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Optical Design for Addressing of Single Ions in a 3-D Paul Trap

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Abstract

One of the fields at the frontiers of modern physics is that of quantum information. With the aim of creating a quantum computer, one of the main techniques to implement such an architecture is that of trapping ions. The use of calcium ions in an ion trap allows the encoding of information in the internal states of the ions, as well as the preparation of quantum states of motion such as squeezed states. This report describes the design of the imaging system used to manipulate single trapped ions. First, the geometrical optics approach is described and assessed, then a gaussian optics approach is considered for the wavelengths of interest. The differences between the two approaches are evaluated and the laser beam waist at the focus is calculated using the optical design software Zemax.

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1 Introduction

During the last century, the development of quantum mechanics, a novel description of the physical phenomena, revolutionarized our understanding of the world. At the same time, classical computation gained several achievements and computers quickly became an essential tool for our lives. The major role that computers are covering in our daily lives encourages us to study in detail its possibilities and limitations. Indeed, it turns out that classical computation presents severe limitations in speed, efficiency and in the ability to safely encode and transmit information. As the requirements of a fast evolving technology become higher, improvements in the current classical computers are necessary. This is when computers and quantum physics meet. The link between the two was first proposed in the early eighties by Feynman and Deutsch [1], [2]. Nevertheless, the proposals did not gather much attention until 1994, when Shor devised a quantum algorithm capable of factorising large numbers much faster than a classical one [3]. When the first quantum error correction proposals where formalised, quantum computation started to become a more realistic project. Since then the field of Quantum Information has undergone a real "boom".

1.1 Quantum Information and Quantum Computers

Inspired by the findings of Shor [3] and Grover, who came up with a quantum algorithm for a fast data basis search [4], several scientists around the world set off to the non-trivial task of implementing a quantum computer. The basis for a quantum computer is the ability to store and process information exploiting the laws of quantum mechanics. This requires a system which has the following characteristics: it is long lived, in order to preserve the memory of the stored information; it can be well isolated from the environment, to reduce decoherence and manipulate it individually; it can be controlled well, in order to perform quantum operations. Scientists have investigated several systems which could be good candidates for the development of a quantum computer. The rather abstract concept of quantum information processing has literally sprung a concrete engagement of a remarkable number of fields of fundamental physics, from atomic physics to quantum optics, to nuclear and magnetic resonance spectroscopy, to mesoscopic and quantum dot research. The reason for such a variety lies in the fact that quantum information is essentially built upon the most fundamental ideas of quantum mechanics, which is at the heart of virtually all fields of physics. One of the most promising approaches for the implementation of quantum computers utilizes single ionised atoms confined in a trap.

1.2 Trapped Ion Quantum Information

In trapped ion quantum information, the internal state of each ion represents the smallest unit of quantum information. Analogously to classical computation, where information is encoded in the bits 1 and 0, in quantum computation it is possible to identify two atomic states of the system, $|0\rangle$ and $|1\rangle$, which are known as the two "qubits" or QUantum BITs. However, despite the DiVincenzo claim that "*it does not require science fiction to envision a quantum computer*" [5], even elementary quantum information processing operations represents challenging demands in terms of the experimental techniques. It was DiVincenzo himself who first listed the well known five requirements for the implementation of quantum computation [5]. The first DiVincenzo *criterium* is a scalable physical system with well characterized qubits. Such a system is simply a quantum two level system which can be represented by many pair of quantities such as spin, polarization or electronic levels of an atom. The challenge in this case is that the qubit system has to be fully known, which implies its internal Hamiltonian and couplings to other qubit states and to external fields have to be known. The second DiVincenzo *criterium* is to being able to initialise the state of the qubits to a simple fiducial state such as $|000...\rangle$. The third is having long relevant decoherence times, much longer than the gate operation time. Decoherence is a harmful mechanism for quantum computers in that it is the mechanism which leads to the emergence of classical behaviour. It is represented by the coupling of the system with its environment and this coupling destroys the coherence of the system, making it classical. Therefore it is fundamental in quantum computation to achieve long decoherence time over which the quantum operations are not affected. As decoherence is a very system-specific phenomenon, it is important to have full knowledge of the experimental system in use. The fourth DiVincenzo *criterium* is the availablility of a universal set of quantum gates. Gates are used to implement quantum algorithms, which are represented by a series of unitary transformations identified by a series of Hamiltonians, which generate such transformations. The fifth and final requirement is a qubit-specific measurement capability. This requirement clearly stems from the need to read out the result of a computation.

Even before the DiVincenzo criteria, Cirac and Zoller proposed a quantum computer implemented with cold ions in a linear trap and interacting with laser beams. They also showed that this system supported quantum gates and that decoherence was negligible [6]. Dave Wineland focused greatly on the experimental challenges of ion trapping and on possible scalable architectures. Subsequently many efforts were put around the world to implement ion trapped quantum information experiments [13], [8].

1.3 Aim of the Project

This report is focused on one of such experiments at ETH Zürich. In particular it is concerned with a 3D ion trap experiment and with the imaging system of the trap initially only used to detect the ions. The imaging system was designed and built several years ago using a geometrical optics treatment. The present project aims at assessing the validity of such an approach in the case in which laser beams are used. Laser beams are characterised by a gaussian profile and gaussian optics does not coincide with geometrical optics. The limitations of the geometrical optics approach are identified and assessed. Moreover, a novel design for the implementation of individual addressing is investigated and proposed. Individual addressing is at the heart of quantum computation as it allows the individual manipulation of each ion. It will be explored further in later paragraphs. In the following section, the 3D trap experiment and its main features are briefly described.

2 Experimental Set-Up and Theoretical Background

Before presenting the details of the project, a broader description of the 3D trap experiment is given. In particular the trap is briefly described and the two ion species used, calcium and beryllium, are presented. Later sections on the imaging system and gaussian beams concern the project more directly.

2.1 The 3D Ion Trap

In order to store and manipulate ions, it is necessary to confine them to a specific and well controlled position. To this aim, due to the nature of ions being charged atoms, electric fields can be used. The electric field creates a potential, and a trap is achieved where the potential has a minimum such that the potential force is pointing towards that position from all three dimensions. Such a potential minimum cannot be achieved by a static electric field alone according to Earnshaw's theorem. It is possible, with a static electric field, to trap the ion in two dimensions, but not three. Hence a combination of static and time-varying electric fields is used. In a linear ion trap, the axial confinement is provided by the static potential applied to the DC electrodes, whereas the radial confinement is provided by the potential applied to the RF electrodes [9]. In our 3D experiment, a segmented linear Paul trap is used to trap two ion species simultaneously: calcium and beryllium ions. Details about the trap design and fabrication are presented here: [10]. Figure 1 shows a schematic drawing of the vacuum chamber with its surrounding components and a picture of the ion trap.

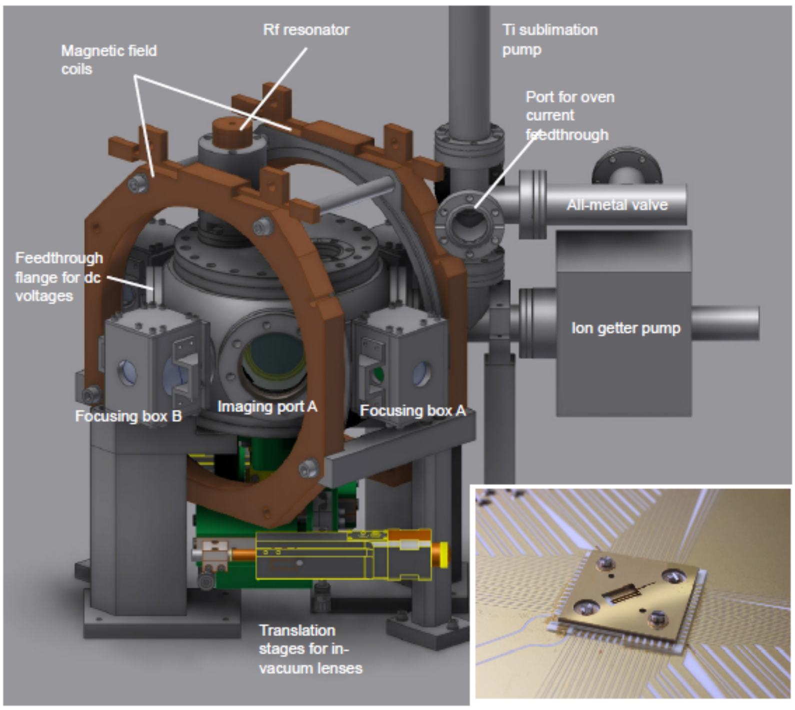

Figure 1. The 3D mixed species experiment and the segmented linear ion trap [10].

