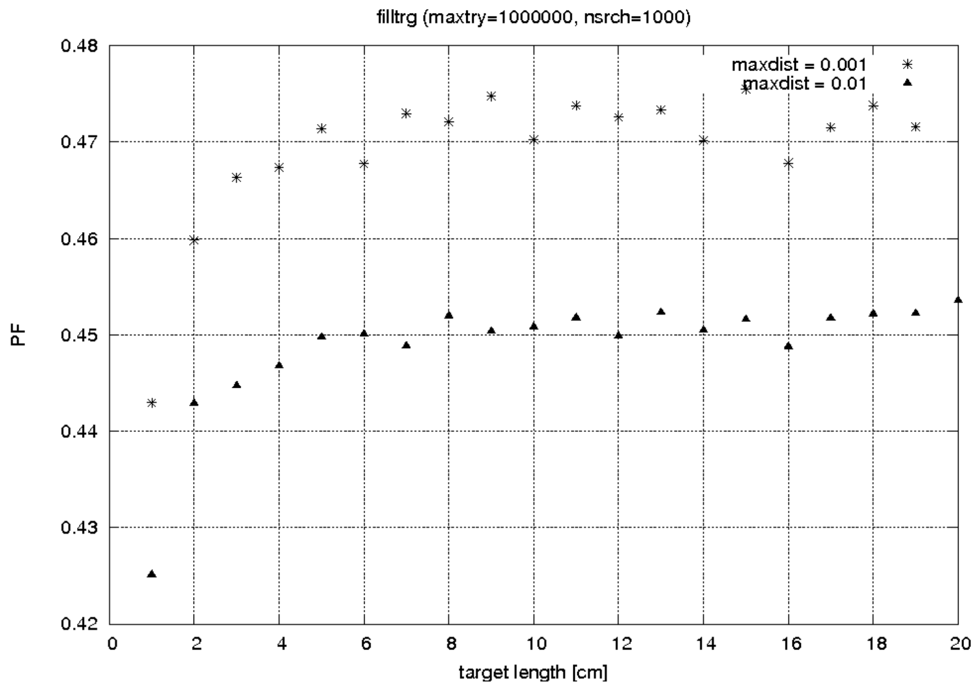

Figure 4: Dependence of PF on the target length. The program *filltrg* was used. *nsrch* is the number of times each bead repeats the operation of getting an initial position and dragged down. When a given initial position is not a valid one (e.g. inside the other particles) then a new position is tried. *maxtry* is the maximum number for this trial. Both *nsrch* and *maxtry* were kept small in order to get results in a short computing time. Obviously, larger PF can be obtained if these values are made larger. When the number of trials exceed *maxtry*, then this operation is aborted and the volume is assumed to be full. A bead is dragged down until it comes close to other beads or the wall within the distance of *maxdist* cm.

4.2 Simulation of movement in xz plane

A bead is dragged down until it hits other beads. There is a possibility that a bead may stop in a physically unstable position, e.g. a bead staying on top of others without slipping down. Also, since the material density of ^{6}LiD is close to the density of LN_2, it is likely that the ^{6}LiD grains were floating when being packed into the target cell. Hence, it is furthermore unnatural to assume that beads are only dragged in the vertical direction.

The program was modified so that the bead is dragged in the vertical direction and also transferred randomly in the horizontal direction at the same time.

Modified *pfsim6cm* was run 9 times under the condition *maxtry*=50000000, *nsrch*=5000, the number of times each bead is tried to be dragged was 100, initial values of *dy* and *dx* were both 0.2, and the reduction ratio of the dragging of vertical and horizontal directions were both 0.77. The average packing factor was 0.552936 and the height of unfilled volume was 0.19911 cm. The definition of these terms are explained below.

4.3 Optimization of reduction rates for dragging

In the original *pfsim6cm* simulation program, beads are dragged toward the -y direction several times. Each time a bead is dragged down at intervals of a certain distance *dy*, and when it crashes into something, the bead is moved to the last position before it hit others. Then the bead is tried to be dragged again in the similar way, except that this time the interval is reduced by a certain ratio. This procedure is repeated for a certain number of times, and in this way the y coordinates of the beads are minimized.

It is obvious that the more number of times each bead is tried to be dragged, the more the y coordinates of beads will be minimized and hence the PF will increase. But when it comes to the reduction ratio of the dragging interval each time beads crash into others, the value of the ratio that makes dragging most effective is not so obvious. The most effective value for packing may not be the most realistic value for simulating the experiment, but this question is interesting by itself. Furthermore, when the modified program discussed in the previous section faces this problem, the difference of the reduction ratios between the vertical and horizontal direction may actually have a physical meaning, since the relative strength of gravity could be traced by adjusting these values to appropriate numbers.

