Technical report for my Summer Student project

Improvements of the optical detection setup of COLLAPS

Design of a shutter system for photomultipliertubes and testing

by

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Experiment: COLLAPS @ ISOLDE

Abstract

In Collinear Laser Spectroscopy of rare isotopes it is crucial to keep the background of the measurements low. Using photomultiplier tubes for those measurements, the dark count rate should be as low as possible and the signal gain high. Therefore, it is important to use the right type of photomultiplier tubes for the purpose of single photon detection with a low signal rate. Thus, I tested several different types of photomultiplier tubes for their dark count rates and noise to signal separation. The results have identified the most suitable type of photomultiplier tubes, but further measuring for verification might be necessary.

Therefore, it is very important to keep the photomultiplier tubes shut from light. Exposing the photocathode to light implies life-long damage and increased background for several days. So far, when dismounting one of these photomultiplier tubes from the setup, a big cage around the optical detection setup was covered into black sheets to keep it as dark as possible inside. Still, the photomultiplier tubes got exposured by some light. To avoid this, a shutter system was developed. This system contains a slit for reducing stray light, a system for adjustment of the distance between the photomultiplier tubes and some focusing lenses and the actual shutter, that can be closed in case of dismounting a photomultiplier tube. This shutter already has been tested and the results are promising.

Contents

1 Motivation

The COLlinear LAser SPectrometer COLLAPS at ISOLDE at CERN is studying fundamental properties of exotic short-lived nuclides like ground state spin, changes in the root mean-squared charge radii and ground state electromagnetic moments. By exiting band electrons of ions or atoms to higher energy levels and subsequent detection of fluorescent photons, hyperfine structure spectra can be measured. For this purpose, a laser beam is getting overlapped with the ion beam. The laser frequency is getting scanned by Doppler-tuning to determine the excitation frequency of those electrons. After the excitation the ions or atoms fall back to the ground state or lower lying states and emit fluorescence photons that can be measured by the optical detection system.

At COLLAPS, the optical detection system consists of four photomultiplier tubes, two on the left and two on the right side. A set of lenses are placed in front of each PMT for focusing the photons on the photocathode. Additional spacers ensure the right distance between lens and photocathode. Also, the support structures of the PMTs like housings, shieldings, bases etc. are important. A screenshot of the 3D model of the experiment can be seen in figure 1.1.

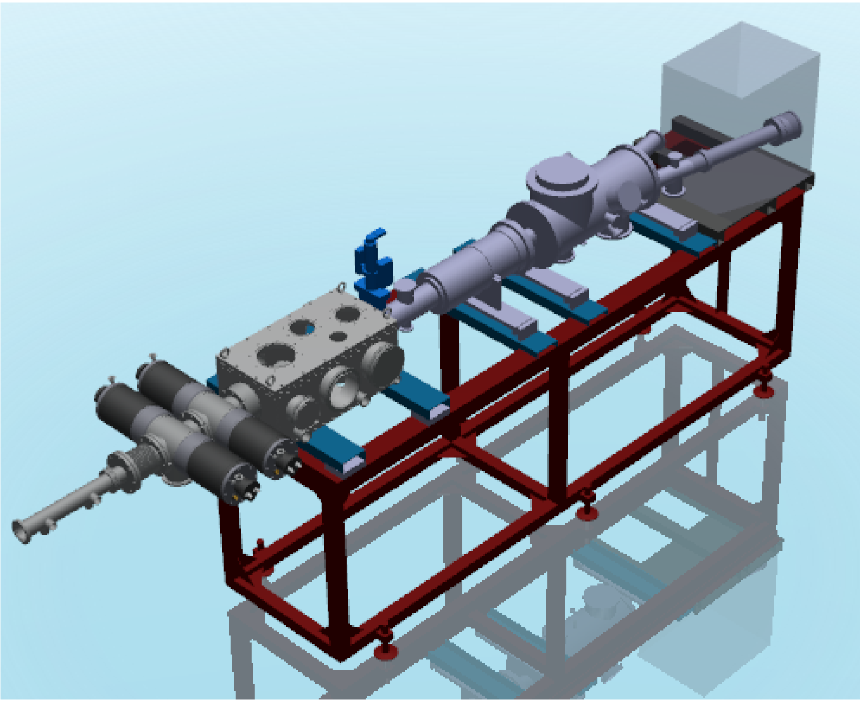


Figure 1.1: The beamline of the COLLAPS experiment.

Initially there were two different kinds of PMTs in usage and a third kind in storage. On the right side of the beamline, the ET Enterprise 9814QSA were mounted, on the left side the ET Enterprise 9829QSA and in storage were the Photonis XP2020. Since all these different types need different support structures, different voltages applied and show a different behaviour, one should decide on one kind of PMTs. To find out which type of these PMTs show the best characteristics, one of my challenges was to analyse the behaviour of the available PMTs. The results of the measurements at different voltages in different conditions have to be compared.

Since the PMTs are used for single photon detection, the signal should be significantly higher than the electric noise amplitude and also the background rate should be as low as possible. When a PMT gets exposed to light, even if no voltage is applied, the photocathode emits electrons. These electrons can influence the measurements for a certain settling time of several days. If a PMT is about to get replaced, for maintenance or inspection, its surrounding must be as dark as possible. Since one can never manage to cover his surroundings perfectly while dismounting a PMT, there is always some light the PMTs are exposed to. Due to this issue, after every replacement the optical detection setup cannot be used for around two days. If for example a PMT breaks during a beamtime and has to be replaced, there is no way to continue with the measurements for another two days, which is a serious problem. Due to this issue, a shutter system should be designed to remedy this challenge. Those shutters should be located between the lenses such that the shutter can be opened and closed all the time. Therefore, when replacing a PMT, one can close all of the four shutters, remove the PMT, mount a new one, open the four shutters again and continue with the measurements instantly. Furthermore, the replacement of the PMTs would be much more comfortable, time saving and safer, since dismounting the PMTs in quite total darkness in between of black curtains is inelegant

The focusing point of the lenses depends on the wavelength of the fluorescence photons due to dispersion. Therefore the distance between lens and PMT is different for ech experiment. Thus, the spacers have to be replaced every beamtime. Since the PMTs are mounted on the spacers, they must be removed. This again leads to light exposure and settling time of the PMTs. A system to vary the distance between the lens and the photocathode without light exposure would therefore be advantageous.

One of the main tasks during my project was the design of a system that could combine a shutter and adjustable spacers to solve the aforementioned problems.

2 Testing of the PMTs

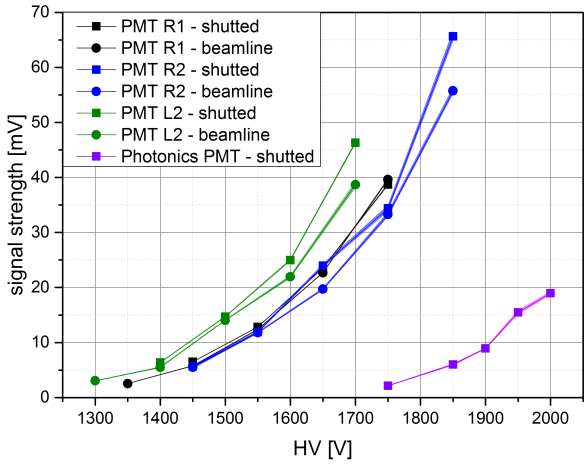
When measuring single photons with PMTs, the signals strengths are fairly small. Therefore it is important, that the signals are well separated from the noise level. For historical reasons, COLLAPS is currently using two different types of PMTs. Even if one type seemed to have better properties, COLLAPS bought a new model of the other type. The purpose was to ensure that this issue was not due to the ageing effect of PMTs. Photocathodes for single photon detection must not see light, their performance is compromised. Therefore it is hard to tell from a single PMT, that the whole type is not suited for this application.