2.2 $^{40}Ca^+$ and $^{9}Be^+$ as Qubits

The calcium ion and the beryllium ion differ on the atomic level, as shown in the figure below. Calcium ions have no nuclear spin, and therefore no hyperfine structure, whilst beryllium ions have a nuclear spin of = 3/2 and displays hyperfine structure. Having a mixed species ion trap offers additional possibilites in quantum computation. In ion trapped quantum computations, two types of qubits have been investigated: hyperfine qubits and optical qubits. In the former, the information is encoded in two hyperfine levels. In the latter, the ground state and an optically accessible metastable excited states are used for the encoding.

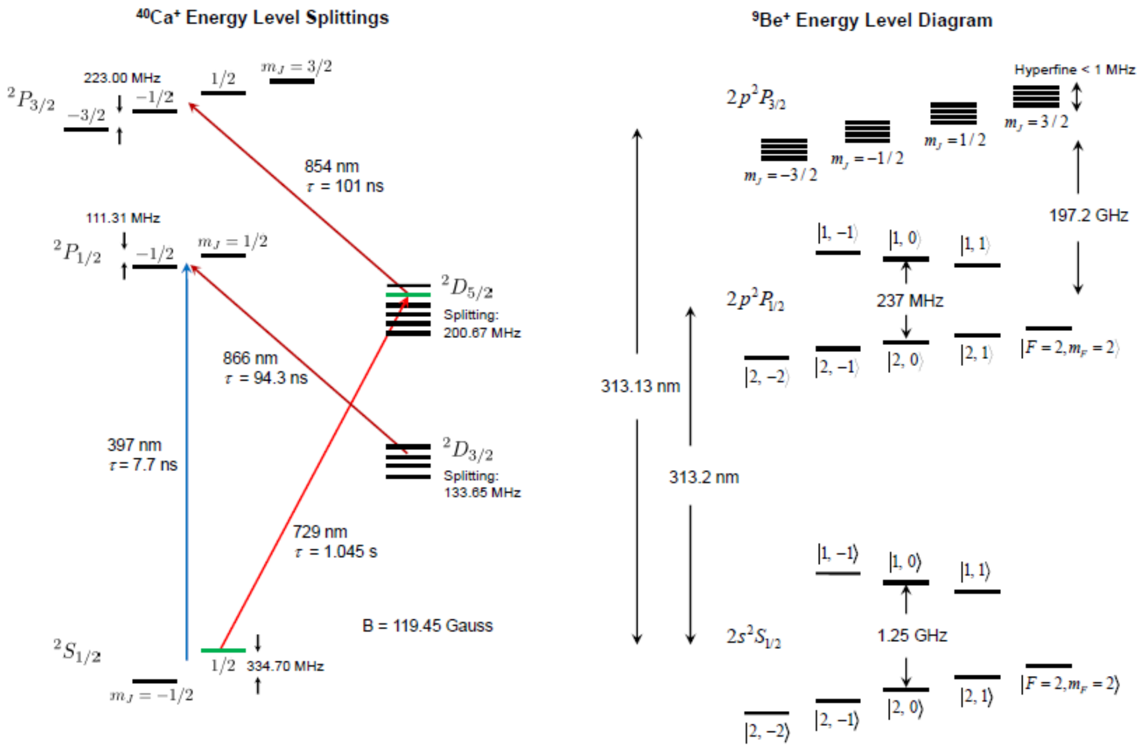

Figure 2. The atomic level of the calcium and beryllium ion. For the calcium ion the green levels are the ones used to encode the two qubit states. For the beryllium ion the transitions are all around a wavelength of 313 nm. [9].

One of the substantial advantages in using the $^{40}Ca^+$ ion is that light sources for all transitions involved are provided by diode lasers without the need of complicated optics. On the other hand, beryllium ions are chosen for their low mass, allowing higher trap frequencies to be used. In the case of the calcium ion, usually the optical qubit is chosen, where the two qubit states are identified with the $4S_{1/2} = |S_{1/2}, m_J = 1/2\rangle \equiv |0\rangle$ and the $3D_{5/2} = |D_{5/2}, m_J = 3/2\rangle \equiv |1\rangle$ as shown in the figure. This implies also that the main relevant transitions are at 729 nm and 397 nm. For beryllium, the relevant transition is at 313 nm.

2.3 The Imaging System

The imaging system has the role of detecting the trapped ions and collecting the photons during the readout phase. Moreover it can be used to individually address the ions [11]. Individual addressing has not yet been implemented in our experiment and this report gives details about a novel design. Details about the design and assebly of the imaging system for detection can be found here: [9]. A diagram for the imaging system is given below. In order to detect the fluorescent emission from the ions, an objective with a large numerical aperture is preferred. The current system consists of an in-vacuum objective made of 5 lenses, designed and manufactured by Sill Optics. Moreover, outside of the vacuum chamber, a telescope lens is used to focus the beam and constrains the total working distance. The light is then collected by a camera and a photomultiplier tube (PMT) as shown in Figure 4.

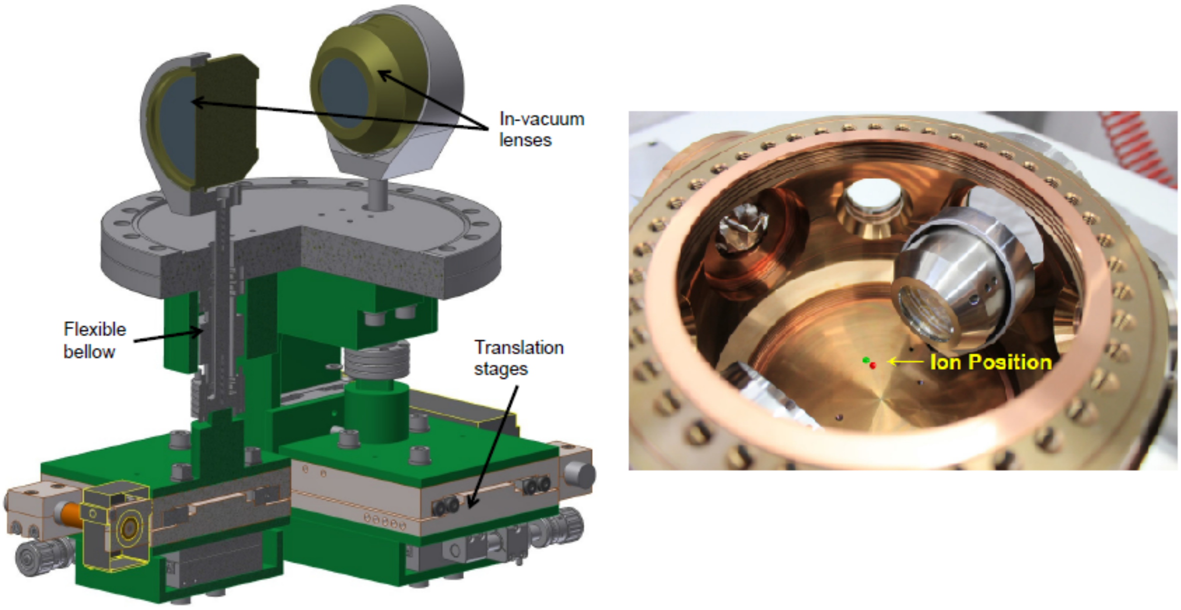

Figure 3. The imaging system design and a zoom of the in-vacuum objective. The position of the ions is highlighted. [9].

The imaging system was designed to collect light at 397 nm and 313 nm. These are the fluorescence transitions of calcium and beryllium, as described in the previous section. As it will be shown later, this constitutes a challenge for the individual addressing design using 729 nm, as the objective is optimised for a different set of wavelengths. After the assembly of the imaging system, a chain of ions with a 5 microns ion-ion separation was successfully loaded and imaged [9]. A twin imaging system is mounted on the opposite side of the vacuum chamber. The imaging system was design using the optical design program Zemax which will be described in more detail in later sections.

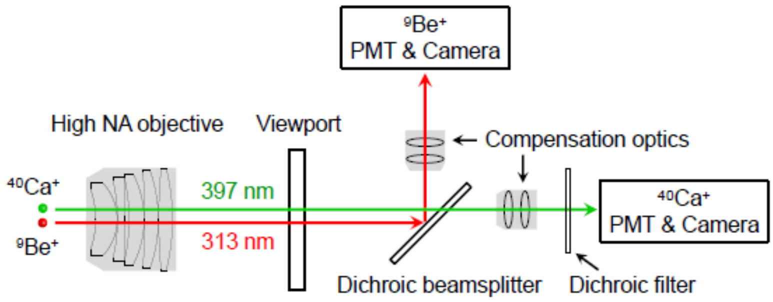

Figure 4. The imaging system set up. The position of the ions can be visualized within the vacuum chamber. The 5-lenses objective is also within the vacuum chamber. Outside, a telescope lens is used to expand the beam and a camera and PMT collect the light. [9].

