Lund University

Master's Thesis

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Single ion detection setup

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June 20, 2013

Abstract

This thesis covers the design of an optical system for detecting single rare-earth-ions sitting inside a crystal that's being cooled down inside a cryostat to around 3-4 Kelvin. The thesis is not a complete setup ready to use but rather a first step towards a final setup.

To detect the ions a fluorescence measurement will be used. Although since the number of ions sitting inside the crystal is dense enough to make it impossible to distinct them from one another if all of them fluoresced at the same time, properties of the ions sitting in the crystal will be used. The Ce-ions which will be used as the target ions have a very thin homogenous linewidth of 3MHz and when they are placed in a host crystal the homogenous linewidth will shift. The range of the shift which is called inhomogeneous linewidth is as big as 30 GHz, so by tuning the laser to the ends of this interval where very few will have had their linewidth shifted the hopes are that single ions can be found in a small enough vicinity.

Throughout the thesis different alternatives are weighed against each other and special considerations are discussed that should be considered in future works on the design. The setup that has been chosen is an optical setup that applies confocal microscopy techniques to get a high resolution. Since confocal microscopy doesn't allow for very big area of detection the sample is being scanned by moving the sample inside the cryostat using small nano-positioners. Because of this a special holder that is compatible with the scan system had to be designed. Since the cryostat uses a coldfinger technique to cool the sample the design of the holder had to include a thermal bridge to the sample. Thiscaused difficulties since such a smalll piece of copper would normally not have enough heat conduction to keep the sample cold.e. To solve the problem the thesis also includes an oxygen annealing method to increase the thermal conductivity in high purity copper by internal oxidation.

Contents

1 Introduction

1.1 Background

The next big step in computing is believed by many to be quantum computing. With the ability to use quantum bits instead of the usual bits we use today in our everyday computer it would be possible to do certain calculations at a dramatically faster speed. An example is Shors algorithm created by Peter Shor in 1994 [1] which would be able to do prime number factorization and would so be able to break the RSA encryption today used for protecting many web pages, email and so on [2]. Further, computations on quantum systems themselves that are not possible today would even be possible [1] which would further increase our understanding of what happens and how to manipulate things on such a small level.

The quantum computing field is an interesting field indeed but one that has a long way to go. The qubits used by quantum computers can be implemented in a number of ways. This thesis concerns the use of rare-earth-ions sitting inside a crystal whose hyperfine levels represent the different states and whose state are controlled using optics. The reasons that rare earth doped crystals are suitable for quantum information applications are numerous and for the interested further details can be found in [1].

In the approach with rare earth doped crystals there are two major ways for representing the qubits. The first one used for representing qubits was to use ensembles of about 10^9 ions. This approach however has a big disadvantage when it comes to scalability. Year 2000, David DiVincenzo listed five requirements for making a quantum computer, the first one being just that, scalability. So there needs to be many qubits in the system and they need to be able to interact with each other. For ensemble qubits to interact with eachother each ion in the ensemble needs to be able to interact with at least one ion from the other qubits in the system. However this chance is very low and scales as p^{n-1} as the number of qubits n increases. The reason for this is that the value of p is around 0.1-1% [1] for ensembles and so the probability will decay fast as the number of qubits increases. Therefore the single ion approach for representing qubits has been considered with the reason behind it being that with the single ion approach each ion only needs to interact with one other ion. That ion can then interact act with another ion and so on. This way chains of interacting qubits can be made and the system no longer scales as p^{n-1}. The difficulty with this approach is instead to find ions that have a unique resonance frequency.

There is however one big disadvantage or challenge with using just a single ion as a qubit and that is detecting the ion and its state. To solve this problem it has been proposed by Stefan Kröll et al. in [3] to use an additional readout ion. The readout ion will then be coupled to the qubit ion andby having a very short lifetime it can be allowed to send out multiple photons during the lifetime of the qubit, or be prevented from emitting, dependingon the state of the qubit.

So here is where this project comes in. In order to be able to detect the photons from a single readout ion a very efficient optical system is needed and the design of a system capable of this is one the goals for this thesis.

One of the main reasons for using rare-earths is the long coherence time of the rare-earths. For this to be true though and not have the rare-earths disturbed by lattice phonons in the crystal [1] the rare-earths needs to be cooled down

to liquid helium temperatures of 4 Kelvin. This fact gave the next part and goal of this thesis namely to design a holder for sample and focus lens inside the cryostat and also the design of a thermal link that could transport the heat from the sample to the cold-finger of the cryostat.