For the characterisation of the PMTs, I measured the pulse-height distribution of all four PMTs. The shapes of the measured spectra were analyzed to extract the relevant values such as the signal strength and FWHM. These spectra can be seen in the figures 7.1 to 7.3 in the attachment in chapter 7.

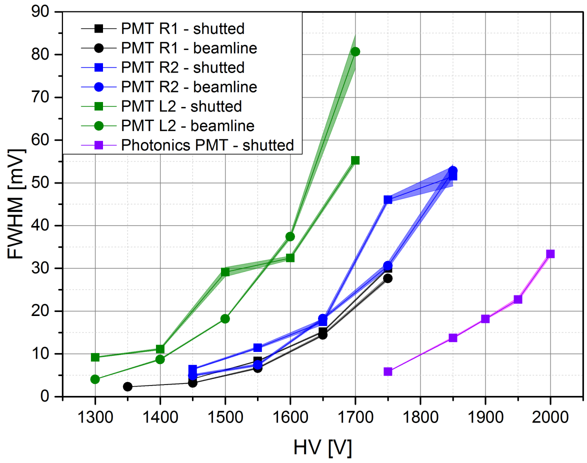
The spectra shown in figure 7.3 are old data from previous measurements. One can see a difference of the behaviour of the 9814QSA-type and the 9829QSA-type. While the darkcount rate/signal is well separated from the noise by the right detectors, the photopeak is hard to separate from the noise level at L1. The goal is to set the threshold between the noise level and the photopeak and to get as little background as possible. The background signals are composed of dark counts of the PMTs, actual light in the beamline and stray light of the laser. The spectra of figure 7.3 shows, that around 50% of the background is due to the laser. To reduce this background could be a future task.

However, my task was to find out which type of PMT has the best separation of the signal from the noise. Therefore I measured pulse-height distributions of the PMTs in different conditions: totally shutted (figure 7.1) and mounted on the beamline (figure 7.2) with different bias voltages. Additional measurements with a running laser while mounted on the beamline were planned, but could not be completed due to problems with the laser. Previous spectra of measurements of this kind are shown in figure 7.3. The signal strengths, which is the center of the gaussian peak, and the FWHM of the different measurements plotted against each other are shown in figure 2.2.

These spectra show clearly, that PMT R1 and R2, which are both of the 9814QSA-type, show a similar behaviour. The difference is due to different ages and statistics. The signal strength of PMT L2, which is of the 9829QSA-type, is a bit higher than of the 9814QSA-type. However, since the PMTs are can be set to different voltages for optimal operation, this effect might be insignificant. The maximum voltages used for this measurements are the voltages the PMTs are currently used at. These values are shown in table 1.



(a) signal strengths of all the PMTs at different voltages.



(b) FWHM of all the PMTs at different voltages.

Figure 2.1: The results of the PMT tests. The higher the signal strength, the larger is the separation between photopeak and noise level. Also, the higher the FWHM, the broader is the peak and thus the stronger is the influence of the noise.

Type	Number	High voltage
ET Enterprise 9814QSA	R1	1750 V
	R2	1850 V
ET Enterprise 9829QSA	L1	1900 V
	L2	1700 V
Photonis XP2020		2000 V

Table 1: Maximal voltages applied to different PMTs.

Therefore, the signal strength of PMT R1 is quite similar to the signal strength of PMT L2. Also, the signal strength of PMT R2 is even higher.

On the other hand, the FWHM of PMT L2 is also higher than the FWHM of PMT R1 and R2. But this time, the FWHM is even higher at the currently used voltages from table 1. Also, the FWHM of PMT L2 is larger than the the signal strength of PMT L2, in contrast to PMT R1 and R2. Besides, the deviation and the errors of PMT L2 and R2 are much higher than of PMT R1. This is also approved by the plots of the division of the FWHM over the signal strength in figure

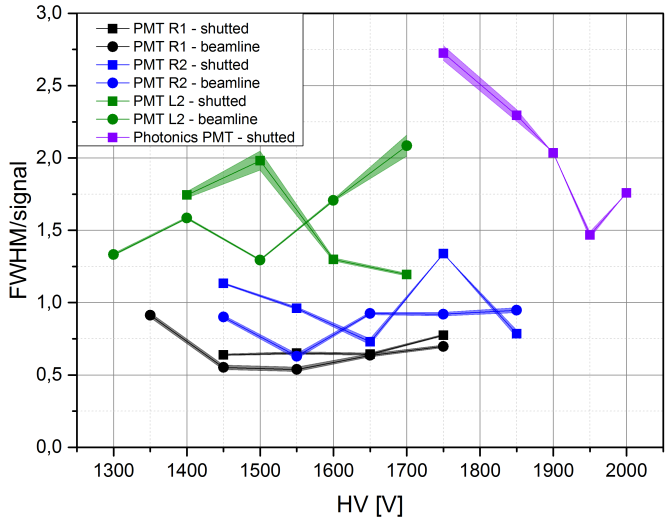


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Figure 2.2: This Graph shows plots of the FWHM over the signal strength. As one may see in this more comparable plots, PMT R1 got the lowest FWHM compared to the signal strength and the Photonics PMTs the highest.

Probably, PMT R2 is older and has been exposed to more light than R1. That might explain this difference. Since PMT L2 is the newest of all this PMTs, this is not an argument for its results.

All this leads to the conclusion, that the 9814QSA-type might be better suited for this purpose than the 9829QSA-type.

The Photonics XP2020 was not yet tested at the beamline, because the housing is different and thus I was not able to mount this PMT. However, the dark count spectra are already quite promising. Since the nominal voltage of the Photonics PMT is much higher than of the ET Enterprise PMTs their curves are hard to compare. Yet it is clear that the FWHM is much larger than the singal strength, similar to PMT L2. Also, the signal strength is quite low compared to the ET Enterprise PMTs, even on the recommended voltage of 2000 V. At this voltage, the FWHM is around a factor of two larger than of PMT R1, while the signal strength is still lower. This leads to the conclusion, that also the Photonics PMTs are less well suited for this purpose compared to the ET Enterprise 9814QSA PMT.

3 Design of the shutter and the adjustable spacer

The main part of my project was the design and 3D modelling of a shutter system for these PMTs combined with a design to adjust the distance between the lenses and the photocathodes. This shutter design is based on the shutter system of the TRIGA-LASER setup of the Johannes Gutenberg-Universität Mainz. There two different screws are used to fix and move a window between two plates with holes in the center. A screenshot of this model can be seen in figure 7.4 in the attachment (chapter 7). Analogously to the model of the shutter used in Mainz, the new design for COLLAPS also consists of three parts: One solid metallic base, which contains the thread for the screw(s), one window, which will be moved, and a top plate for fixing the window and closing up the edges.