2.4 Individual Ion Addressing

Individual ion addressing is a fundamental tool to manipulate ions. It consists of using laser beams to address single ions with minimal overlap with the neighboring ions. To fulfill this requirement, the laser beam used needs to have a beam size at the ion position much smaller than the ion-ion spacing of 5 microns. The implementation of an optical design which provides a beam size close to the diffraction limited size of ≈ 1 micron is experimentally very challenging. Details on an optical design for laser addressing will be given later. The Innsbruck group has successfully implemented individual laser addressing at the wavelength of 729 nm with an optical system not too different from our system [11]. The addressing in their case is implemented in two steps: first, a wide laser beam is used to illuminate globally the entire register uniformly; secondly, a tightly focused laser beam is used to address each ion [12]. Individual addressing has been recently implemented also using microwave field gradients [13], however we opt for laser addressing of the Innsbruck fashion.

2.5 Geometrical and Gaussian Optics

Geometrical optics is a powerful description of the behaviour of light in the absence of diffraction and interference effects. It is also known as ray optics since it traces straight rays to describe the path taken by light. In systems in which diffraction and interference effects are negligible, such an approach can produce good results. However, when diffraction and interference have more weight, a gaussian approach needs to be taken into account.

Laser beams are also known to propagate according to gaussian optics. According to Maxwell's equations, a time-harmonic wave propagates in space following Helmholtz equation:

$$(\bigtriangledown^2 + k^2)E(x, y, z) = 0 \tag{1}$$

where $k = n\omega/c$ and E is the electric field. Upon substituting the expression for

$E(x, y, z,) = \psi(x, y, z)e^{ikz}$ for a z-polarized wave in the Helmoltz equation one can apply the paraxial approximation, according to which the variation of propagation is slow on the scale of the wavelength and on the scale of the transverse extent of the wave. The paraxial approximation leads to the paraxial wave equation:

$$(\nabla_T^2 - 2ik\frac{\partial}{\partial z})\psi(x, y, z) = 0 \tag{2}$$

where $\nabla_T^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$ and ψ is the transverse profile of the wave. From the paraxial wave equation, assuming a gaussian solution, the main parameters used to describe a gaussian beam can be derived [14], [15]. These parameters are:
the complex radius of curvature $q(z)$, given by

$$q(z) = z + iz_R \tag{3}$$

where z is the distance from the origin along the optical axis and z_R is the Rayleigh length given by $z_R = \pi n \omega_0^2/\lambda$.

The beam waist, or minimum spot size, defined as the point at which the phasefront is parallel to the optical axis, or the radius of curvature is infinite:

$$\omega_0 = \sqrt{\frac{\lambda_0 z_R}{n\pi}} \tag{4}$$

the beam size at an arbitrary position z:

$$\omega(z) = \omega_0\sqrt{1 + (\frac{z}{z_R})^2} \tag{5}$$

and the radius of curvature:

$$R(z) = z + \frac{z_R^2}{z} \tag{6}$$

these quantities are illustrated in the figure below:

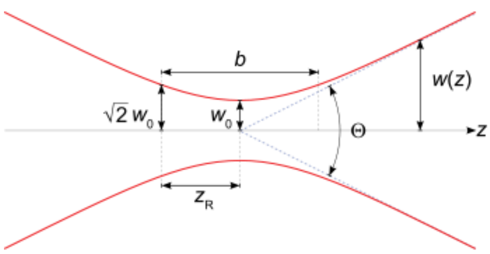

Figure 5. A gaussian beam propagating in space. The beam waist, beam size, Rayleigh length and divergence angle are shown [14].

Note that the Rayleigh length z_R is the position at which the gaussian beam has expanded by a factor of $\sqrt{2}$, so the Rayleigh length, along with the divergence angle, gives a measure of the collimation of the beam. The confocal parameter b, shown in the figure above, is given by b=$2z_R$. Clearly the smaller the beam waist, the higher the divergence and the shorter the Rayleigh length. A beam which is tightly focused will have a smaller waist but a larger divergence. In the present project, we are interested in focusing a gaussian beam. The beam is produced by a laser diode and delivered to the imaging system via optical fiber. Laser diodes typically produce skew gaussian profiles, however when such beams are coupled into fiber they are given an almost perfectly circular gaussian profile. Therefore the quality factor $M^2 \approx 1$. Focusing a beam with a lens or a more complex imaging system can be studied with both the geometrical and gaussian optics approaches. Figure 6 illustrates the two approaches. It is important to note that the geometrical focus does not correspond to the position of the gaussian beam waist. The gaussian beam waist is located just slightly inside the lens focal length. This will be an important point later in the discussion.

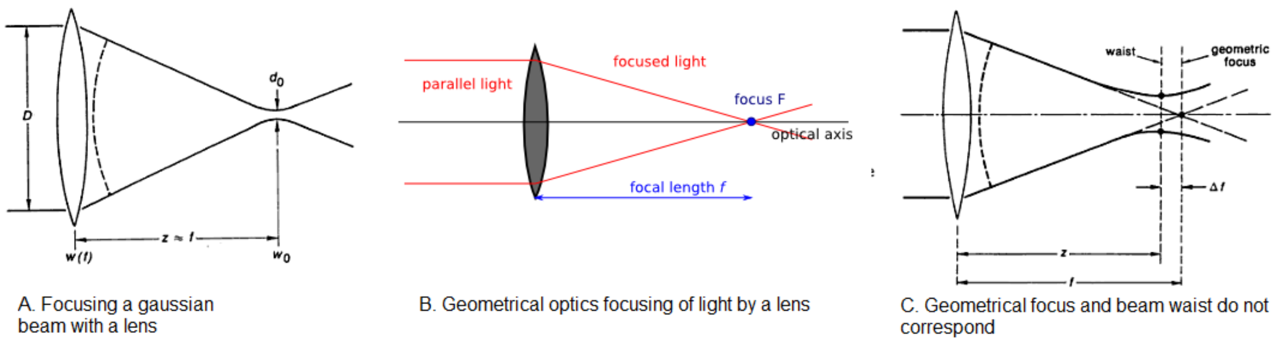

Figure 6. The focusing of a beam in the gaussian optics and geometrical optics approach. The difference in location of geometrical focus and beam waist is shown [14].

3 Methods and Results

This section will focus on the work carried out during the project. In particular it will present all the results obtained in the analysis of the imaging system and for the design of the individual addressing laser system.

3.1 Zemax

The work of this project was entirely carried out using the optics design software Zemax. Several other programs were initially investigated such as Oslo and CODE V, however on one hand Oslo was limited to a lower number of lenses than our set up, on the other hand, the old design was already made using Zemax, so it seemed more sensible to stick to this software. However, the old design was implemented using the geometrical optics approach alone. Hence a great deal of the time was spent learning the features of the gaussian optics approach. Zemax offers two different analysis: paraxial (or skew) guassian beams and Physical Optics Propagation (POP). The former one traces an ideal gaussian beam through the system without taking into account any of the aberrations and interference of different beams. The latter is a more complete version, which considers aberrations and interference. For this reason POP is only available in the EE or Professional version of Zemax [17]. While learning the program, I found it useful to collect its main features in a document with relevant references included. This short guide is attached as an appendix.

3.2 Imaging System Analysis

The imaging system used for the detection of the ions was described in the previous section. In more detail, it is a system which has a numerical aperture (NA) of 0.41, a magnification of 40 and a total working distance of 1 meter. The field of view is 100 microns and the depth of focus is 20 microns. The ion-objective distance is 30 mm. The design is shown in the figure below. The aberrations are well optimised and the RMS spot diagram is fully within the diffraction limited Airy Disk.

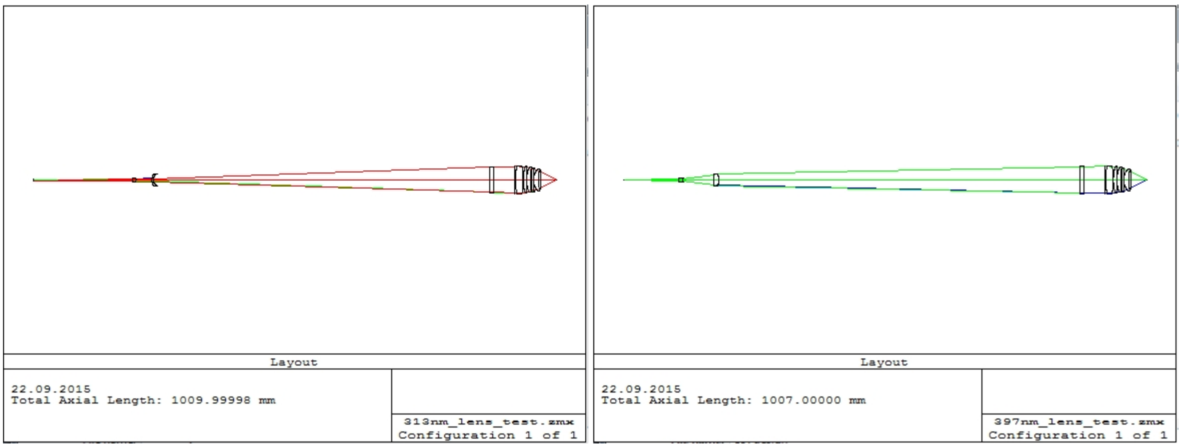

Figure 7. The design of the already implemented imaging system for 313 nm and 397 nm fluorescence detection using ray optics. [9].