1.2 Problems to be solved

As mentioned earlier the overall purpose of this thesis was to design an optical system capable of detecting single readout ions in cooled crystals and also designing the holder and thermal link that will sit inside the cryostat. The more specific requirements that was put on the system are as follow:

- To be able to detect light from a single ion light from a volume of $1\mu m^3$ is desirable
- Design the optical setup to have 2-3% collection efficiency of the light from the readout ion
- Be able to scan a area of $100\mu m^2$
- Design a holder for the sample and focus lens that fits inside the cryostat
- Design a thermal link that can keep the sample at 3-4 Kelvin

1.3 Disposition

Section 2 will cover the theory needed to understand what is discussed thru ought the report. Section 3 will go over the different procedures that was used under the project and explain the many design choices made. Section 4 will show what the whole project has resulted in. Section 5 will be a discussion of the whole project and specific parts that are important. More so suggestions of what to do next with the project are put down so the next person taking over can do so smoothly. Section 6 is a short conclusion of what has been done during this project.

2 Theory

2.1 Quantum theory

Although it is not necessary to understand any quantum mechanics to understand whats going on in this project, a basic coverage of the theory concering quantum computing will be presented here so the interested reader at least can have some idea of what the system will be used for and why it is of interest.

2.1.1 Quantum computing

So what is it that distinguishes a quantum computer from a normal computer? What makes quantum computing so interesting and promising that a lot of research is put into the subject? The big difference lies in how the most basic cornerstone of the computer works. For a regular computer this would be the bit which is represented as a zero or one as a zero or one. All information in a computer is encoded in bits, as sequences of zeros and ones. For quantum computers this is also somewhat true but, the qubit can be zero or one but at the same time it can be both or rather in a superposition of the two. Until you have actually checked what the qubits value is, it will remain in a so called superposition state which means it will have a probability for each of the two states.

Here is an example to show how two qubits can actually hold more information than two regular bits. With two regular bits you need just that, two bits to represent what state they are in (are both 0 or is one 1 and the other 0 etc). But for the qubit case since you have the superposition of the states you will need the probabilities for four different scenarios: that both is 0 or 1 and for when one is 0 and the other 1 and the other way around. So you could say that the 2 qubits system would contain information equal to 4 bits and even then the four bits would not be real bits per say but rather probabilities which could have any value. It is easily realized that this difference in information contained increases rapidly as the number of bits increase, to be more precise it would for N qubits contain the information of 2^N regular bits. There is however a big catch and the big reason quantum computers will not be able to do todays computing algorithms faster. As mentioned earlier, as soon as the state of the qubits are read out they will all end up in a classical state (either 1 or 0) and all information about what superposition they were in will be lost. So when the read out has been done a set number of N qubits actually would have just as many states that a regular system of equal number of bits would have, 2^N.

So the idea for the quantum computers that will make them able to do calculations regular computers cannot and run certain algorithms much faster is to utilize that until they are read, the qubits actually are in a superposition of all the possible states. It could be simplified as to that the quantum computer would do many calculations in parallel and would therefore for certain algorithms need much fewer computions.

2.1.2 Qubits in this project

There are a number of ways to characterize a qubit. In the setup concerned in this thesis, different qubits will be rare-earth-ions in a crystal that will have different resonance frequencies. When the rare-earth is placed inside the crystal

it will have some of its energy levels shifted. This shift is completely random and can shift the resonance frequency of the rare earth over a so called inhomogeneous linewidth (frequency span) of around 5GHz. Then to get well defined and narrow resonance peaks for which a limited number of ions will resonate, a special spectrall hole burning technique is used. The hole burning technique burns a pit in the spectra where none of the ions will resonate. Then by applying so called burnback pulses [2] narrow spectral bands in the inhomogeneous linewidth will be allowed to resonate and these will be the different quantum bits that can be created.

Not only will the single rare-earth-ions inside a crystal be hard to detect due to that it is a single ion,but the characteristic of long life times will even further increase the difficulty of detecting it (long lifetimes meaning that it will stay excited for a long time and thus not send out many photons for detection). So since a single ion will not leave much light for detection a so called read-out ion has been proposed [3]. The readout ion will be connected to the qubit ion in the way that depending on which state the qubit ion is in it will either be able to resonate at its resonance frequency or not. The good thing about the readout ion is that it has no need for long lifetimes and so it will by choice have very short lifetimes. This gives it the ability to excite and de-excite many times during one round for the qubit ion and so send out much more light for detection.

2.2 Optics

This part of the report will introduce the basic theory of optics needed for designing the detection system

2.2.1 Fluorescence

The physical phenomenon that is used to detect the ions is called fluorescence. Molecules and atoms that are hit by photons have a chance to absorb that photon, if the molecule is in its ground state and the energy (wavelength) of the photon agrees with one of the resonances of the atom or molecule. It can then emit a new photon with a longer wavelength. So the whole process is that first if the photon is absorbed the molecule will leave its ground state and move up to a excited state (see Fig 1). The energy of the photon is now stored in the molecule which now have a higher energy. Normally the molecule will thereafter drop in energy by collisions with other molecules [4] and so move to a lower discrete excited state. As these collisions continue to happen, if the collision energy can't be absorbed by the neighboring molecule, a photon will be emitted. This photon will have lower energy and so a longer wavelength and also the direction of the photon will be completely random. This whole process is what's called fluorescence. As said that is the normal way fluorescence is done but at liquid helium temperature there are no collisions. Instead the discrete states are replaced by vibrations. The vibrations of the molecules are also released after a while but this time instead as phonons (heat).

