

CERN Summer Student Report
**Laser spectroscopy of short-lived
radionuclides in an ion trap: MIRACLS'
proof-of-principle experiment**

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1 Introduction

Since 1978 Collinear Laser Spectroscopy is done at COLLAPS [1], which is located at ISOLDE, CERN's facility for synthesizing radioactive ions, to explore the nuclear shell structure of the most exotic atomic nuclides far away from stability. At COLLAPS a laser beam is overlapped with a radioactive ion beam. If the wavelength of the laser corresponds to the energy difference of the electronic transitions, the laser excites the ions. The excited ions decay back to the ionic ground state and emit fluorescence photons that can be detected with photomultiplier tubes (PMTs). By measuring the hyperfine structure of the involved ionic states one obtains information about the nuclear spin, the nuclear magnetic dipole moment and the nuclear electric quadrupole moment. This hyperfine splitting is caused by the interaction of the bound electrons with the atomic nucleus. The electrons induce an electromagnetic field at the place of the nucleus that interacts with the electromagnetic nuclear moments and the nuclear spin.

By calculating the difference in fine structure splitting of two different isotopes of the same element we get the isotope shift that is related to the nuclear mean square charge radius. A change in the neutron number leads to a different size of a nuclide's charge distribution which results in a shift in the energy of the (ionic) fine structure state. Due to its high precision and accuracy, Collinear Laser Spectroscopy remains a very important experimental technique to access nuclear spins, magnetic dipole moments, electric quadrupole moments and mean square charge radii of short-lived nuclides far from stability and to obtain knowledge about the shell structure of the most exotic nuclides[1].

However, COLLAPS is limited to nuclides with production yields of typically more than a few 1000 ions/s delivered from ISOLDE. To measure the most exotic nuclides far from stability, that can already be produced with low production yields, novel experimental techniques have to be envisioned. One shortcoming of COLLAPS is that the radioactive ions only interact with the laser in the time scale of some μs , whereas the half-life of the ions is between tens of milliseconds to seconds. To make use of the rare isotopes over their entire lifetime and therefore enhance the sensitivity of COLLAPS by a factor of 20-800, the concept of a Multi Ion Reflection Apparatus for Collinear Laser Spectroscopy of radionuclides (MIRACLS) was introduced. The general setup of MIRACLS can be seen in figure 1. A bunched ion beam is trapped between two electrostatic mirrors and the laser interacts with the ion bunch during each revolution. Therefore the observation time is extended and only limited by the half-life of the ions or by the maximal trapping time.

At the moment a proof-of-principle experiment is carried out with an existing electrostatic ion beam trap EIBT, also called multi-reflection time-of-flight MR-ToF apparatus, which was built at the University of Greifswald for the purpose of mass measurements in a student lab. This proof-of-principle experiment is performed with ion beam energies of about 1.3 keV, whereas the real experiment should run at 30 keV in order to minimise the Doppler broadening. At the proof-of-principle experiment (see figure 1) the ion beam formed in an offline ion source is bent by 90 degrees by a quadrupole bender before the ions enter the Paul trap, where we obtain a bunched beam with low energy spread. After their release from the Paul trap, the ions are

trapped for several revolutions inside the MR-ToF and interact with the laser beam during each revolution. The emitted fluorescence photons are detected by PMTs. This report will focus on improvements of the sensitivity of MIRACLS by optimizing the offline ion source (chapter 2.1), reducing the scattered laser light (chapter 2.2) and checking and improving the EIBT alignment (chapters 2.3 and 2.4) .

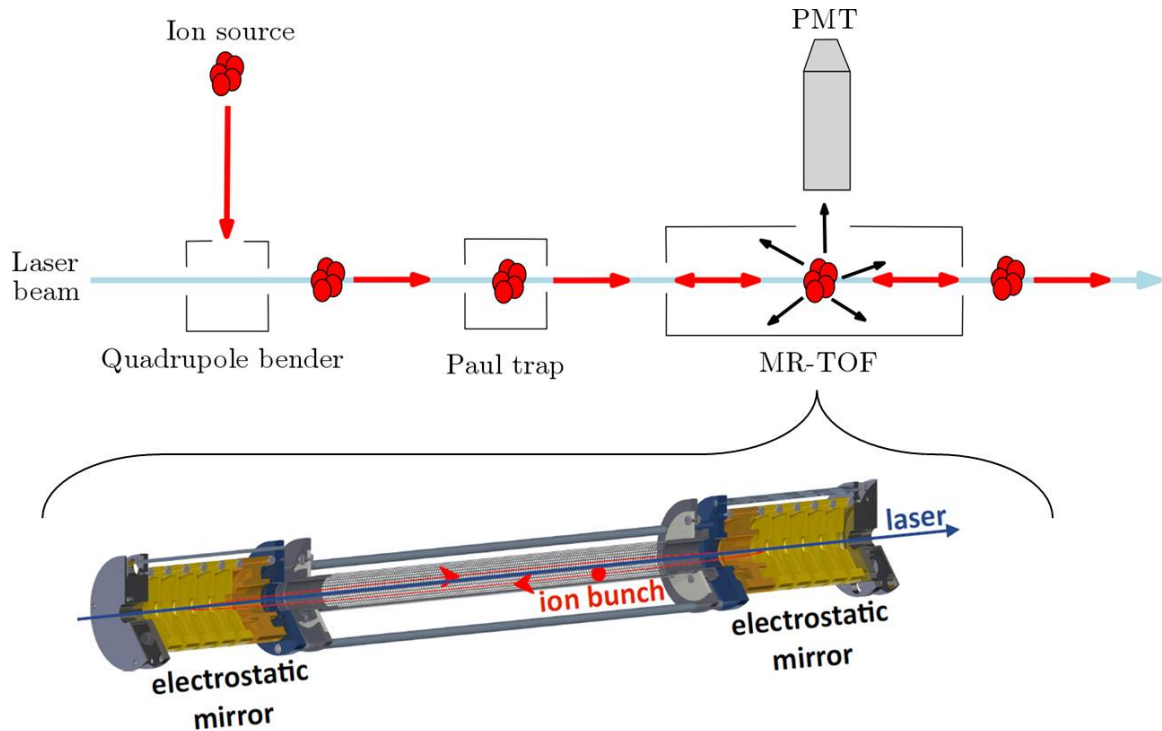


Figure 1: Schematics of MIRACLS' proof-of-principle experiment. See text for details.

2 Methods and Results

2.1 Simulations of the Ion Source

For the proof-of-principle experiment an offline ion source (see figure 2) is used which produces a stable $^{24}\text{Mg}^+$ beam. $^{24}\text{Mg}^+$ is used because its ionic transition has a simple closed two-state structure. Due to the fact that Mg is not already in the gaseous state, it has to be vaporised by an oven that heats the Mg above its vaporisation temperature. The Mg atoms are then ionized by the impact of electrons that are emitted from a hot filament. An extraction electrode is used to obtain a field gradient at the ionisation region. The beam of Mg ions gets focused along the beam axis by an einzel lens. The ions have to pass a collimator with a hole of a diameter of 8 mm. The collimator is used to separate the vacuum volumes of the ion source and the MR-ToF.