Using this imaging system, both calcium and beryllium ions spaced by 5 microns are imaged 0.2 mm apart (according to a magnification of 40). When this system is analysed using the paraxial gaussian beam calculator for an input beam diameter of 0.2 mm, the size of the beam at focus is in good agreement with the geometrical optics 5 microns separation. This implies that an ideal gaussian beam well resembles the geometrical optics model in this situation. However when the POP feature is used, there is a difference of a few microns, as shown in the table below. This means that there are some aberrations and that including the interference between rays does make a difference in the dimension of the beam size at the ions. For systems which are extremely well optimised, paraxial gaussian beam calculations and POP calculations should match well.

In this situation, it is important to remember that the ions are emitting the fluorescent light, and we are modelling them as point source emitters. Therefore this system might not be entirely a gaussian system, which could be the reason for this discrepancy in the results. According to the simulation, this system can be treated using the paraxial gaussian beam model. From this simulation we also read that the distance between the waist of the ideal beam and the geometrical focus is around 18 microns, which agrees with the theoretical depth of focus calculated with the geometrical optics model. In practice,

	313 nm (Beryllium)		397 nm (Calcium)	
	Paraxial G.B.	*POP*	*Paraxial G.B.*	*POP*
Radial beam size at IMA	2.405 microns	7.560 microns	2.297 microns	4.253 microns
Waist size	2.285 microns	7.166 microns	1.946 microns	3.566 microns
Waist position relative to IMA	17.189 microns	173.26 microns	18.782 microns	65.401 microns

Figure 8. Comparison between the performance of the imaging system for detection on paraxial gaussian beams and Physical Optics Propagation. Both 313 and 397 nm are considered. The calculations are carried out for an input beam waist of 0.1 mm.

the system is much less ideal and there are several additional sources of uncertainty and misalignement such as small tilts, which make the depth of focus much shorter.

3.3 Design of the Individual Addressing System

The set up needed to implement addressing of individual ions differs from the detection one. In this case, a collimated beam enters the system to then be tightly focused at the position of the ions. In our experiment, the in vacuum objective is already fixed in position, therefore all the optimisation and optical design has to be done with extra lenses placed outside of the vacuum chamber.

Initially, using a wavelength of 729 nm was proposed. This is also the wavelength for qubit control in our experiment. However it was soon realised that this wavelength was not very suitable to achieve a very tight focus, due to the fact that the in-vacuum objective is optimised for 313 and 397 nm. A design for 729 nm was obtained using commercially available lenses. Analysing this set up with paraxial gaussian beam gave a beam size at the ions of 6 microns, a waist of 3.6 microns, located 76 microns away from the ions. It was noted that whereas for the detection design there was a discrepancy between the beam and waist size in the paraxial calculations and the physical optics calculations, such a difference was negligible in the individual addressing design. This is due to the fact that a collimating beam is used for addressing, which has a much lower divergence.

After discarding the 729 nm wavelength, the attention was turned to two wavelengths closer to the fluorescence wavelength of calcium ions: 395 and 391 nm. These two wavelengths differ in the amount of detuning from resonant transitions and therefore in the amount of scattering from these transitions. A set-up was optimised for both wavelengths using commercially available Thorlabs lenses, namely an air-gapped achromatic doublet and a negative meniscus lens [16]. The paraxial gaussian beams results agreed well with the POP results. The design is shown below and there are minimal differences between the set ups for the two wavelengths.

It is known from theory that the size of the waist after an imaging system is determined

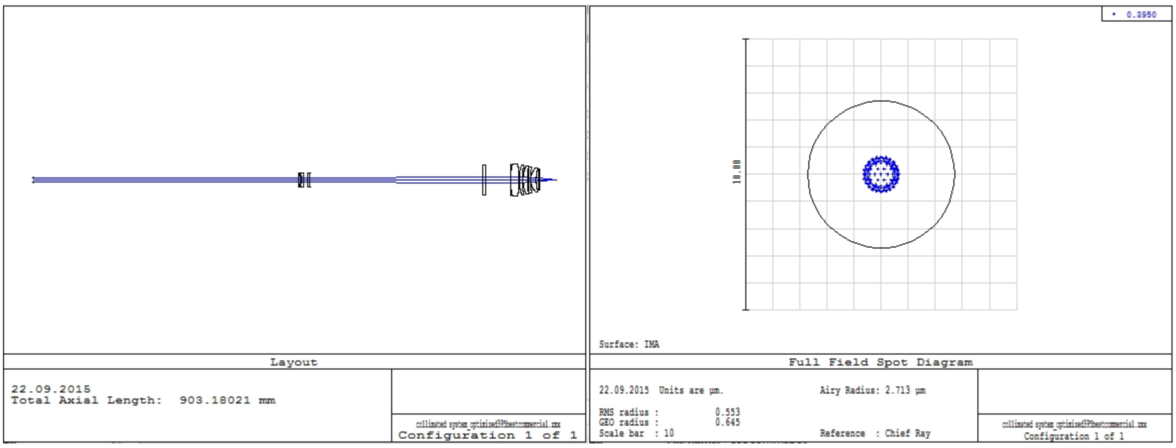

Figure 9. The design for the individual addressing at 395 nm and its spot diagram. The aberrations are well optimised but the system has a low NA.

by the size of the input beam waist. The relation between the two is given by:

$$d_0 \approx \frac{2f\lambda}{D} \tag{7}$$

where d_0 is the effective diameter of the focused gaussian spot and D the input beam diameter, f the effective focal length of the imaging system [14]. Hence, different input diameters were used in order to find the minimum waist and beam size. It was found that an input beam waist of $\approx$ 4 mm, or an input diameter of $\approx$ 8 mm corresponds with the minimum waist and beam size. This set up gives a radial beam size at the image plane (IMA) of 1.98 microns and a beam waist of 1.4 microns located $\approx$ 15 microns away. This implies a beam diameter at the ion of $\approx$ 3.8 microns which is below the ion-ion separation of 5 microns and could therefore be suitable for individual addressing. The one disadvantage of this set up is that the NA is rather low (well below 0.2) due to the optimal input beam size of 8 mm and the fixed semi-diameter of the commercial lenses.

Finally, a novel design was created using a single custom made lens. This set up, which has a working distance just below 1 meter, performs much better than the commercial design as the optimisation can be carried further. It also has a higher NA of 0.25. The optimal input beam waist for 391 nm results to be 10 mm, which is why the NA is higher. It was noted that a higher NA indeed corresponds to a smaller waist, however as the waist location does not correspond to the geometrical focus, as explained earlier, care had to be taken when reading and interpreting the gaussian optics results. This custom-made lens design gives a beam size at the ion of 0.53 microns and a waist of 0.47 microns located less than a micron away. This would give an effective beam diameter at the ion of just above 1 micron, which is also the best achievable spot considering the theoretical limitations imposed by diffraction.

After obtaining the design, thoughts went into its practical implementation within the existent set up in the laboratory. The collimated beam will be delivered from the laser to the imaging table via an optical fiber. Depending on the choice of design, the collimated beam diameter has to be adjusted to the size of the optical fiber using a single lens beam expander. Moreover, a dichoic mirror or an interference filter has to be positioned such

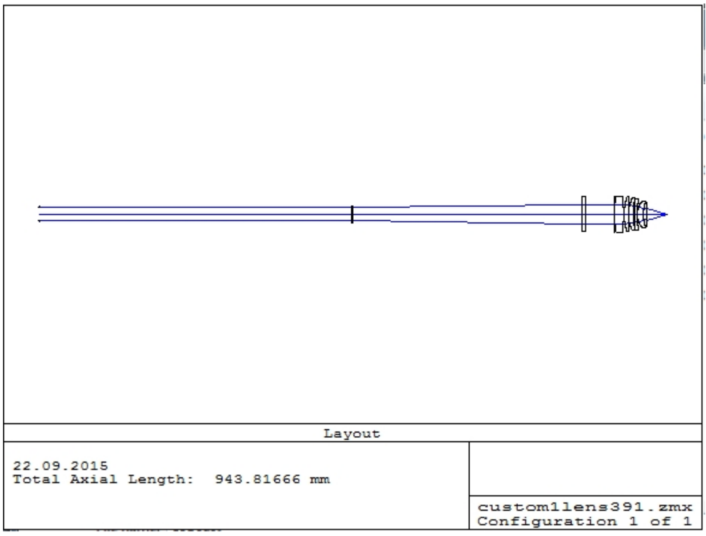

Figure 10. The custom-made design for the individual addressing at 391 nm.