One challenge was to modify the design to use only one screw since having two screws leads to some problems. First of all it is hard to tell if the shutter is open or not. Secondly it is harder to store, because one screw is always protruding. Also, it is inconvenient and more time consuming to move two screws. Another challenge was the size of the hole and thus the whole shutter. Since our PMTs have a greater size than the ones used in Mainz, the hole in the window also has to be bigger. Finally, it was important to design a shutter that was combinable with the adjustable spacer.

The idea for the adjustable spacer was to use threads for moving the PMT setup. By turning the PMT by 180° the distance can be adjusted accurately to a millimetre. The threads was meant to be around the whole design. Therefore there was the possibility one either put the female thread on the lens part and the male thread on the PMT setup or the other way around. Due to the lack of space for the shutter, I decided for the second option.

For the shutter I modelled three different designs:

I) In the first design I made use of springs to get rid of the second screw. The springs should push the window in one initial position (open or closed) and the screw can push the window in the different direction. This design can be seen in figure 7.5 in the attachment in chapter 7.

II) In the second design I used one screw for moving the window. This screw should be fixed on the solid base, but still be rotatable. It should be screwed in a thread in the window, which is not rotatable, but moveable. Thus, instead of rotating the window should move to close or open the shutter.This design can be seen in figure 7.6 in the attachment (chapter 7).

III) The third design was a backup design which basically copied the concept of the shutter used in Mainz with both screws, but adapted to the dimensions our setup. This design can be seen in figure 7.7 in the attachment (chapter 7).

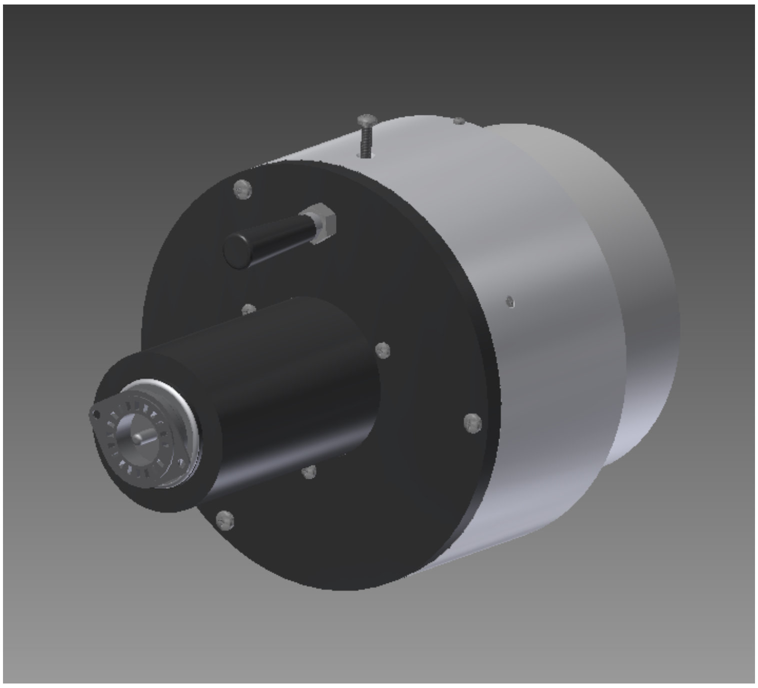
A prototype of the first design was build in order to characterize its performance. My decision was lead by the thought that this design might be easier to realize than the second one and more durable, because with every time moving the window, there is a significant pressure on the top and the thread. Also, it's more practicable than the third design. First tests of the prototype are discussed in chapter 4.

When modelling the whole design including the adjustable spacers, there were many issues to pay attention to and many additional requirements to follow. The design is shown in figure 3.1.

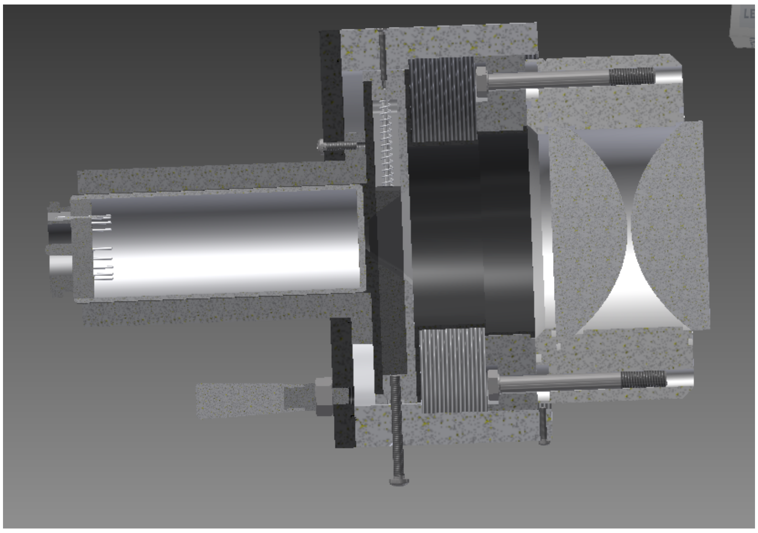
One of the main sources of background is stray light of the laser beam. Hence, it is important to reduce stray light in the setup and to get as little stray light onto the photocathode as possible. To achieve this, it is mandatory to avoid the use of reflecting materials or surfaces used in the design as possible. Commonly, reflecting surfaces are painted with black paint. Since the design around the PMT is based on a large female thread, it is not possible to paint it, because the paint would wear down after some time. Also, it is not recommendable to produce this parts of plastic, because the thread is not that durable. My solution was to use aluminium for this part and to add an additional plastic pipe, which shields the light from the reflecting metal. This plastic pipe is mounted on the shutter and can be painted.

To get rid of some stray light, COLLAPS used a slit in front of the PMT. The height of the slit is defined by the diameter of the ion beam and linear optics. The lenses are focusing the photons coming from the beam to the photocathode. The deviations from the center of the focus are dependent on the deviation of the ion beam from the center of the beam. Since the beam is travelling in one direction on the horizontal plane, the focus is not defined on this axis. The stray light is coming from random directions and thus has no focus of the lenses. The goal is to shield the PMT from the stray light, but having a horizontal slit for the incident fluorescence photons. This slit was made of paper so far and will be more advanced in my design. The slit is contained in the final version of the shutter. The back of the shutter is in touch with the PMT and the height of the hole is exactly the same height as the current slit. To deflect incoming stray light away from the PMT, the parts of the shutter have an oblique cut. A angle of 45° would be optimum. Due to space constraints, the maximal possible angle was 30°.

The next challenge was the high voltage that is applied to the beamline of the optical detection region but not to the PMTs themselves, which are lying on ground



(a) Full view on the final whole shutter design.



(b) Crosssection view on the final whole shutter design.

Figure 3.1: Model of the final whole shutter design. The part around the PMT can be moved by turning the whole setup. Thereby, the required distance can be set.

potential. This is accomplished by separating the HV of the adjustable spacers and the shutter from the PMT.