Due to the observed fact that in the experimental setup only a small fraction of ions can be transported into the MR-ToF, SimIon simulations of the ion source were carried out to find the optimal potential of the einzel lens and the extractor such that

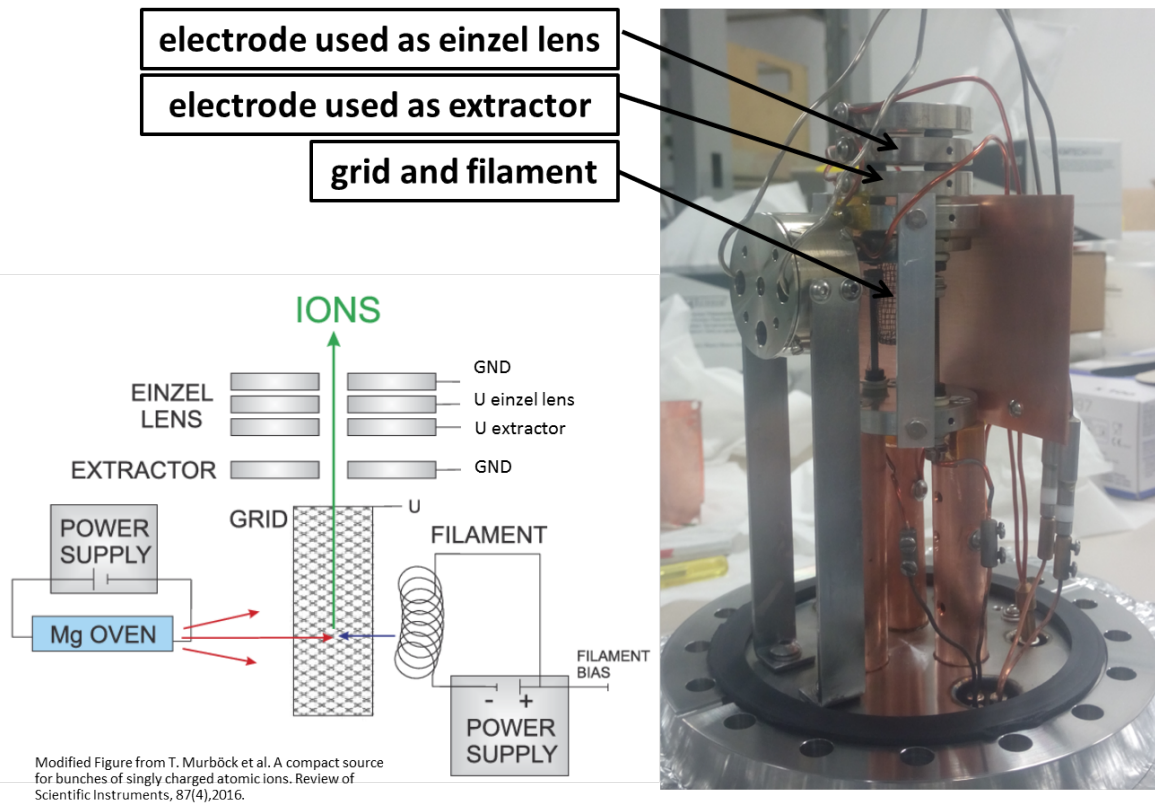


Figure 2: Schematic view and photograph of ion source

the highest number of ions pass through the 8 mm hole of the collimator. The ion source was simulated with SimIon by importing the CAD assembly file. In the first simulation the electrons are emitted homogenously from the electron emission wire surface and the electron distribution function along the direction of the Mg atoms is calculated. In the second simulation a set of ions with random starting positions according to the previously calculated electron distribution function inside the grid is created [4]. The trajectories of the ions can be seen in figure 3. The trajectories are extrapolated to estimate how many ions pass through the collimator in a distance of 43 cm after the ion source.

If the einzel lens has a potential of -500 V and the extractor has a potential of -150 V, 14% of all the created ions are passing through the hole of the collimator. All the other combinations of the potentials of einzel lens and extractor lead to worse results, as can be seen in figure 5 (on the top). If we place a new, additional new einzel lens between the ion source and the collimator, the ion trajectories will be better focused and 30% of the ions can pass through the collimator. Figure 4 shows a 2D contour histogram of the simulation results without (left side) and with (right side) the additional einzel lens. It can nicely be seen that the new einzel lens leads to a better focus of the beam. The simulation therefore strongly suggests to install a new einzel lens between collimator and ion source. However, simulation and experimental results without the new einzel lens are not in good agreement, as can be seen in figure 5. For the simulation we get the highest number of ions passing through the collimator for an einzel lens potential of -500 V and an extractor potential between

0 and -500 V. For the experiment we obtain the highest current for an einzel lens potential of -100 V and an extractor potential of -800 V. Apart from the difference in the location of the optimal settings between experiment and simulation, the overall trends of the measurement could not be reproduced by the simulation (compare to figure 5). Why the experiment and the simulation data do not fit remains an open question. One reason could be a misalignment of the ion source in respect to the collimator. Such a misalignment could be corrected by an ion steerer setup. Ongoing modifications to the beamline of the ion source will hence include such ion-steering capabilities. As demonstrated by this work, the new setup will furthermore add an einzel lens between ion source and collimator.