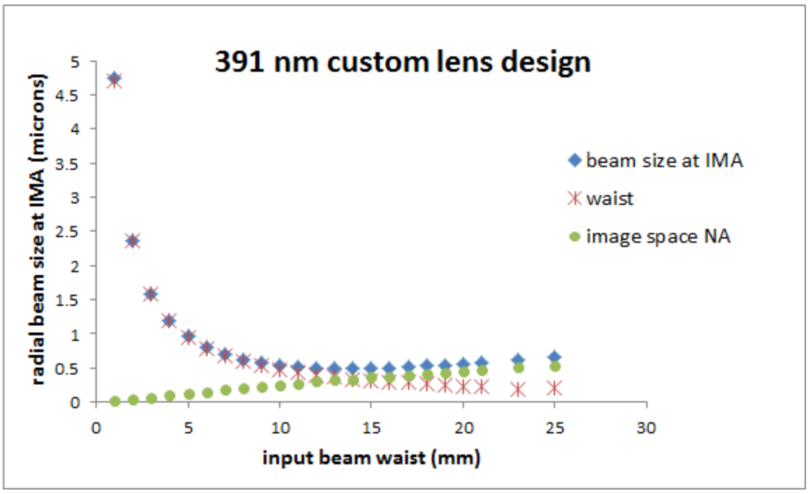

Figure 11. The plot illustrates the variation of NA, beam size and waist with different input beam waist sizes for the custom made design at 391 nm.

that the addressing laser light is split from the 397 nm light. A schematic diagram of the system is shown in Figure 11.

The dichroic mirror required to split either 395 or 391 nm from 397 nm turned out to represent a challenge for the producing company. Due to the close separation (2 nm or 6 nm) between the reflected and transmitted wavelengths, the coating of the dichroic results to be very difficult to produce. However, it is not impossible and reflectance graphs were obtained from Altechna [18] and are shown below. It can be seen from the graphs that the dichroic 397/391 nm has a higher reflectance and it is also easier to produce.

Details regarding both the commercial design and the custom-made design for a 391 nm wavelength of input beam waist of 4 mm and 10 mm respectively are provided in the appendix, along with the Thorlabs lens specifications.

A final design was obtained while trying to improve the NA of the system, where the current fluorescence detection set-up was combined with an air-spaced achromatic doublet

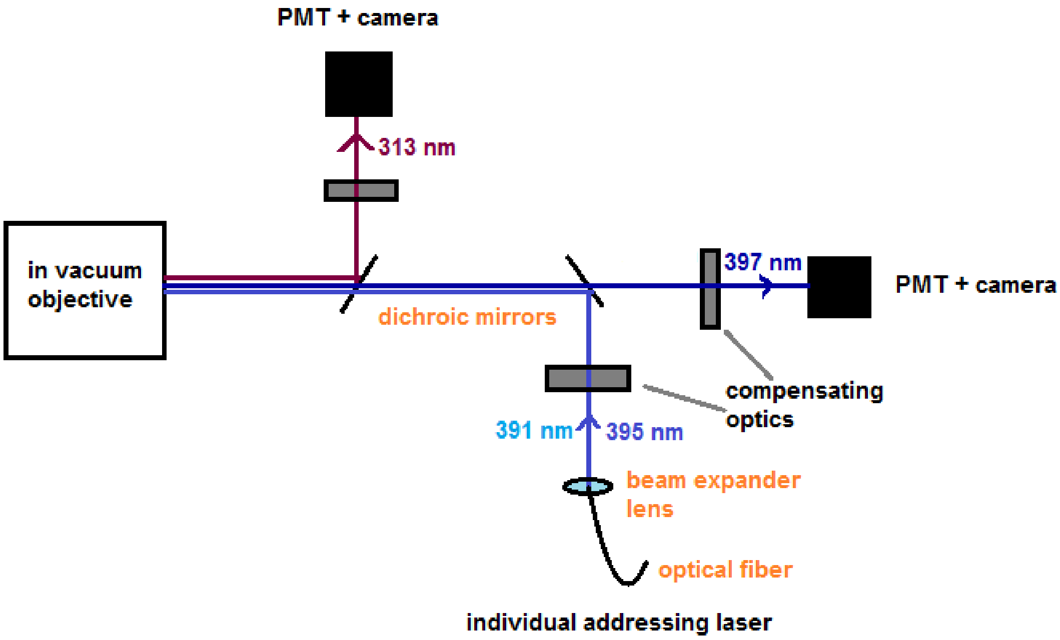

Figure 12. Schematic diagram of the detection and addressing system including the optical fiber and beam expander lens.

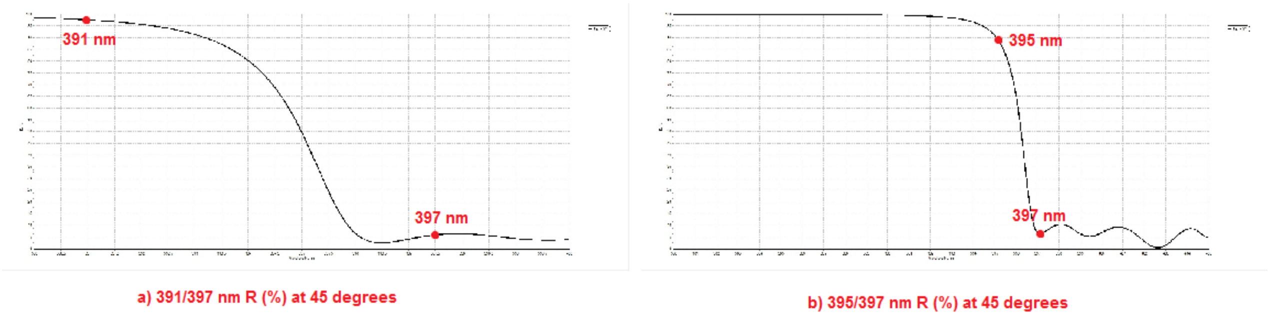

Figure 13. Reflectance graphs for dichroic mirrors at 397/391 and 397/395 nm at 45 degrees angle.

in order to achieve tight focusing. This design, which is using the set up which is already in place and just an extra doublet placed before the telescope lens, is performing only slightly worse than the one custom-made lens design. However it has a better NA and the aberrations are well optimised. This design achievies a radial beam size at the ion of 0.56 microns for an optimal input beam diameter of 3 mm. The NA is 0.31. The design is shown below and details are included in the appendix.

All designs can be implemented in the laboratory, however the choice is delicate as the fluorescence detection system and in-vacuum objective are already mounted. This practically limits the access to specific zones of the optical table. Considerations regarding where to place the dichroic mirror are required.

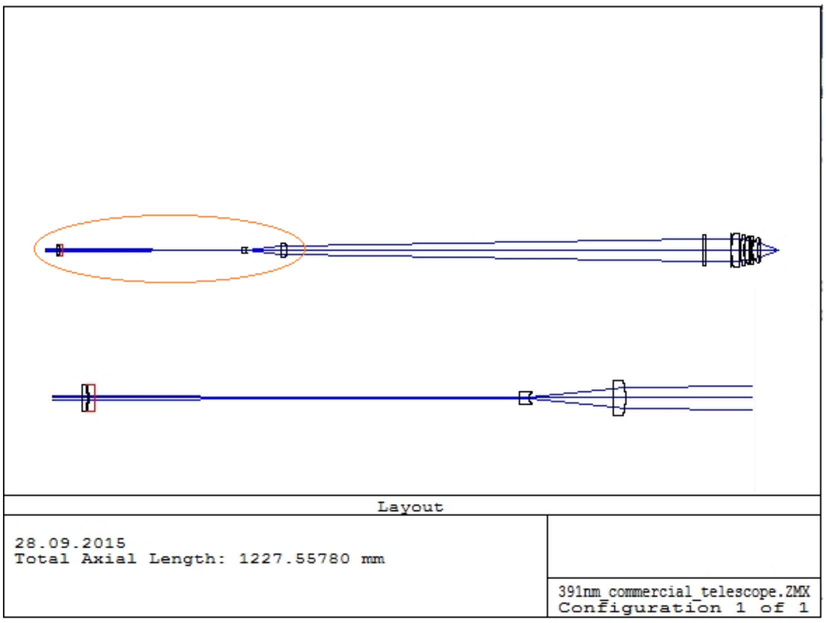

Figure 14. A commercial design utilising the 397nm telescope set up.