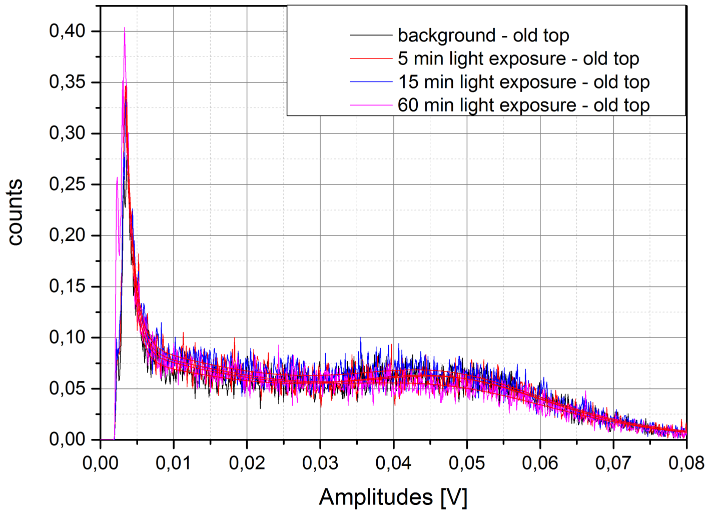
Finally, one has to consider the machine shop capabilities to produce individual pieces, the sequence of assembly of the setup as well as standard norms. Finding a good balance between all of these requirements leads to the success of this project.

4 Tests with the shutter

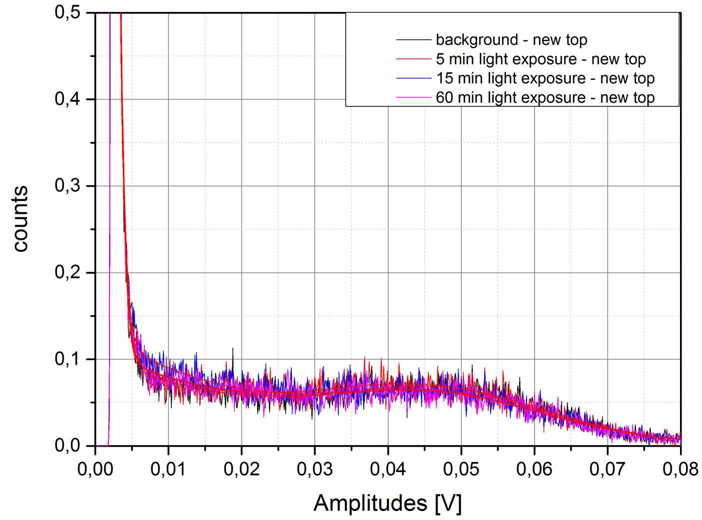
For the tests of the prototype of the first shutter design mentioned in chapter 3 an additional adapter to mount the shutter on the PMT housing was machined. First of all, the concept to use springs and one screw to move the window works properly. The window is moving smoothly while moving the screw and also the spring pushes the window up, yet the turning the screw it not too hard. With the tests described in this chapter, I tried to benchmark, if one can use a PMT instantly after the whole setup was exposure to light with the closed shutter. Hence, I mounted the adapter with the shutter on one PMT housing (PMT R1). The entire test setup was fully covered by black curtains such that it was not exposed to light at all. After the settling time of two days, I turned on high voltage and observed the PMT signals on the oscilloscopes (Tektronik TDS 2014 and LeCroy wavePro 725Zi). The settings of the oscilloscope like trigger level, scales etc. must not be changed during the tests, since the count rate is dependent on those setting. I first measured the background of the PMT. Then I manually read out an approximated count rate on the Tektronik scope, noted the range of the fluctuations and an *estimated* average. Afterwards I took a pulse spectrum with the LeCroy scope. To get the real background without noise, it is necessary to fit an exponential curve superpositioned with a gaussian to get the minimum in between the noise and the photopeak to separate those. Afterwards, I decreased the voltage, uncovered the shutter setup and put it on the ground with the shutter still closed where it was exposed light. After $\Delta t = 5$ min of light exposure, I covered it again with black curtains to repeat the measurements. I repeated this procedures also with time differences of $\Delta t = 15$ min and $\Delta t = 60$ min. The pulse spectra are shown in figure 4.1a.

For the design of the adjustable spacers, there were two possibilities. Either, the female thread would be on the lens part and the male thread on the PMT setup, or the other way around. This designs can be seen in figure 7.8 in the attachment (chapter 7) and figure 3.1 in chapter 3. One of the disadvantage of the first variant was the lack of space inside, and thus the size of the shutter. Due to the oblique cut for deflecting the stray light, the shutter is only closing on one edge between base and window. A big advantage of the final shutter design is that the window does not only close on this one edge, but also on a second edge, between window and top. And still, the oblique cut in the window can be provided. To test the shutter under the conditions of both design types, additionally to the first shutter design I let produce an extra top, were the hole is shifted and smaller, so that the window is closing on both edges. So the same procedure was repeated while using the new top.

The measured spectra are shown in figure 4.1b.



(a) measurements with the old top.



(b) measurements with the new top.

Figure 4.1: Pulse-high distribution of the dark counts for each PMT after some minutes of light exposure. Notice that all spectra exhibit similar behavior and therefore it suggests that the light exposure did not affect the count rate significantly.

The figure shows, that there are no significant changes in the count rate. To support this observation I plotted the overall counts, the background only and the average observed count rate of every plot in one diagram. The results can be seen in figure 4.2.

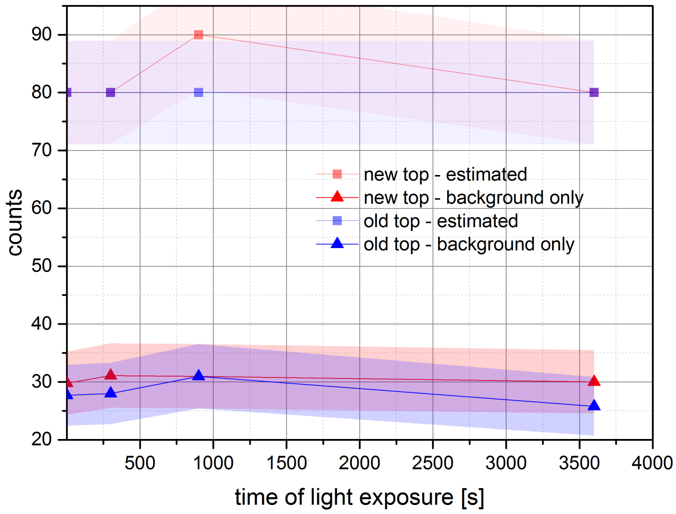


Figure 4.2: Results of the tests with the shutter. The transparent values are rough estimations of manually read out count rates. One can see, that the differences in count rates only show some fluctuations. It seems like the exposure to light had no significant impact on the measurement results and thus the shutter works.

These measurements show indeed, that the count rate is not significantly changing after exposure to light. The fluctuations, that are due to statistics, are smaller than the measurement error, which leads to the assumption, that the count rate is not changing. Even if it looks like the count rate might increase after the first light exposure, the value with the lowest count rate was measured after one hour of light exposure. Therefore, the little increase might be caused by moving the PMT.

Also, the results for both tops are quite similar. Actually, the count rates for the previous top are slightly lower than for the improved top. Thus, the overlapping edges are sure enough to shut the PMT.

Therefore the shutter works and is ready for production, which will improve the optical detection setup of COLLAPS.