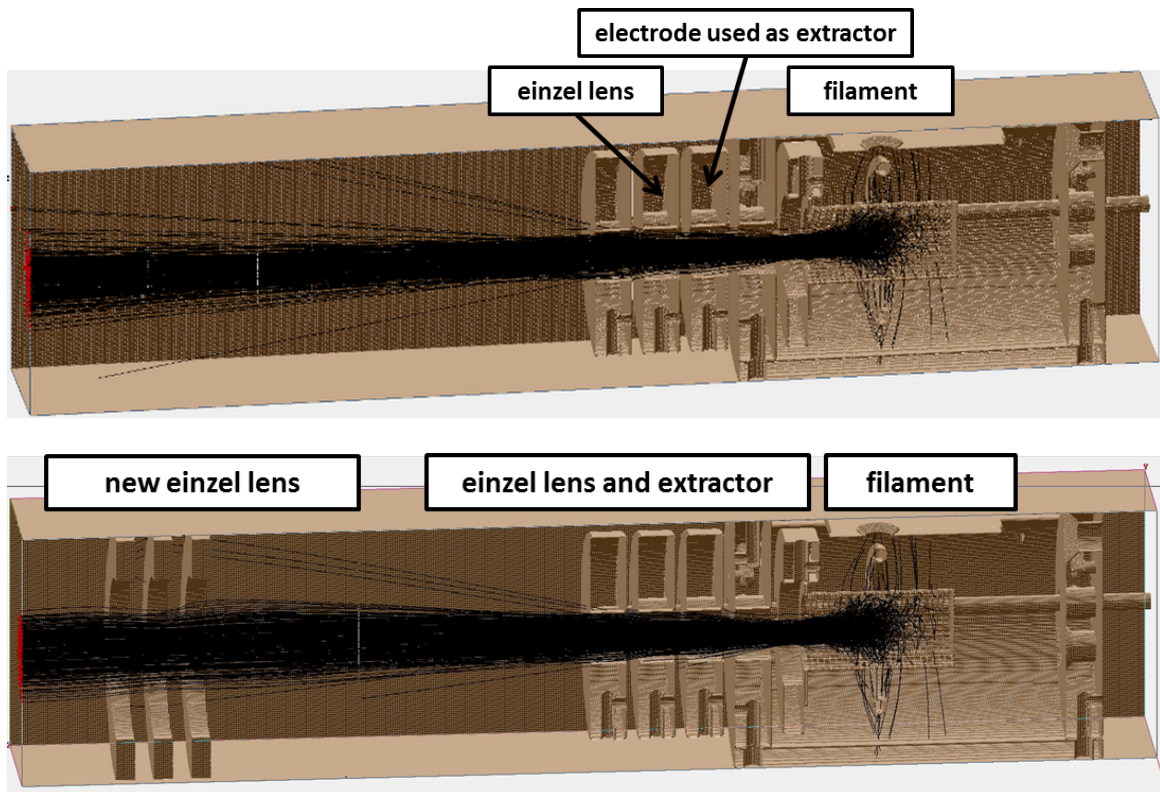


Figure 3: Visualisation of the result of a SimIon Simulation of the ion source with (top) and without (bottom) an additional einzel lens. The trajectories of the ions are marked in black. Please note the unusual dimensions of the new einzel lens. While we expect better performance with a typical design of an einzel lens, the present choice is motivated by limited computing power in this detailed representation of the ion source.

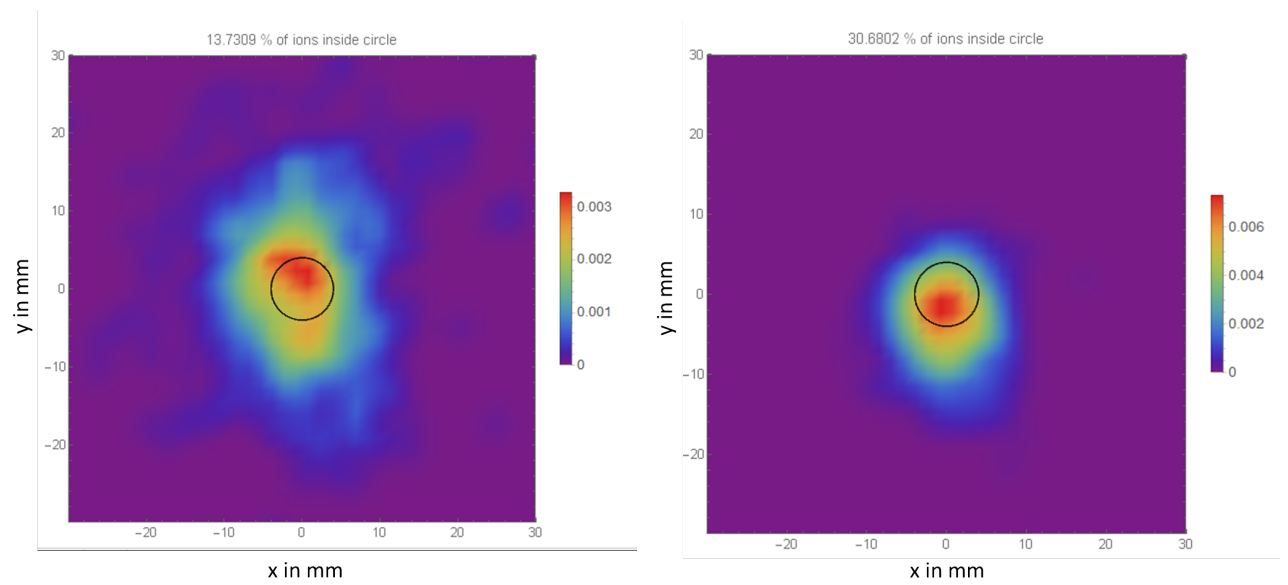


Figure 4: 2D contour histogram of the simulation results without (left) and with (right) the new einzel lens. By placing a new einzel lens between ion source and collimator a better focus through the collimator can be obtained. The hole of the collimator is marked by a black circle.