Simply, the effectiveness of each reduction ratio value can be discussed by comparing the packing factor it generates. Also, proportion of the number of times of successful dragging (the ones which did not crash into others) to the total number of times dragging was attempted should be examined. It is expected that when large PF is obtained, also the successive rate should be large. (However, it is also likely that large successive rate doesn't necessarily imply large PF.)

First, the original program which moves beads only the vertical direction was examined. The dependence of the packing factor and successive dragging rate on the reduction ratio is shown in Fig. 5. As easily expected, the successive rate is a monotonically decreasing function of the reduction ratio. With the packing factor, it doesn't seem to have a difference as long as the vertical interval is reduced in some degree.

Next, the modified program was examined. The dependence of the packing factor and successive dragging rate on the reduction ratio for vertical and horizontal direction is shown in Fig. 6.

Basically, the successive dragging rate is a monotonically decreasing function of the reduction ratio of each direction as expected, however, notice that the dependence on the reduction ratio in the vertical direction is stronger.(Although it may be difficult to see only from this figure.)

With the packing factor, a ridge can be observed on the (reduction ratio of horizontal direction) = (reduction ratio of vertical direction) line. The peak packing factor ($\sim$0.50) was obtained by reduction ratio $\sim$0.75 for both vertical and horizontal direction. These numbers may vary with values sucn as *nsrch* and the number of times dragging is tried, however, the fact that the largest PF could be obtained by setting the two ratios in different directions equal probably doesn't change and is interesting.

References

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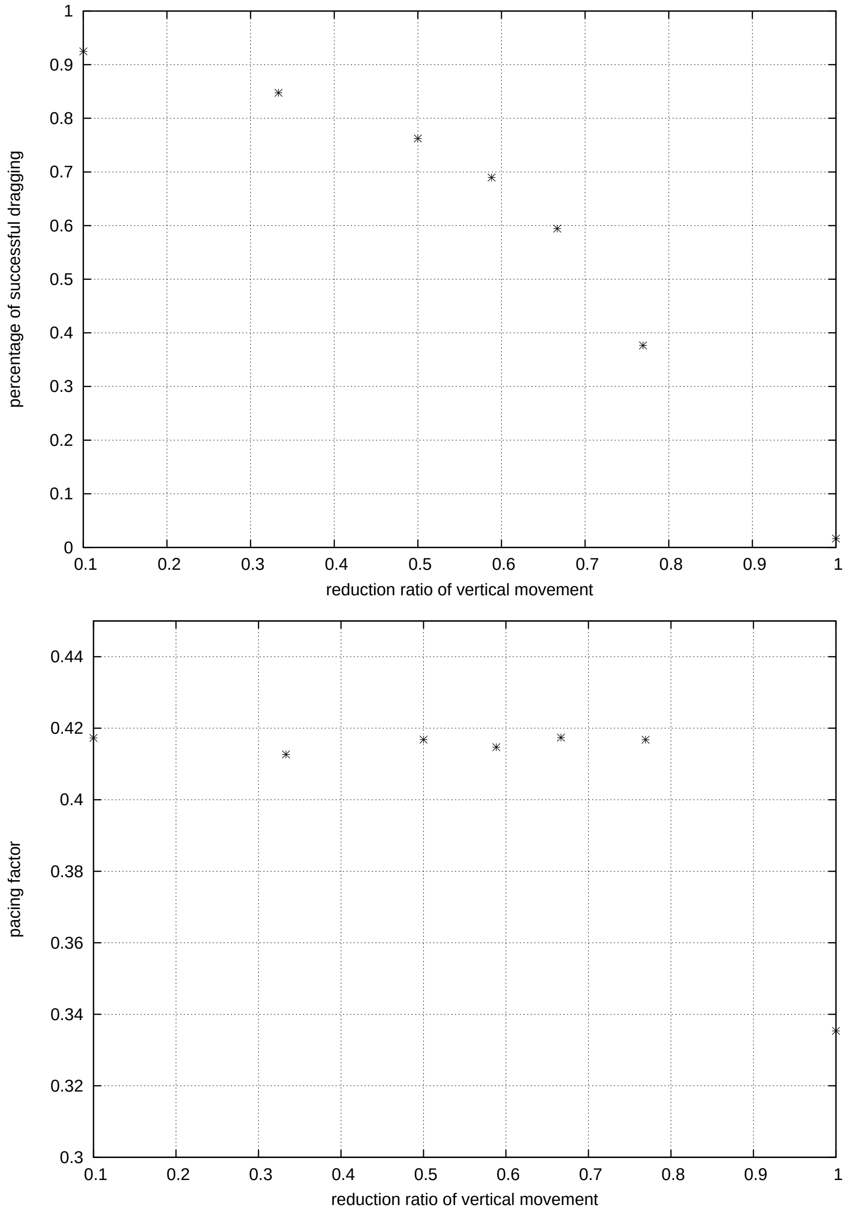
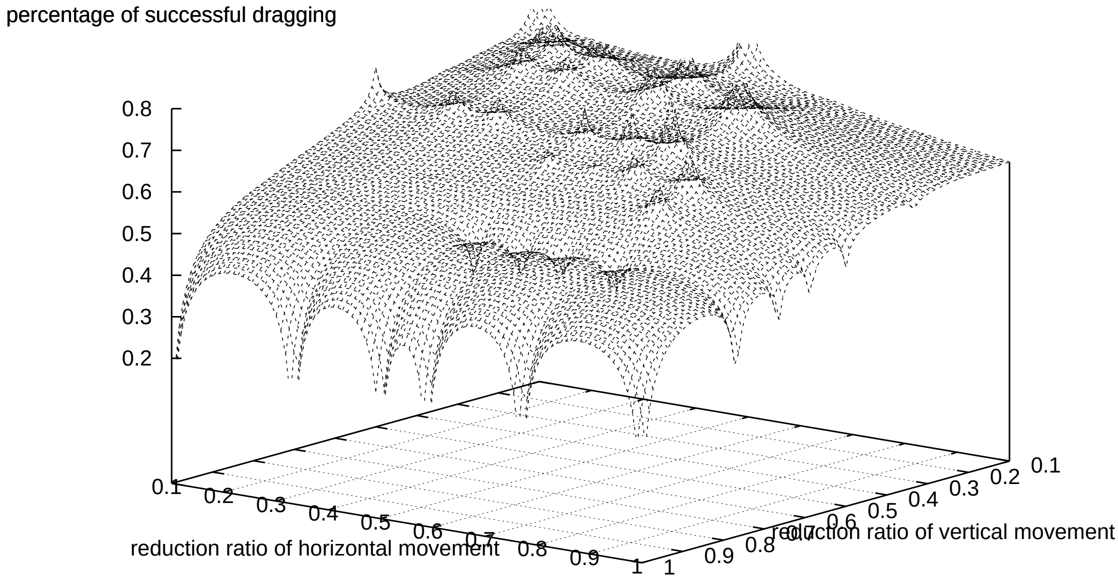