5 Additional tasks

Additionally to my main project, I assisted in the preparations for the beamtime. I designed a plug for the charge exchange cell of the ROC setup, assisted in designing the readout for the ion flux in atom direction, designed the exit window for the laser beam, built and tested a backup detection chamber for the β-detection system together with the other COLLAPS Summer Student and took care of the power supplies for the β-detection chamber of the ROC setup including the gain matching.

0In this chapter, I will describe my steps to the gain matching. But first a brief introduction on the used β-detector chambers. The chambers consist of two scintillators, a small one in the center and a big ring around it, and five PMTs, one for the inner scintillator and four for the outer scintillator. The idea is to get rid of dark counts and some background by measuring in coincidence as well as measuring the total deposited energy. The β-particles, emitted during the β-decay of an ion implanted on the tape, are supposed to pass both scintillators. So only signals encountered by the inner and one of the outer detectors are recorded. To obtain full energy information of the β-particles it is important to set the voltage so that the gain of the PMTs is the same for all outer PMTs.

To achieve this, I looked at the dark counts of the all the outer PMTs due to cosmic muons. The trigger was set by the coincidence between inner and outer detector. I adjusted the voltage of each PMT, until the average amplitude of all signals exhibited the same height. After doing so, I took pulse spectra of the dark counts of each detector and plotted and fitted them. The center of the gaussian distribution was used as parameter to define the right voltage. If the position of the Gaussian peaks did not coincide for all PMTs, I increased or decreased the voltage regarding to the results and took spectra again. The idea is to repeat this steps until the peaks are at the same position and thus the gain is matched. A example of such a graph can be seen in the following figure 5.1:

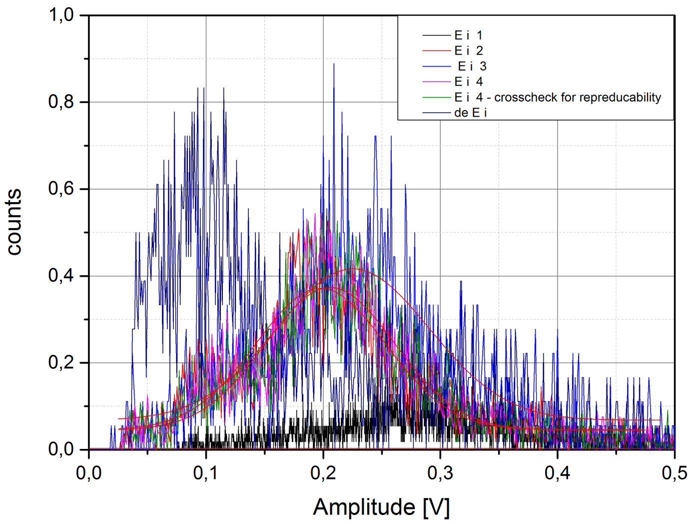


Figure 5.1: Histogram of amplitude distributions used for gain matching of the outer detectors of the radiation detection chambers. The voltage of PMT Ei three is to high and has to be decreased.

6 Conclusion and Outlook

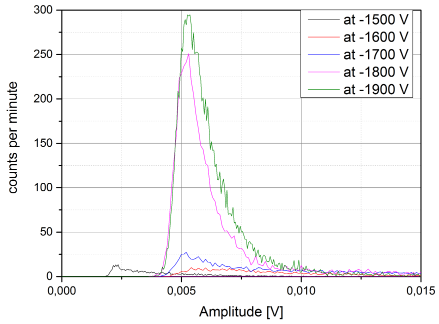
My measurements have shown, that the optical detection setup can be improved.

The performed PMT tests with the available equipment was quite promising. PMT R1, which is not even the newest PMT, clearly shows the most suitable behaviour. Since PMT R2 probably shows the second most suitable behaviour, the results lead me to the assumption, that ET Enterprise's 9814QSA are the suited best for the purpose to be used in COLLAPS' optical detection setup. Nevertheless, this results are based on the available equipment and should be verified. Since PMT L1 was practically not testable, I only had one PMT of the ET Enterprise 9829QSA and Photonics XP2020. Thus, more PMTs should be compared to ensure that ET Enterprise's 9814QSA are suited best. Also, one should compare PMTs of different ages of the same type and test how great the impact of the aging effect is and how it differs from type to type. But the most important test, which should be done, might be a test with an actual source/beam. Since the detection efficiency plays an important role for single photon detection, this should also be observed.

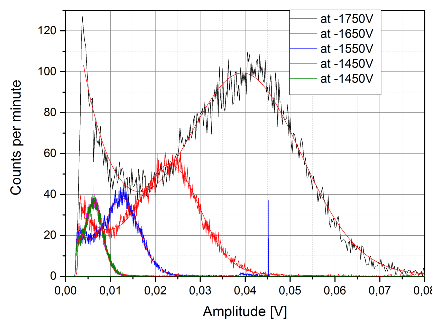
The modelling of the whole shutter design including the adjustable spacer is finished and thus a prototype should be produced. It remains crucial to benchmark whether everything is well sealed, if everything is fitting to the existing setup properly and if it is possible to assemble the parts (in the dark when a new PMT is mounted to a shutter). Also, some high voltage tests should be done. The whole design should be tested for functionality and light tightness. If all those tests are promising, this setup around the PMT can be produced five times in total. The male thread, which is fixed on the lens, only need to be produced four times. One of the PMTs will be stored with the remaining setup and the shutter closed and probably an additional cover to ensure that the PMT sees no light, until it is needed.

The tests of the shutter have also shown that the shutter probably works. Since the measurements with the PMTs exposed to light for one hour showed a lower count rate than the other measurements in both cases, i assume that there are other aspects like the moving of the PMTs shortly after turning off the high voltage and the frequently turning on and off of the high voltages that could have a bigger impact than remaining light which passes through the tiny slits in the shutter.

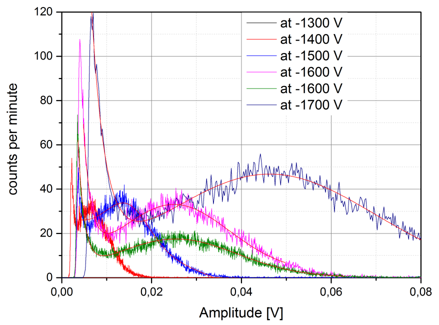
7 Appendix



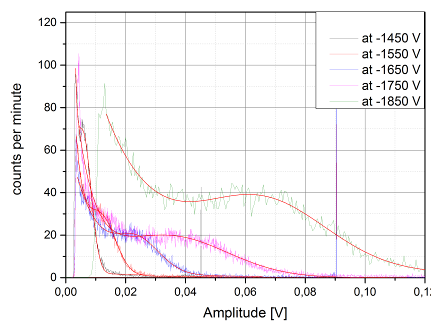
(a) PMT L1 (ET Enterprise 9829QSA).



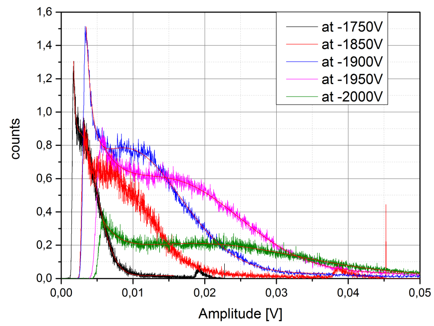
(b) PMT R1 (ET Enterprise 9814QSA).