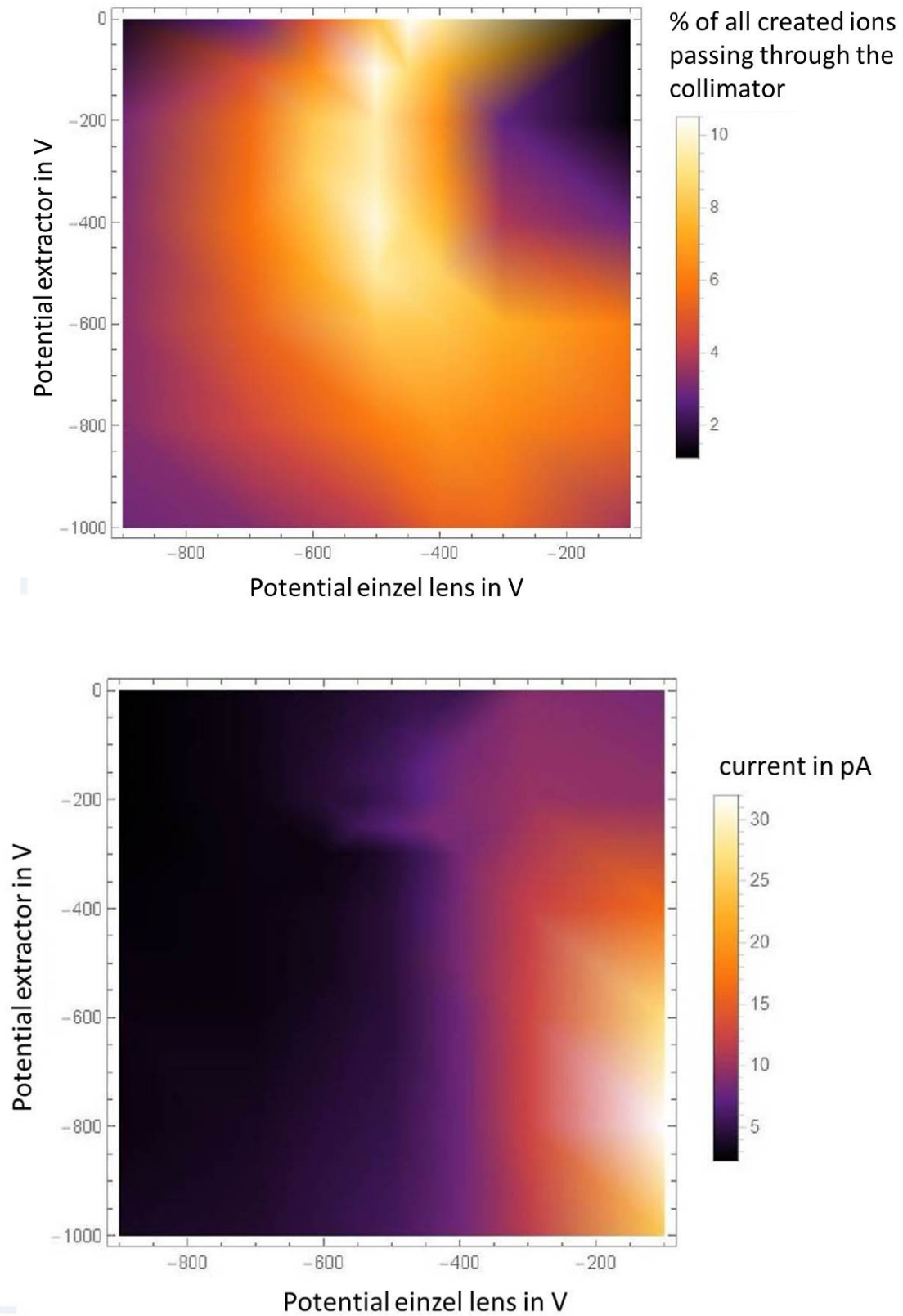


Figure 5: Comparison between simulation (top) and experiment (bottom). See text for further informations.

2.2 Reduction of the Laser Light Scattered in the Apparatus

Due to the many small holes in our setup which the laser beam has to pass - the smallest one has a diameter of only 2.5 mm - the tails of the gaussian shaped laser light get scattered. This scattered light leads to a large background signal in the photomultiplier tubes (approx. 1 MHz when a 0.6 mW laser beam is sent into the setup). The schematic overview of this problem with stray light is shown in figure 6. Figure 7 provides a solution to minimise this stray light by building two aperture systems that are installed before the laser enters and exits the setup. The aperture system at the exit is used to minimise the stray light of the backscattered laser light from the exit window. The exit window is positioned in the Brewster angle to minimise the reflection.

The aperture system is based on a design of collaboration partners at the TU Darmstadt, but was modified for the present purpose. These modifications involved the limited space available at MIRACLS, increased flexibility as well as vacuum considerations. The system consists of three fixed apertures with an inner diameter of 6, 8 and 10 mm. (After applying the modifications described in the next chapter the smallest hole would have a inner diameter of 12 mm instead of 2.5 mm.) Alternatively, for increased flexibility, these fixed apertures can be exchanged by the D12S iris of Thorlabs with a flexible inner diameter between 0.8 to 12 mm. Some laser light will still be scattered at the sharp edges of the first aperture, however, a large fraction of the scattered light is absorbed by the two other apertures so that it can not enter the PMTs any more. The three apertures are put into a self-designed tube with holes for improved pumping in the vacuum as can be see in figure 8. This tube is then put into a CF40 nipple. The position of our new tube inside the CF nipple can be changed in radial direction by ± 3 mm with screws in order to have the middle points of the apertures exactly lying on the optical axis of the MR-ToF apparatus.

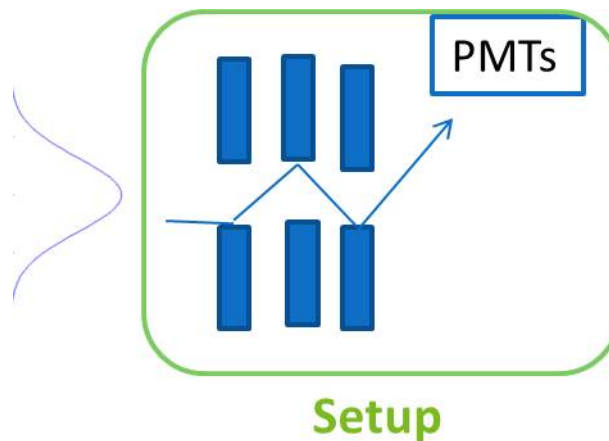


Figure 6: The tails of the Gaussian shaped laser light get scattered at the surfaces of the small holes in the setup and the scattered light leads to a large background signal in the PMTs.

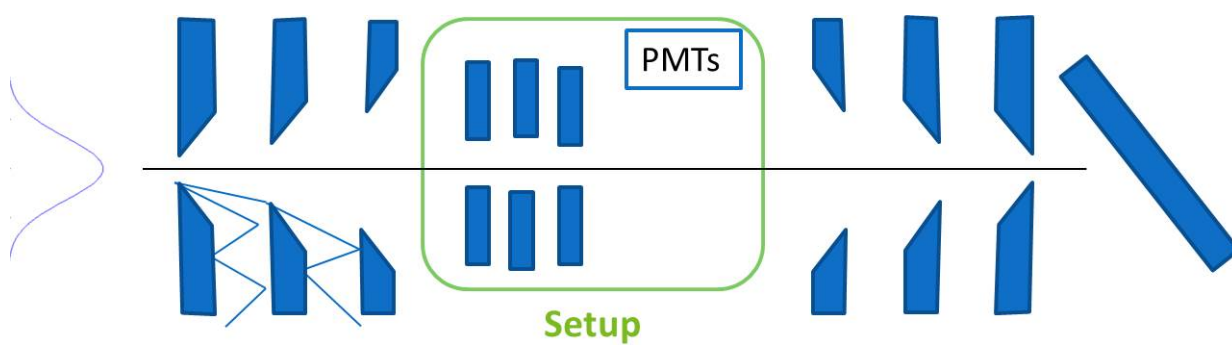


Figure 7: Aperture system before and after the setup: The scattered light is collected by the apertures and less stray light can enter the PMTs.