4 Conclusions

This report presented the results of a brief internship within the Trapped Ion Quantum Information group at ETH. First, the existent imaging system used to detect fluorescence light was analysed using a geometrical and a gaussian optics approach. It was found that while the paraxial gaussian beam calculations agreed closely to the geometrical optics results, the Physical Optics Propagation results deviated from them by a few microns. Therefore, when dealing with laser beams, the POP treatment seems to be the most complete and inclusive of all aberrations and interference effects. Secondly, in view of a future implementation of individual addressing of ions in the experiment, designs for the optical system were proposed. Four different designs were obtained, a commercial design for both 395 nm and 391 nm, which gave a minimum radial beam size at the ion of 1.9 microns, and a custom made design which gave a radial beam spot size of 0.53 microns. A design combining the existent 397 detection set-up and a commercial achromatic doublet was also obtained, giving a radial beam size of 0.56 microns. All the proposed designs lead to a spot diameter at the ions < 5 microns, the ion-ion separation.

It remains to make a choice between the 395 nm or 391 nm based on the production of the dichroic mirror and considerations regarding the scattering rate and Raman transitions for both wavelengths. An Inventor design was initiated and has to be finalised. Then the lenses can be purchased and assembled.

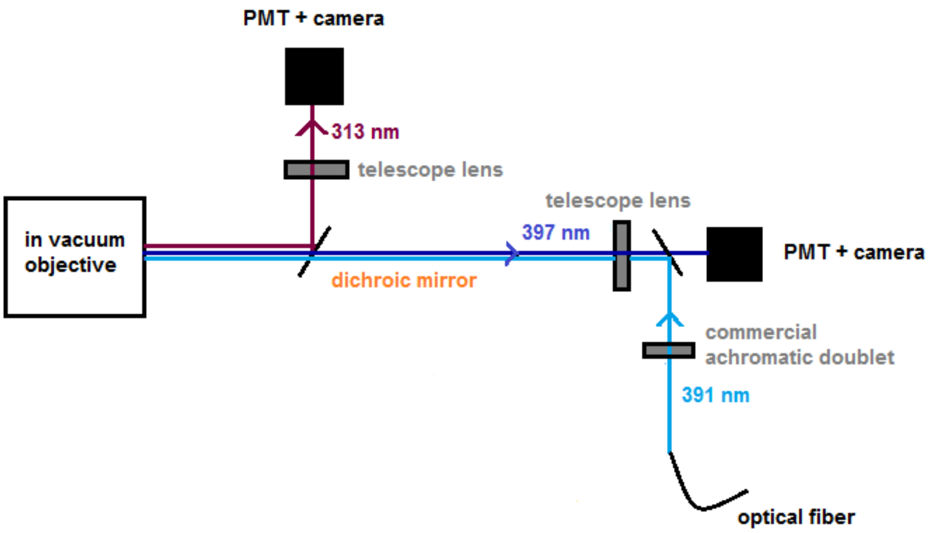

Figure 15. The optical set up for the implementation of the telescope and commercial lens design. In this case the dichroic is placed after the telescope lens for 397 nm.

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Appendix

This appendix contains several things. First, the designs for the 391 nm individual addressing are given for an input beam waist of 4 mm and 10 mm respectively. The POP simulation results agree with the Paraxial Gaussian beam results. The commercial design using the telescope lens for 397 is also shown. The commercial lenses from Thorlabs are also shown. Finally, a short guide to the software Zemax which I wrote while learning the program can be found.

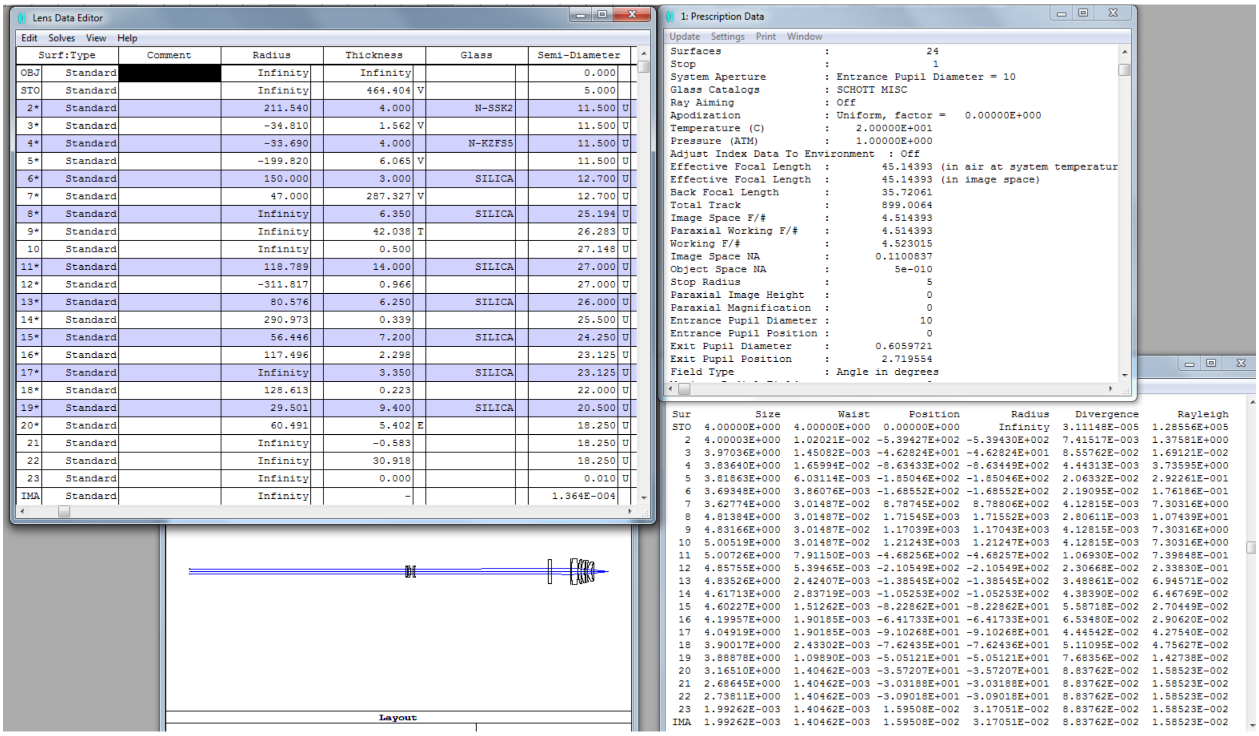

Figure 16. A commercial design for the 391 nm and input beam waist of 4 mm.

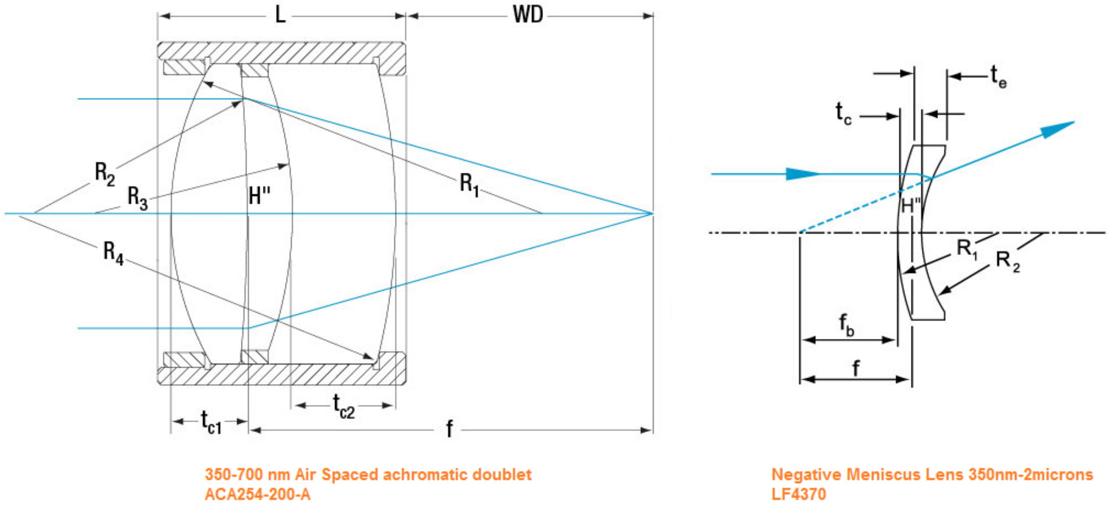

Figure 17. Thorlabs lenses required for the commercial 391 nm design.