(c) PMT L2 (ET Enterprise 9829QSA).

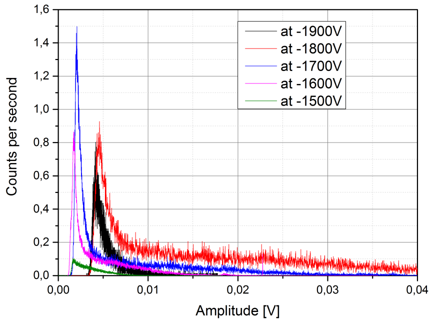


(d) PMT R2 (ET Enterprise 9814QSA).

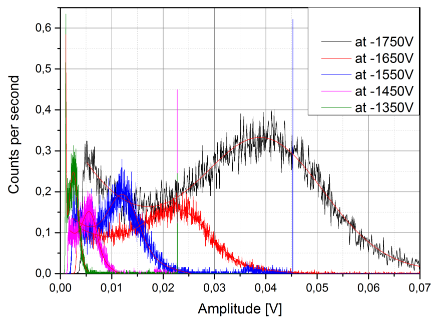


(e) One of the stored Photonics XP2020.

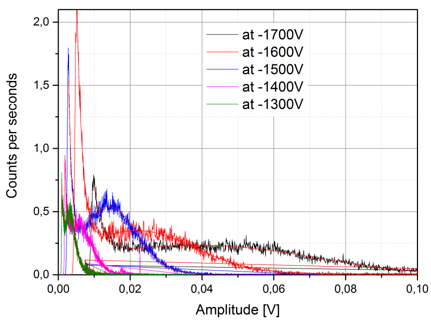
Figure 7.1: Dark count spectra of the different PMTs for different applied voltages. The fit curves show superpositions of an exponential curve with a Gaussian distribution.



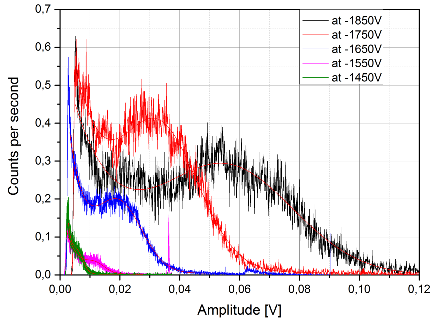
(a) PMT L1 (ET Enterprise 9829QSA).



(b) PMT R1 (ET Enterprise 9814QSA).

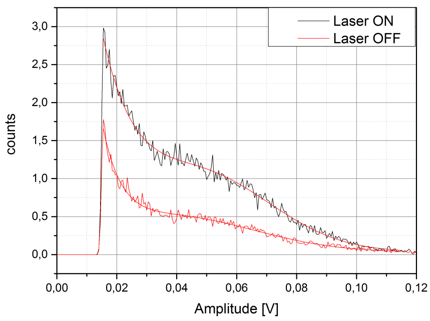


(c) PMT L2 (ET Enterprise 9829QSA).

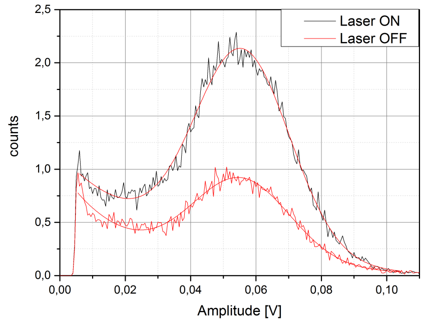


(d) PMT R2 (ET Enterprise 9814QSA).

Figure 7.2: Pulse-height distributions of the different PMTs with different voltages applied while being mounted to the beamline. The fit curves show superpositions of an exponential curve with a Gaussian distribution.

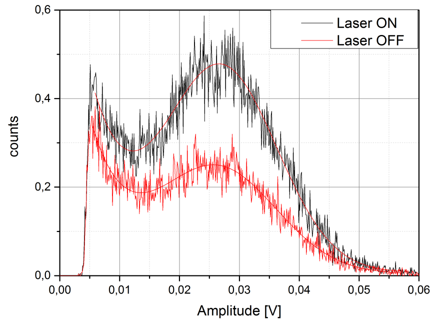


(a) PMT L1 (ET Enterprise 9829QSA).



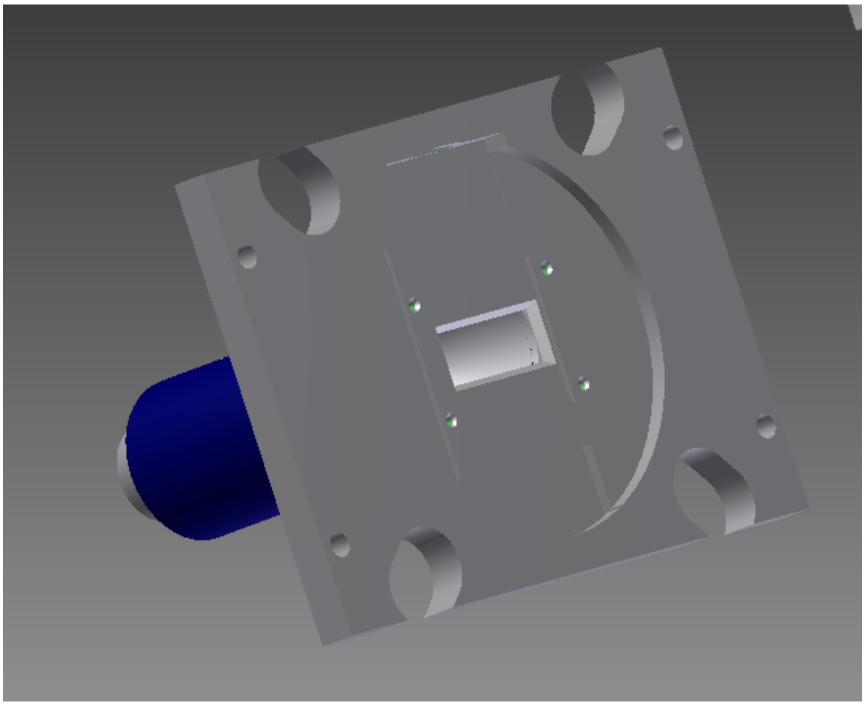
(b) PMT R1 (ET Enterprise 9814QSA).

(c) This detector got replaced in the meanwhile.