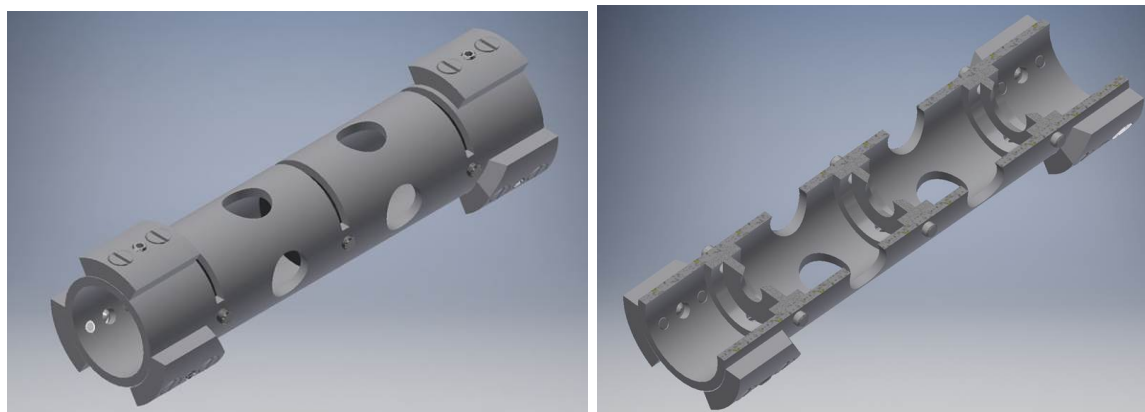


Figure 8: Tube hosting the aperture system

2.3 MR-ToF Alignment and an Improved Setup

To make use of the previously discussed aperture system for the reduction of the stray light, the optical axis of the MR-ToF can maximally be ± 3 mm away from the centre of the apertures' holes. So we checked the alignment of our setup with a theodolite. There are three holes with a diameter of 2.5 mm along the beam axis in our setup. One of these holes is located at the electrode of the einzel lens for the injection of the ions into the Paul trap, and the other two holes are located at the entrance and exit of the Paul trap. The present work revealed that these holes do not lie on a straight line (misalignment by approximately 0.5 mm in vertical and horizontal direction). Furthermore, the centre of the exit of the Paul trap is 4-5 mm above the axis defined by the entrance and exit electrode of the MR-ToF. This misalignment leads to a large laser stray light and likely has a negative impact on the overlap of the ion and the laser beam. A potential reason for this large misalignment is the shipment of the apparatus from Greifswald, Germany, to CERN. Moreover, the construction uses long rods which might get sagged over the time.

To improve the laser-ion alignment and to reduce the amount of stray light the position of the Paul trap will be changed such that the laser does not have to pass through the 2.5 mm holes in the Paul trap any more. The Paul trap, the acceleration zone and the lift will be taken out of the setup and put into a 90 degree rotated beamline as can be seen in figure 9. Therefore the laser beam only passes the quadrupole bender and goes straight into the MR-ToF, where it excites the ions. In the new setup the smallest holes which the laser has to pass through have a diameter of 12 mm. New steerer and einzel lenses are used to get an optimal ion path in the MR-ToF.

2.4 Simulation of Ion Optics for Improved Setup

The previously discussed modifications on the entire setup demand the simulation of the planned ion optics in SimIon to ensure optimal ion transfer from the new position of the Paul trap into the MR-ToF apparatus. I.e. the position and electric potential of the two lenses before the quadrupole bender, the two lenses after the quadrupole bender and the four electrodes of the quadrupole bender have to be chosen such that the highest number of ions is trapped in the MR-ToF apparatus. For the simulation, we started with 1000 ^{24}Mg ions that are created in the middle of the exit hole of the Paul trap with a diameter of 2.5 mm. This tube is floated to 180 V. The position of the ions inside the hole is given by a cylindrical distribution, where the start position is uniformly distributed in a cylinder with a radius of 1.25 mm and a length of 2.5 mm. For the direction of the ions we use a cone distribution with a half opening angle of 5 degrees. The kinetic energy at the start of the ions is Gaussian distributed with a mean of 38 eV and a standard deviation of 10 eV or 1 eV. (The standard deviation of the kinetic energy at the start of the ions is called initial energy spread throughout this report.) The 38 eV represent the difference in electric potential of the positions where the ions are stored in the actual experiment prior to their ejection from the Paul trap and the extraction tube. The starting values for position and direction of the ions are chosen as worst case scenario limited by the geometry.

The ions pass through the acceleration zone and then continue straight into the lift

region (compare to figure 9). When the ions are in the middle of the lift 1, the potential of lift 1 is changed from -1750 V to ground. Hence, the ions remain at their gained kinetic energy of around 2 keV.

The ions pass through an einzel lens, are bend by the quadrupole bender and then pass through two einzel lenses before the injection into the MR-ToF apparatus. To pass the first mirror the incoming ions must have a kinetic energy that exceeds the maxima of the mirror potentials. Next, the ions „climb“ the potential hill created by lift 2, which is floated to 673 V. When the ions are in the middle of the lift 2 tube, the ions have a kinetic energy of 1.3 keV. At this moment, the potential of the lift 2 is switched to ground potential and the ion energy is not high enough to pass the mirrors any more. The ions are bouncing back and forth in the MR-ToF for a certain number of revolutions. To extract the ions from the MR-ToF apparatus the lift 2 tube is switched to 673 V again and the ion energy is high enough to pass the exit mirror. This principle is called in-trap lift switching [2].

The laser interacts with the ion cloud every time when the ions pass the middle of the MR-ToF from left to right - provided that the laser beam overlaps with the ion beam. The ions should therefore have small radial position deviations from the MR-ToF axis (parallel to x-axis) every time when they pass the middle of the MR-ToF from left to right. Additionally, the velocity components in y and z direction should be small because a non vanishing angle of the ion beam in respect to the laser beam could lead to an unwished frequency shift due to the Doppler effect. By using a Simplex Algorithm implemented in LUA the optimised potentials given in table 2 were found. The potentials of the electrodes of the quadrupole bender, the einzel lenses 2, 3, 4 and the cuboid lenses directly before and after the quadrupole bender were optimised. The minimisation condition for the Simplex Algorithm is given in a way that favours a small loss of ions inside the setup, small velocities of the ions in y and z direction and small radial position deviations from the MR-ToF axis. Moreover, the potential of einzel lens 4 should be chosen in a way that provides a sharp, spatial focus of the ion trajectories in the turning point of the ions.

The simulation with the optimised potentials and an initial energy spread of 10 eV (=standard deviation of the kinetic energy at the start of the ions), that can be seen in figures 10 and 11, shows that 98.7% of the ions starting from the exit window of the Paul trap and performing 10 revolutions between the two electrostatic mirrors are extracted from the MR-ToF. This establishes a high efficiency of close to 100% for all ions which pass the acceleration section even in the considered worse case scenario. (Simulating ion losses during the extraction from the Paul trap and in the acceleration section is beyond the scope of the present work.)

The deviations in radial position of the ions from the MR-ToF axis for an initial energy spread of 10 eV can be seen in figure 12. If the diameter of the laser is chosen with 2 mm, as was previously planned, the laser excites the ions in only 20% of the possible cases. If the diameter of the laser is 4 mm, an excitation of the ions happens in 58.5% of the possible cases and if the diameter of the laser is chosen with 6 mm an excitation happens in 86% of the possible cases. It is interesting to note that a single ion has a different radial displacement on each revolution; i.e. it may be within the 2 mm in one turn, but not in the second turn. The deviations in radial position of

the ions are very much the same for 1 eV and 10 eV.

The Gaussian shaped Time-of-Flight (TOF) distribution for an initial energy spread of 10 eV can be seen in figure 13. The ions need $(9.89 \pm 0.10) \mu s$ to get from their starting position at the exit hole of the Paul trap to the middle of the MR-ToF. The small standard deviation of 100 ns enables us to do mass spectroscopy as well. By using mass spectroscopy measurements one could get rid of unwished ions that are wrongly produced in the ions source. Moreover, the smaller the standard deviation of the TOF is, the shorter the time gate of ions passing the PMTs can be set resulting in a smaller background signal in the PMTs. If the initial energy spread is 1 eV the standard deviation is just 44 ns.