Figure 5: With the original program, the dependence of the PF and successive ratio of dragging on the reduction ratio in vertical direction. Program *pfsim6cm* is used with *maxtry*=50000, *nsrch*=100, initial value of dy is 0.2, number of times dragging is tried is 100.



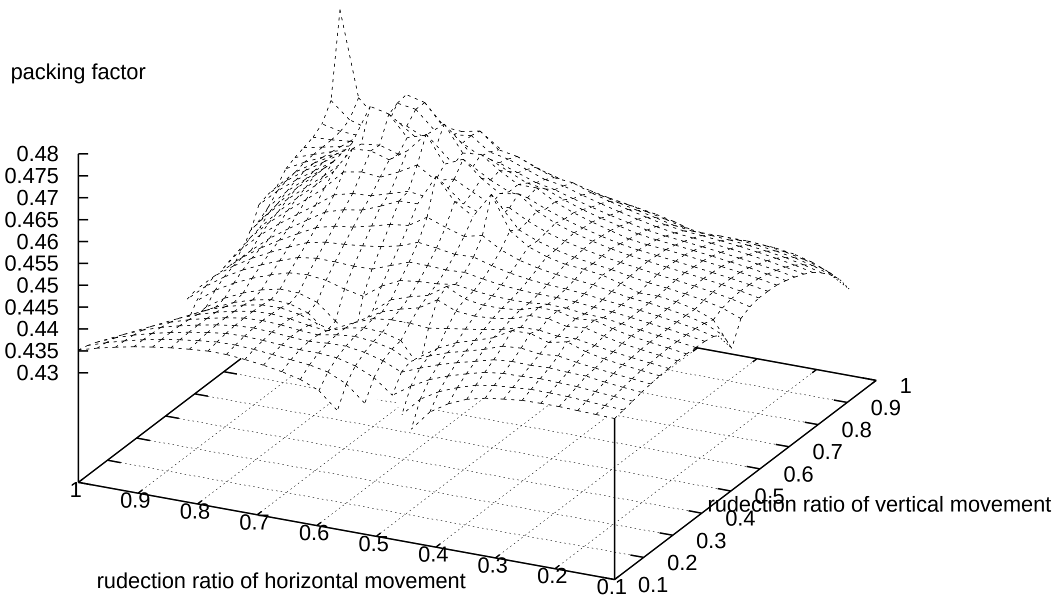


Figure 6: With the modified program, the dependence of the PF and successive ratio of dragging on the reduction ratio in vertical and horizontal direction. Program *pfsim6cm* is used with *maxtry*=50000, *nsrch*=100, initial values of dy and dx are 0.2, number of times dragging is tried is 100. Here, beads are randomly moved horizontally within a circle of radius dx while it is dragged at intevals of dy.