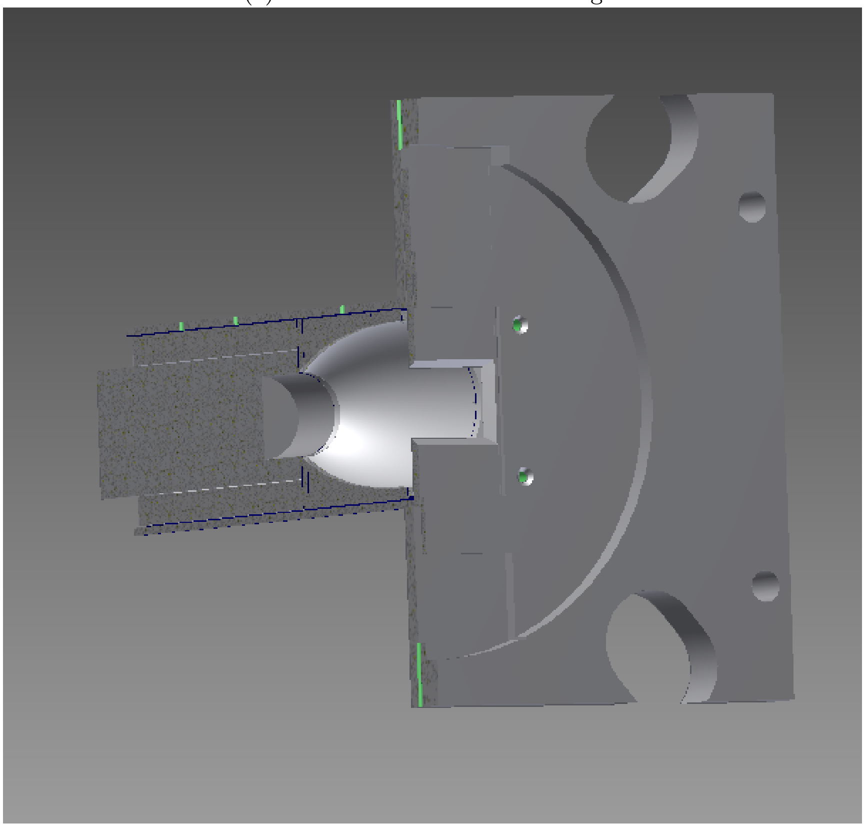


(d) PMT R2 (ET Enterprise 9814QSA).

Figure 7.3: Older pulse-height distributions of the different PMTs with and without the laser beam. The fit curves show superpositions of an exponential curve with a Gaussian distribution.

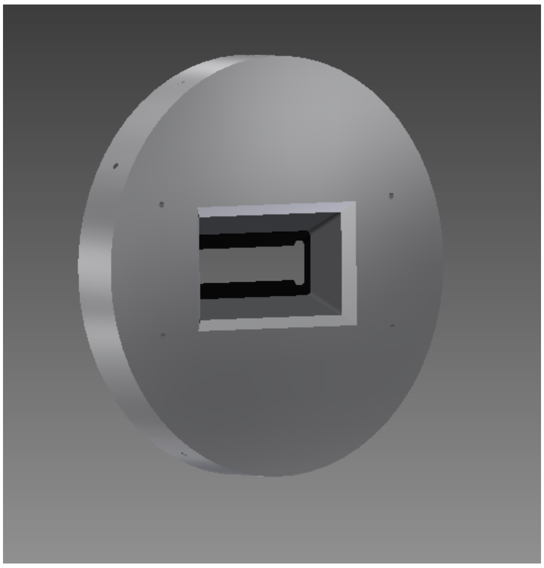


(a) Full view on the shutter design.

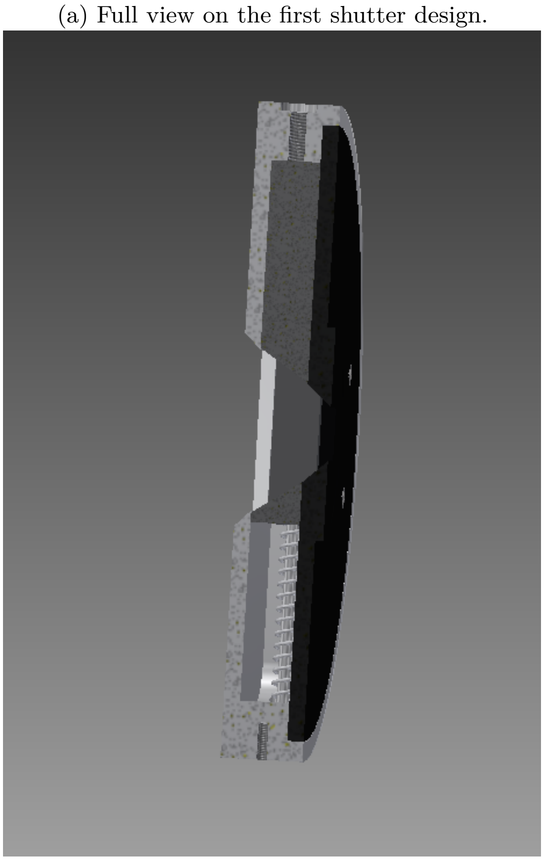


(b) Crosssection view on the shutter design.

Figure 7.4: Model of the whole shutter design used by TRIGA-LASER of the Johannes Gutenberg-Universität Mainz.

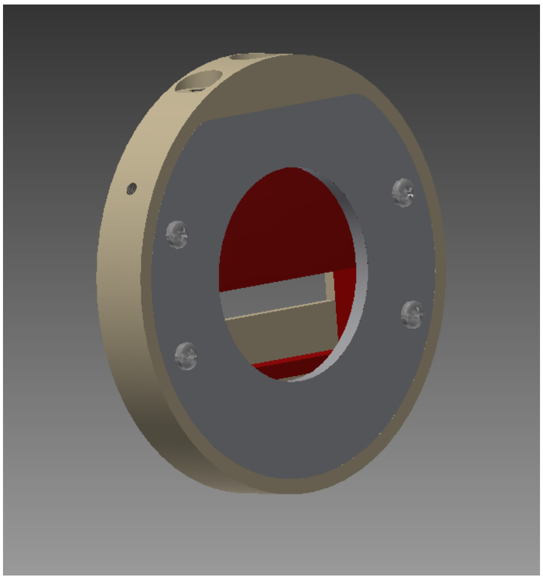


(a) Full view on the first shutter design.

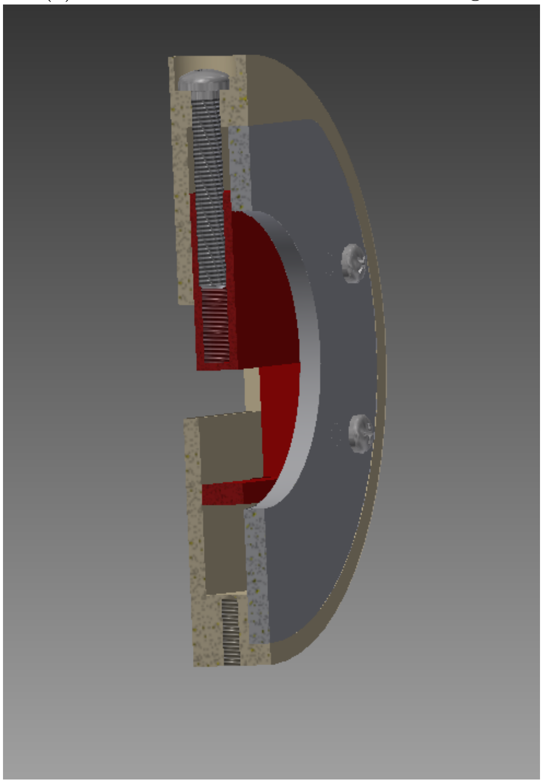


(b) Crosssection view on the first shutter design.

Figure 7.5: Model of the first shutter design. Springs are pushing the window up so that the shutter is open. By using the screw, the window can be moved and the shutter can be closed.