In the middle of the MR-ToF the ions propagate ideally parallel (or antiparallel) to the laser beam with a velocity v_x in positive or negative x-direction. The resonance frequency f_0 of the ion is therefore Doppler shifted in the laboratory system to $f = f_0(1 - v_x/c)$, where c is the speed of light. The resonance frequency f_0 for the transition of the Mg II ions from the ground state ($^2S_{1/2}$) to the excited state ($^2P_{1/2}$) with 4.42 eV and a spin of $\frac{1}{2}$ is 1,069,339,000 MHz [3]. The Doppler shifted frequency spread is influenced by the initial energy spread and the angle between the laser and the ion beam. The velocities in z or y direction should be as small as possible to obtain the highest measurement resolution in f . Figure 14 shows histograms of the frequency spreads for an initial energy spread of 1 eV and 10 eV. The mean values and standard deviations of the Doppler shifted frequency f can be found in table 1. The ions, starting with an initial energy spread of 10 eV, have in the middle of the MR-ToF a mean value of the kinetic energy of 1295.57 ± 0.11 eV with a standard deviation of 11 eV. If they start with an initial energy spread of 1 eV the mean value is (1295.303 ± 0.022) eV and the standard deviation is 2.2 eV. The theoretical kinetic energy of the ions for an initial energy spread of 10 eV is $T = 1750 + (38 \pm 10) + 180 - 673 = 1295 \pm 10$ eV and for an initial energy spread of 1 eV (1295 ± 1) eV. The fact that the mean values of the simulated kinetic energies are slightly larger than the theoretical value, can be explained by the change of the potentials in the lift tubes 1 and 2. By using the Doppler equation $f = f_0(1 - v/c)$ and the equation for the kinetic energy $T = \frac{1}{2}mv^2$, where m is the mass of ^{24}Mg , we get the theoretical Doppler shifted frequency f , that can be found in table 1.

For an initial energy spread of 10 eV the standard deviation of f for the simulated data, caused by the initial energy spread as well as the angle between MR-ToF axis and the velocities of the ions, is the same as the theoretical standard deviation, only caused by the initial energy spread. The initial energy spread of 10 eV is therefore more significant than the angle between MR-ToF axis and the velocities of the ions. For an initial energy spread of 1 eV the standard deviation of the simulated data is twice as high as the theoretical standard deviation of f . One can conclude, that the smaller the initial energy spread is, the more important the angle between ion trajectories and the MR-ToF axis gets. Because the velocity v_x of the ions parallel to the MR-ToF axis can only be lowered, the higher the angle, the larger the asymmetry. Why there is a non-negligible shift in the mean value of f for an initial energy spread of 1 eV remains an open question.

Table 1: statistics of the Doppler shifted frequency f

	mean value of f	st. deviation of f
energy spread of 1 eV, simulation	$(1,069,703,006 \pm 3)$ MHz	300 MHz
energy spread of 10 eV, simulation	$(1,069,703,040 \pm 15)$ MHz	1500 MHz
energy spread of 1 eV, $T = 1295$ eV	1,069,702,973 MHz	150 MHz
energy spread of 10 eV, $T = 1295$ eV	1,069,702,973 MHz	1500 MHz
energy spread of 1 eV, $T = 1295.303$ eV	1,069,703,016 MHz	150 MHz
energy spread of 10 eV, $T = 1295.573$ eV	1,069,703,053 MHz	1500 MHz

Table 2: Best potentials for ion optics that result in a small loss of ions inside setup, small velocities of ions in y and z directions and small radial position deviations from the MR-ToF axis(= shifted x-axis). The numbers of the einzel lenses are explained in figure 9. The potentials that have been optimized with the Simplex Algorithm are marked with (*).

	Potential in V
extraction tube, Paul Trap (endcap)	180
acceleration zone (nearer Paul Trap)	142
acceleration zone (nearer lens 1)	-1750
first electrode of lens 1 (nearer acceleration zone)	-1750
second electrode of lens 1	-450
lift 1 combined with third electrode of lens 1 and first electrode of lens 2	-1750 to GND
second electrode of lens 2	(*) -3000
third electrode of lens 2	0
electrodes of quadrupole bender	(*) ± 1350
other parts of quadrupole bender, f.i. cuboid lenses	(*) 0
first electrode of lens 3	0
second electrode of lens 3	(*) -2800
third electrode of lens 3	0
first electrode of lens 4	0
second electrode of lens 4	(*) -4200
third electrode of lens 4	0
outermost electrodes of electrostatic mirrors	1870
nearly outermost electrodes of electrostatic mirrors	975
nearly innermost electrodes of electrostatic mirrors	1700
innermost electrodes of electrostatic mirrors	-4500
lift 2	673 to GND
first electrode of lens 5	0
second electrode of lens 5	-4000
third electrode of lens 5	0
double and single crosses and tubes hosting the setup	0