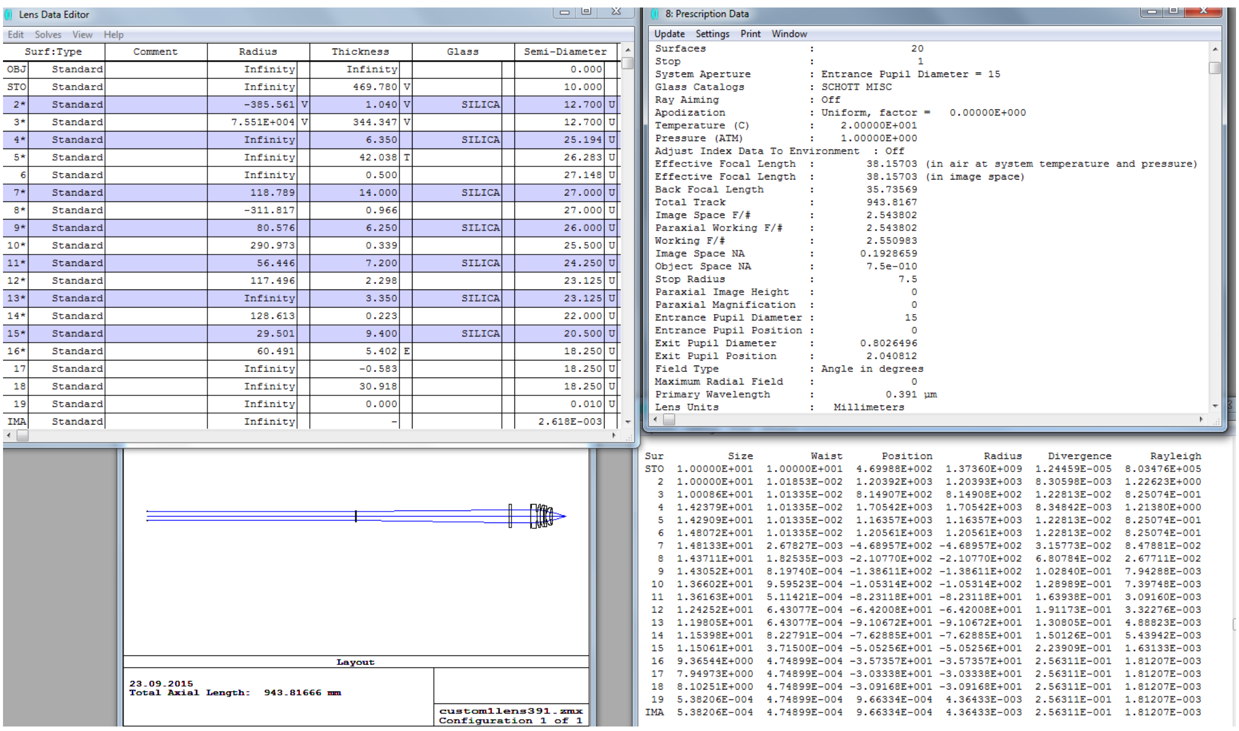

Figure 18. A custom-made design for the 391 nm and input beam waist of 10 mm.

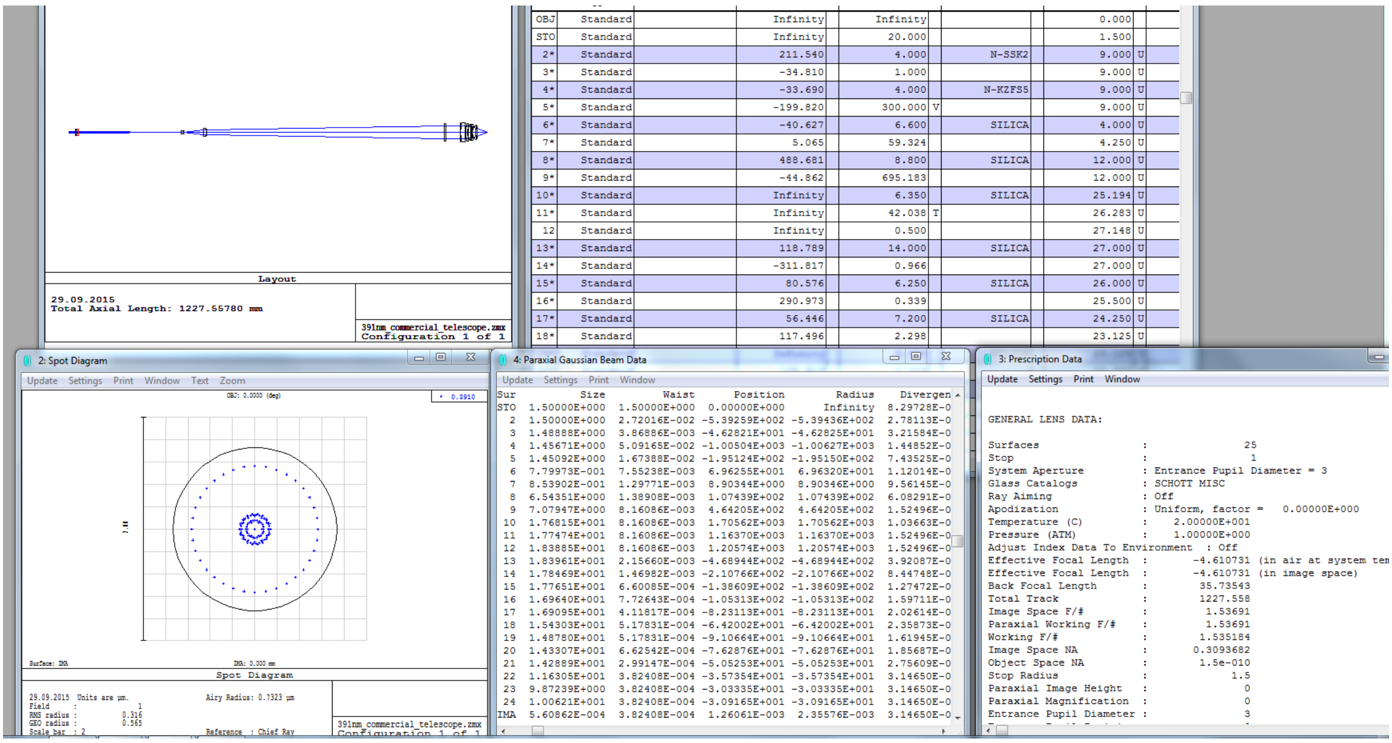

Figure 19. A commercial design for the 391 nm using the 397 nm telescope set up.

Introduction

Zemax is a very powerful optical design software which allows visualization and optimization of optical set ups. It provides the user with the ability to add a number of optical components and it returns its layout and performance. Here I collected the most important features of the program as I was learning them. Of course the software has many more functionalities than those I will describe. This short guide is intended for a first time user which needs a general introduction to the program.

The first place to look if you need to know something about Zemax is the Zemax manual. You can find it within Zemax under the Help button. However that is a very long manual, if you dont want to spend too much time reading that to learn the program, an extensive and detailed description of each feature can be found on the Zemax website knowledgebase page [1], where in depth articles and tutorial will take you step by step through your familiarisation with the software. I also found a series of YouTube tutorials from optics realm very useful [2].

Of course, Zemax will optimize your set up, as long as you have one. It is important to have a clear idea of the geometric optics of your system before inserting it into Zemax and evaluating its performance. In fact, you can optimize the system according to constraints that YOU need to specify.

The first steps in getting to know a bit about ZEMAX and creating the first optical setup are described in the following sections. First of all Zemax has two main modes of function: *sequential* and *non-sequential*. In the first one, you insert the optical components in the correct order in which the light ray propagates. In the second one, it is Zemax who decides the path of the light for you, according to your input parameters. In our case, only the sequential mode is used.

Basics

The main window which opens when you launch Zemax is the LDE, **Lens Data Editor**. Here you can see the list of all your optical components specified by their surfaces, their radius of curvature, their thickness and material. Through the button edit you can insert new surfaces; they appear just before the current surface. The first surface is called the OBJ, the object. Another essential surface is the STO, the aperture stop of your system which defines the size of your beam. The last surface is the IMA, the image.

The units in Zemax can be modified and can be either mm, cm, inches or m. This is under the GEN button. Usually, mm is used.

Fields and **Wavelengths** can also be inserted from the FIE and WAV buttons. In fields, where you specify the points from which your light beams propagate, one can either give the angle or the height of the object. You can insert as many wavelengths as you have. Dont forget to press select once you have entered the value, otherwise it will not save it.

More information and a tutorial on setting up a singlet lens can be found here: [3], I highly recommend it to learn Zemax features. If you are confused on how to trace rays for different lenses, this Thorlabs page offers a list of lenses and shows the geometrical ray propagation: [4].

Evaluating System Performance

Prior to the optimization stage, the system performance can be evaluated through a series of parameters. By clicking the button LAY, the layout of the system is displayed. Note that you can select between a 2D, 3D and shaded layout. Note also that the ray are traced out according to a geometric optics treatment, neglecting the Gaussian nature of the beams. The **spot diagram**, which gives an indication of the lens quality, is one of the main ways to assess the performance. It gives the image of a point source after the propagation through the system. On the spot diagram, a black circle is shown. It is the **Airy Disk**, it gives the diffraction limited image of the beam in the ideal situation of no aberrations. The points within and outside the Airy are those in which the aberrations have been taken into account. Therefore this is the best way to quantify the aberrations of your system. There are several types of aberrations which give different shapes of the spot diagram.