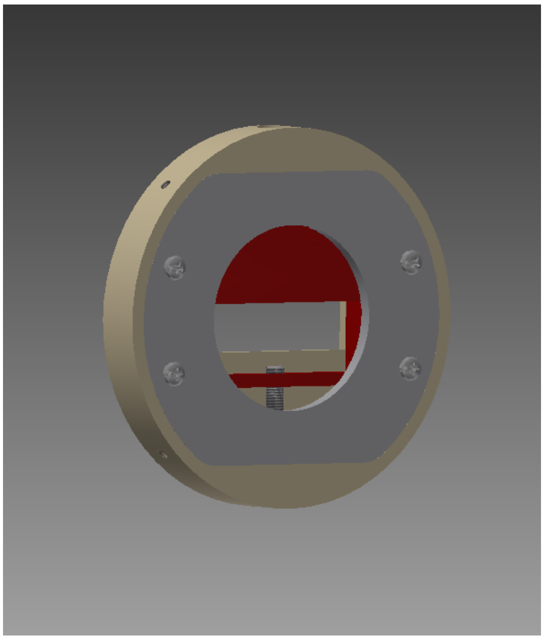


(a) Full view on the second shutter design.

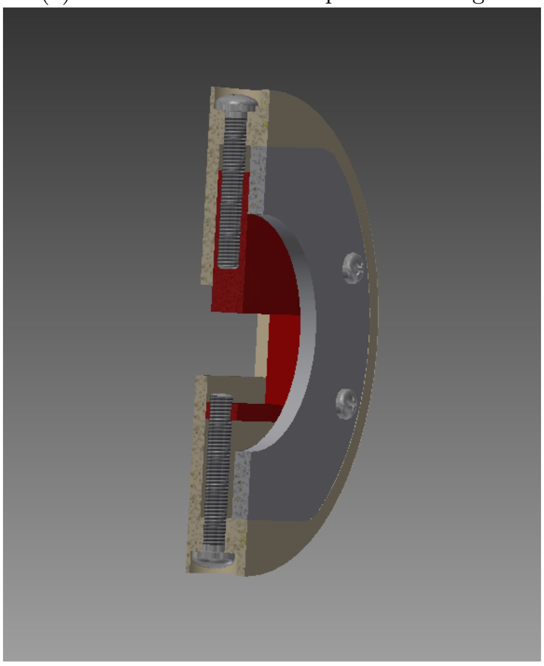


(b) Crosssection view on the second shutter design.

Figure 7.6: Model of the second shutter design. In this design, the window is containing a thread. The screws position is fixed, but it is still rotatable. Thus, by rotating the screw, the window can not rotate and so it is moving up-/downwards.

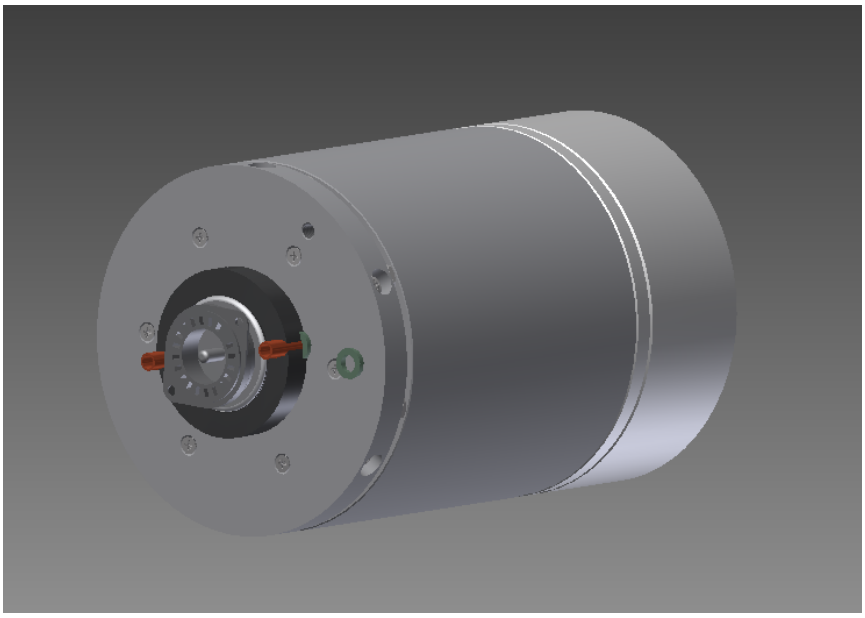


(a) Full view on the backup shutter design.

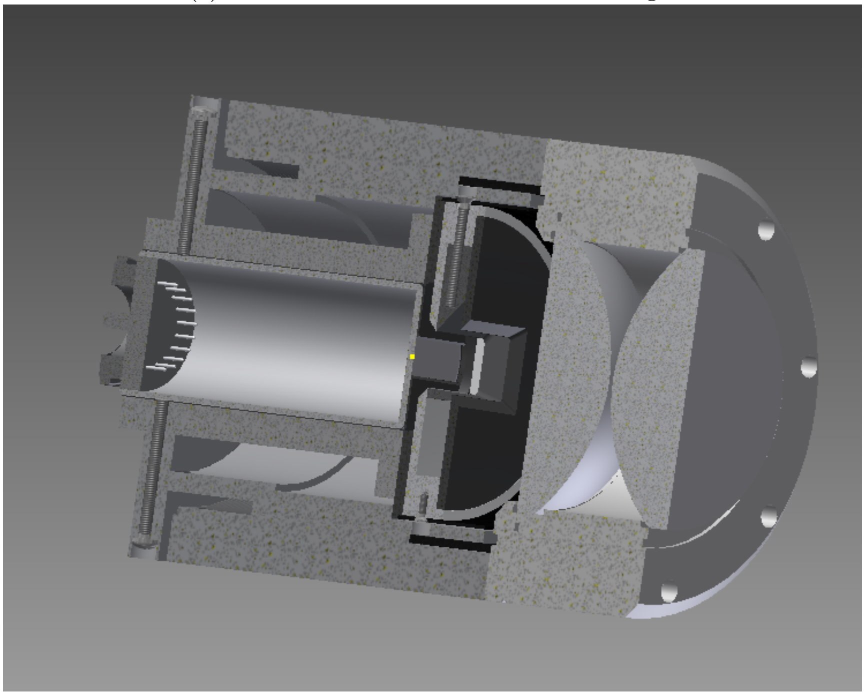


(b) Crosssection view on the backup shutter design.

Figure 7.7: Model of the backup shutter design. This is a copied concept of the shutter used at Johannes Gutenberg-Universität Mainz modified for our dimensions.



(a) Full view on the old whole shutter design.



(b) Crosssection view on the old whole shutter design.

Figure 7.8: Model of the old whole shutter design. This model is not yet fully designed, since I decided to go with the other design. The main disadvantage of this design was the lack of space for the shutter.

7.1 Acronyms

COLLAPS	Collinear Laser Spectrometer
ISOLDE	Isotope Separator On Line DEvice
HV	High voltage
PMT	Photomultiplier tube
ROC	Radioactive detection of collinear-laser optical pumping

7.2 Units

$FWHM$	Full width half maximum (in case of gaussian dist.: $FWHM = 2\sqrt{2ln2}\sigma$)
σ	Standard deviation
Δt	time difference

7.3 List of Figures

7.4 List of Tables