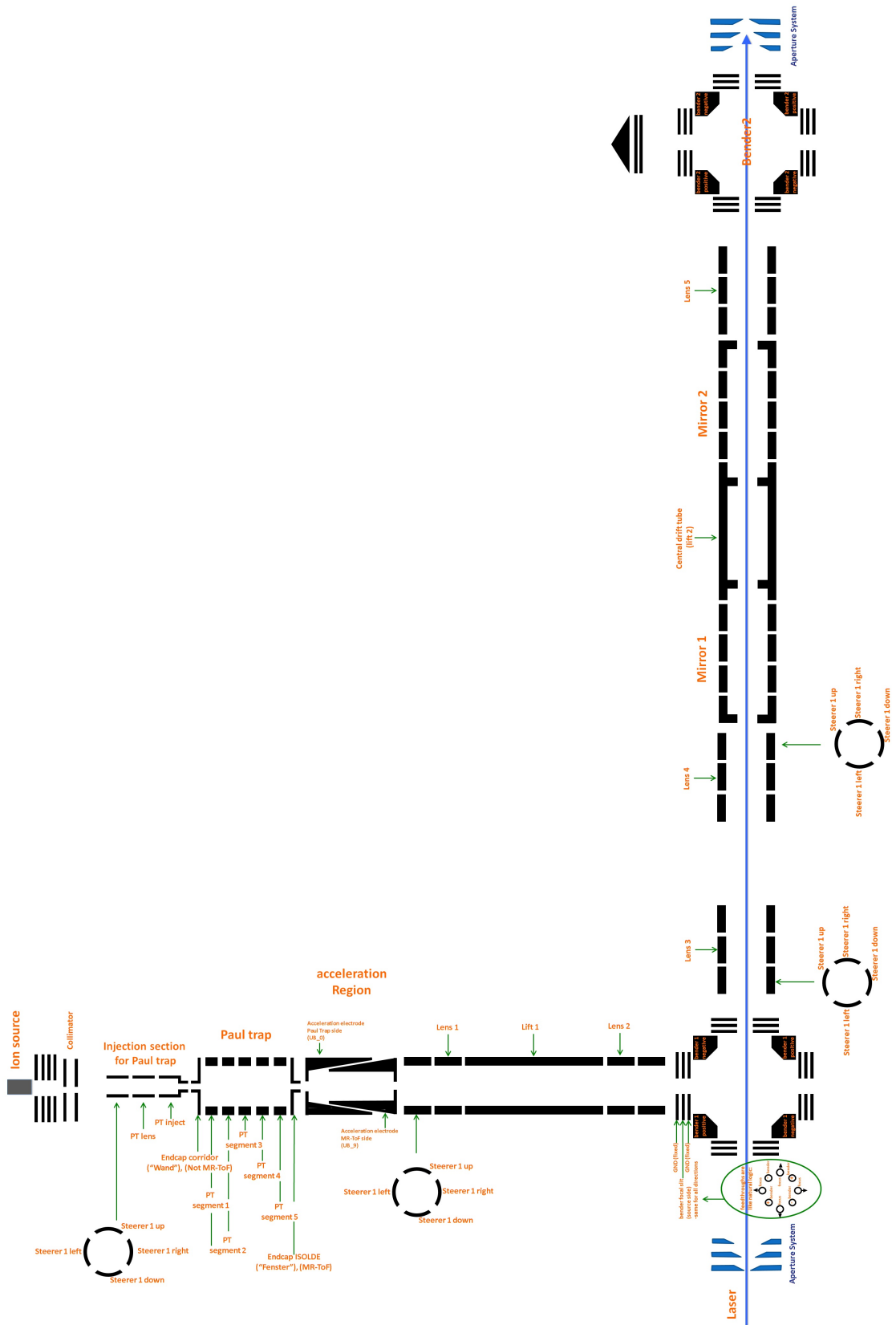


Figure 9: Improved Setup to obtain a better alignment of laser and ion beam as well as a reduction in the amount of stray laser light: The laser is not going through the Paul trap, the acceleration zone and the lift region anymore.

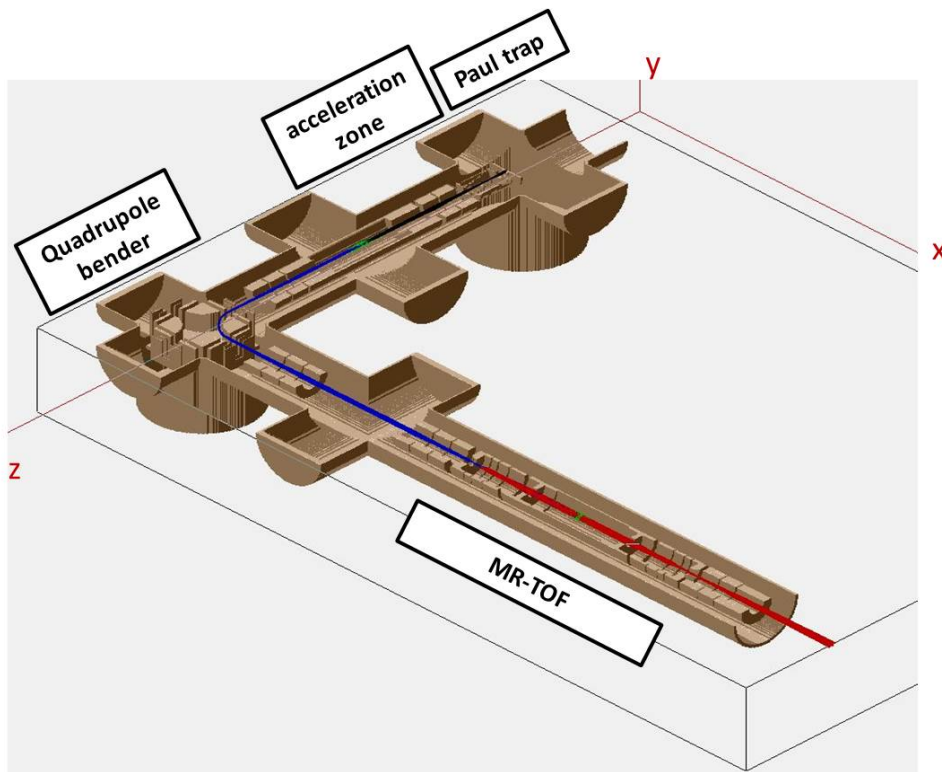


Figure 10: Visualisation of the result of a SimIon Simulation: The ions start from the exit end cap of the Paul trap, get accelerated, pass through einzel lens 1 and enter the lift 1. When the ions are in the middle of lift 1 (the colour of the ion beam changes from black to blue there) the potential of lift 1 is set to ground. The ions pass through the einzel lens 2 and are bend by the quadrupolbender. The beam passes through the two einzel lenses 3 and 4 before entering the MR-ToF (The colour of the ion beam changes to red there.). After 10 revolutions the ions leave the MR-ToF (middle of the MR-ToF is marked in green) and pass through the einzel lens 5.