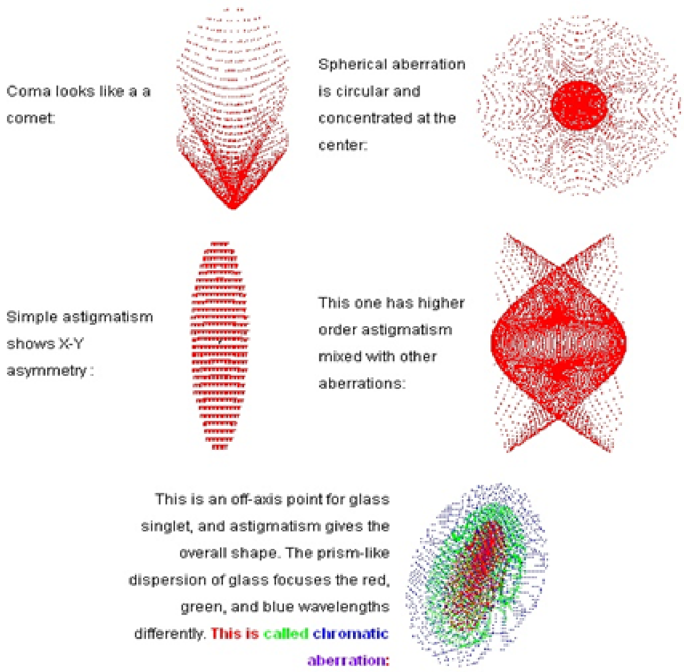

Figure 20. The main types of aberrations.

You can also see the main aberrations of your system by looking at the Seidel Diagram.

You can find it under Analysis, Aberration Coefficients. It will give you a diagram with different kinds of aberrations corresponding to each component of your optical set up.

Important note: the PSF is calculated by tracing a number of different rays from the point source and without considering their interference plotting them at the image plane. No interaction or interference between the rays is taken into account. Moreover note that the diffraction effects are only considered from the last surface to the image plane (single step approximation) ignoring all the other surfaces effects. Therefore this is a rather limited approach which is mainly used to assess the impact of **aberrations** of the system. It is not suited for modelling systems with diffraction. There are several types of PSF : the canonical PSF, described above, the FFT PSF and the Huygens PSF. (More details about them are found in the user manual and here: [5].
The Ray Fan plots the ray aberration as a function of the pupil coordinate. The Quick Focus tool is a way to optimize the position of the image plane to make it coincide with the position of the best focus. It changes the thickness of the lens just before the image plane. It automatically updates it in the LDE.

Optimisation

Once the set-up has been created and the performance evaluated, it is time for optimization. First, it is important to determine the degrees of freedom of the system, i.e. the parameters which can be modified. On the LDE, select each parameter and by right-hand click assign either a Variable (V) or a Fixed (F) value to it. A V or an F will appear next to the variables names. When running optimization, Zemax will maintain the fixed parameters and solve for the variables to find the best solution.

From Editors, open the **Merit function editor**. The Merit Function describes how well your system meets your objectives. Here you can select the type of optimization that you want to perform and input some boundary constraints. Then you can run it and perform the optimization using the button OPT. Automatic it will search for the local minimum of the merit function. At this point, all is left is to update your performance tests and check the improvements of your system. Note that the algorithm looks for the local minumum, not the global one.

Some common operands of the Merit function are the following: AMAG (angular magnification), TTHI (thickness total between two surfaces) DMFS (default merit function) OBSN (object space numerical aperture) EFFL (effective focal length), the full list of operands can be found in the Zemax manual [1].

Gaussian Optics

Of course Zemax has many more features and options. The previous section was dedicated to the geometrical optics analysis only. However many systems involve lasers, which behave according to Gaussian Optics (or Physical Optics). For these cases, a Physical

Optics section is dedicated. Here you find Paraxial Gaussian beams, Skew Gaussian beams, physical optics propagation (POP) and beam file viewer.

Here you can find more information on the Gaussian beams platform: [6] . Real laser beams are characterized by diffraction. Usually, diffraction is the effect in which a wave is altered when encountering an obstacle. The propagation of a laser beam also experiences diffraction. This is due to the fact that when the wavefronts of the wave propagate, they interfere coherently with each other. In this approach, Maxwells wave equation does not provide anymore a complete description of the system and it is necessary to apply the paraxial approximation which leads to the paraxial wave equation. The solution to this equation is a Gaussian function which diverges over time and is characterized by parameters such as the beam waist, the divergence angle and the Rayleighs range.

When using POP, the wavefront is modeled using an array of points. Each point in the array stores complex amplitude information about the beam. The array is user-definable in terms of its dimension, sampling and aspect ratio. If you want a full derivation of these parameters have a look here: [7]. Quoting from the book above: Although in its 2014 manual, Zemax describes this feature in the Physical Optics section in Chapter 7, Analysis Menu and in Chapter 26, Physical Optics Propagation, this feature is still not well known to many users.

Note that laser diode beams are skew (elliptical) Gaussian beams. However, when a laser diode is coupled into a fiber it will result in a symmetric, circular almost perfect Gaussian beam. This reflects in the M^2 factor, which is the quality factor of the beam. For an ideal Gaussian M^2 is 1, otherwise $M^2 > 1$ (1.2 is a common value for laser diodes). This factor describes how the real Gaussian beam compares to an ideal perfect Gaussian beam.

Paraxial Gaussian Beam

This is appropriate for circular Gaussian beams. In the settings one can input the parameters of the beam such as the waist at the first position, the M^2 value and the wavelength considered. It computes the waist, beam divergence and Rayleigh range based on our input parameters. Note that strong aberrations will deviate a Gaussian beam from basic mode and the result of modeling such a beam is not accurate.

Skew Gaussian Beam

This performs the same calculation as the paraxial Gaussian beam but for a skew, elliptical input laser profile. They distinguish the x and y radial sizes and parameters of the beam. They take into account astigmatism and are valid for beams which travel off-axis.

A series of lectures on Optical design with Zemax from the University of Jena can be found here: [8].

GEOMETRIC OPTICS (RAY TRACING)	GAUSSIAN OPTICS (WAVE OPTICS)
Takes a number of **rays** from a point source and propagates them through the optical components. Then it plots their coordinates at the image plane. The **rays do not interact or interfere**. They are perpendicular to the wavefronts.	Considers the **wavefronts**of the wave and propagates it taking into account the fact that the **wavefronts interfere** coherently with each other.
The diffraction effect is considered only from the last surface to the image plane (**single step approximation**).	The **diffraction** effect is considered at all surfaces.
Limited to **axial, symmetric beams**.	Not limited to axial, symmetric beams (**skew beams are considered**).
Useful for assessing the **aberrations** of the system. Not appropriate for simulating systems with diffraction	Useful for systems with **diffraction** (e.g. lasers)

Figure 21. The differences between gaussian and geometrical optics.

Paraxial Gaussian beam vs Physical Optics Propagation

The standard version of Zemax provides only the Paraxial Gaussian beam and the Physical Optics Propagation. However these two types of Gaussian propagation are simplifications. The full treatment of a Gaussian beam is given by the Physics Optics Propagation. The main difference between the two is summarized below:

Paraxial/Skew Gaussian Beam	Physical Optics Propagation
It propagates an ideal Gaussian beam without considering the aberrations of the system	Tracks the phase at every point on the wavefront, therefore it takes into account the aberrations

Figure 22. Comparison of paraxial gaussian beam and physical optics propagation.

Therefore the most complete way of tracking a Gaussian beam is using the Physical Optics Propagation, a feature which belongs to the Professional version of Zemax.

A way to give a good estimate in the case one does not have access to POP, is to combine geometric optics with paraxial Gaussian beam. First, designing the set up in geometric optics will quantify all the aberrations, the design can be optimized in order to minimize them. Once the aberrations are minimized and the PSF lies all within the Airy disk, one can check the size of the beam waist using the paraxial Gaussian beam.

Important note: when paraxial gaussian beam calculations are performed, they input a boz which containes a series of parameters. It is important to fully understand the way Zemax calculates such parameters. A nice example can be found in [7]. The main parameters are for beam waist, which gives the beam waist AFTER the surfance under consideration, the position, which gives the relative position of the waist with respect to the considered surface, the beam size, which gives the effective beam size at the surface and the Rayleigh range. Note that the waist does not usually correspond in position with the surface under consideration. Therefore to know the focus of a beam one has to look at the beam size, rather than the waist.

Physical Optics Propagation, as mentioned earlier, gives the most complete description of the propagation of a gaussian beam. It includes both aberrations and interference between the rays. It then outputs the irradiance and phase of the beam at a specified surface. If the optical system is well optimised for aberrations, the Physical Optics Propagation and the Paraxial or Skew gaussian beam calculations should match.

I hope this very short guide has gotten you started on Zemax, a relatively complex but powerful otical design program. The program contains many more features which were not described here but will be found in the references.

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