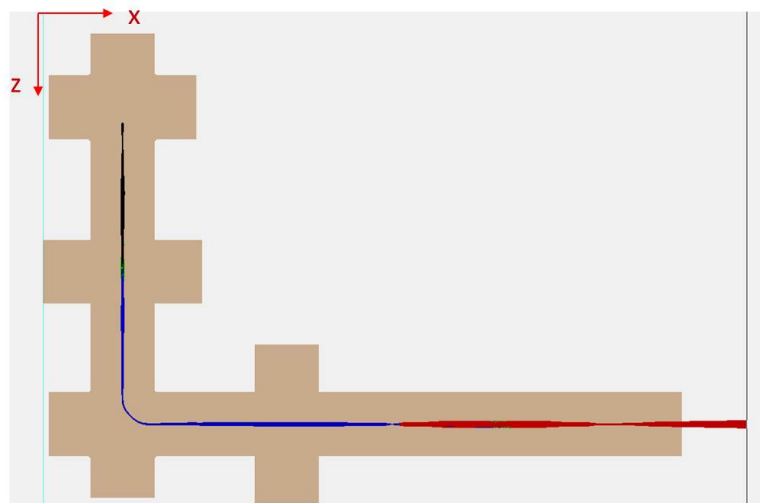


Figure 11: xz-view of the visualisation of the result of a SimIon Simulation

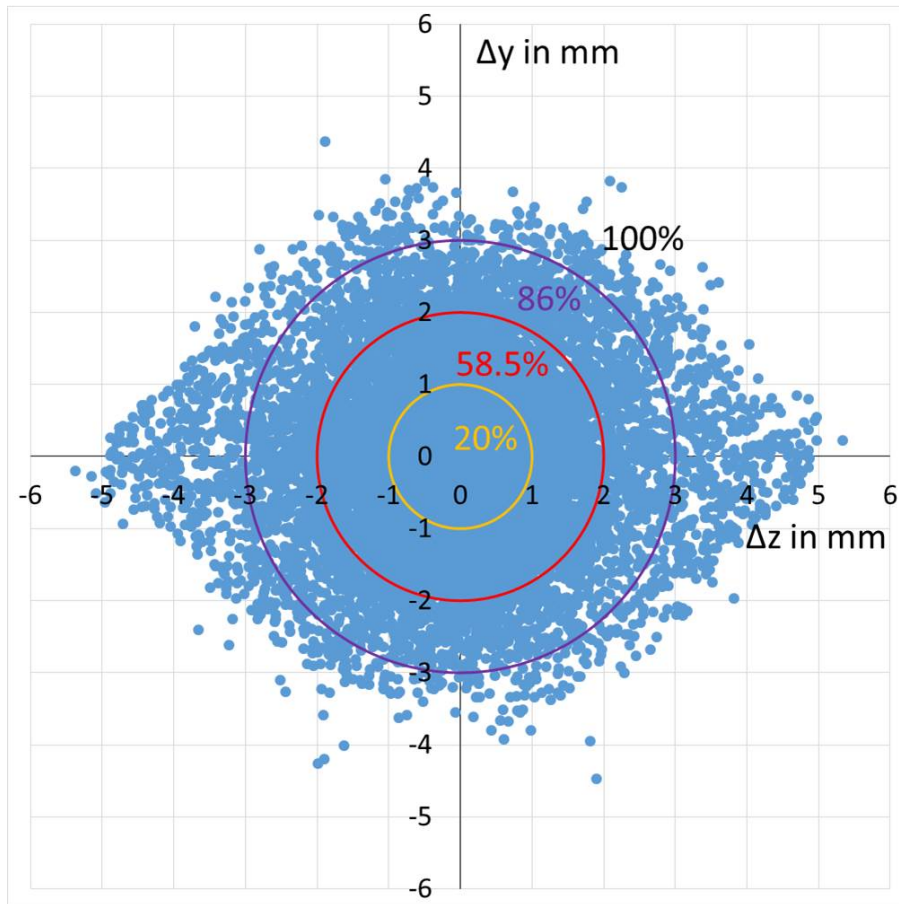


Figure 12: Deviations in radial position of the ions from the MR-ToF axis for an initial energy spread of 10 eV: If the diameter of the laser is chosen with 2 mm, as was previously planned, the laser excites the ions in only 20% of the possible cases. If the diameter of the laser is 4 mm, an excitation of the ions happens in 58.5% of the possible cases and if the diameter of the laser is chosen with 6 mm an excitation happens in 86% of the possible cases. For an initial energy spread of 1 eV no significant difference compared to an initial energy spread of 10 eV has been observed.

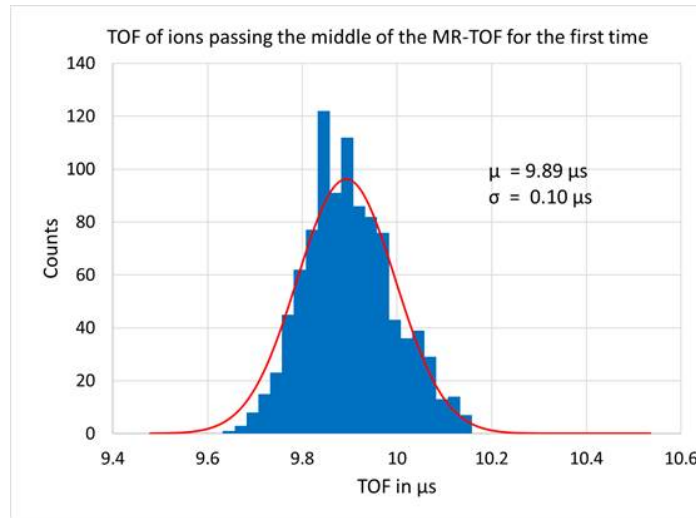


Figure 13: Histogram of the Time-of-Flight (TOF) distribution for an initial energy spread of 10 eV: The ions need $(9.89 \pm 0.10) \mu\text{s}$ to travel from their starting position at the exit hole of the Paul trap to the middle of the MR-ToF. The red curve is a Gaussian constructed from the mean and variance of the simulation data. For an initial energy spread of 1 eV the standard deviation in the TOF is 44 ns.

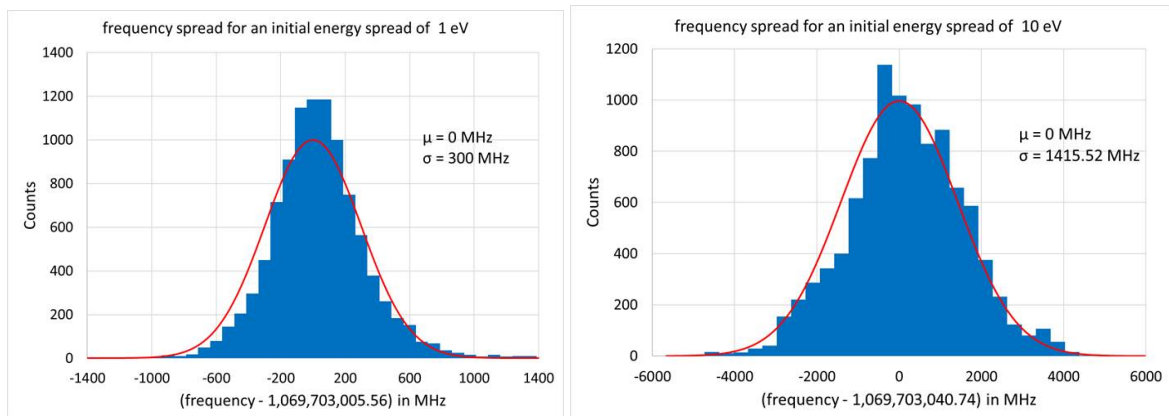


Figure 14: Histogram of the frequency spreads for initial energy spreads of 1 eV (left) and 10 eV (right). The red curve is a Gaussian constructed from the mean and variance of the simulation data.

3 Conclusion and Outlook

An aperture system for the reduction of the light scattered by the laser was built, that is now produced at the machine shop and needs to be tested at our setup. We are confident that with the aperture system the background signal in the PMTs can be lowered from the current value of 1 MHz to a less than a few tens of kHz (as demonstrated in the setup of collaboration partners at TU Darmstadt). To make use of this aperture system the optical axis of the MR-ToF can maximally be ± 3 mm away from the center of the apertures' holes. This limitation should be kept in mind when designing and implementing the modified setup for a better laser-ion beam alignment and less laser stray light.

SimIon simulations for the ion optics of the modified setup were carried out. These simulations show that a laser beam with a diameter of 2 mm only excites the ions in 20% of the possible cases. It would be interesting to see if the overlap of ion and laser beam could be increased by changing the potentials of the electrostatic mirrors of the MR-ToF. If this is not the case, the diameter of the laser beam should be at least 4 mm. However, the larger the diameter of the laser beam, the worse the background rate in the PMTs.

References

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