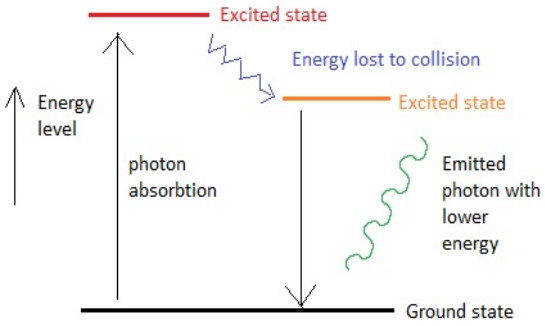

Figure 1: Energy transitions for fluorescence.

2.2.2 Diffraction limit and confocal microscopy

Detecting single ions is not a simple task. A good way to start however, is to try and collect light from as small volume as possible. In order to do this in the best way working at the diffraction limit of an optical system is a must. In classical linear optics, collimated light focused by a lens will focus the light at an infinitely small spot at the focus of the lens. However due to the wave nature of light this is not true in practice and there is actually a minimum for how small the focus of a lens can be. This limit named as the diffraction limit of the lens is found to be according to Eq. 1 [5]. As can be seen in the equation the focus spot diameter d [m] is limited by the wavelength λ [m] of the light and the lens numerical aperture NA.

$$d = \frac{\lambda}{2 \cdot NA} \tag{1}$$

So for a lens to collect light to as small focus spot as possible, light with as short wavelength as possible should be used and the numerical aperture should be large. The numerical aperture is actually a property of the lens and is defined as Eq. 2 [6] where n is the refractive index of the immersion media of the lens and α is half the angle of the light cone as the lens is focussing a collimated beam. So one could say that the numerical aperture is a measure of how big cone of light a lens can collect light from.

$$NA = n \cdot sin(\alpha) \tag{2}$$

Though there is a theoretical diffraction limit this is in practice impossible to achieve. All optical elements will cause some kind of optical aberration that will increase the spot size [7]. There is however one thing that should be done to get the best possible focus and that is to fill the entire focus lens aperture with light of constant intensity. By not doing so the focus spot will increase in size [5].

The small focus point is a good start but there is the task of only collecting light from that spot and getting it to a detector. Here a well-tried method in confocal microscopy is the use of a pinhole in order to block out light from

points other than from the focus point. As seen in Fig. 2 the concept is simple. Points that are not in the focus will not have their beam path passing through the pinhole and so have most of their light blocked by the pinhole.

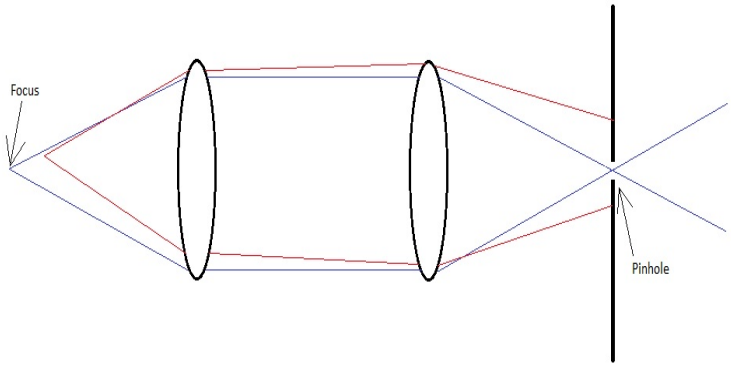

Figure 2: Picture showing how a pinhole blocks out light out of focus.

As discussed earlier, due to the wave nature of light a lens will not focus light to a zero size spot. So therefore in order to block out as much light as possible from points outside the focus point, but still collect as much light from the focus point as possible, the right size of the pinhole needs to be chosen. As discussed by Stelzer in [7] the pinhole should have the size of the airy disc that is the focus spot size of the focusing lens. Although there might be optics in-between the pinhole and focus lens that will have the size of the focus spot magnified and for this the pinhole should also be compensated. The magnification of lenses is easily computed using their respective focus lengths in accordance with Eq. 3 [7] where f_1 is the first lens in the beam path and f_2 the second.

$$M = \frac{f_1}{f_2} \tag{3}$$

It is of course possible to have multiple lens pairs between the pinhole and focus lens and in that case it is as simple as to multiply all the magnifications together to get the whole magnification and so the correct pinhole size.

2.2.3 Telecentric system

Regular cameras, that use only one lens for imaging, has the property that the magnification is dependent on the distance to the object from the lens. This means that for example in the picture of a tall building the walls will lean inwards, because the further away the building gets from the camera the smaller the magnification gets. Although this may seem natural for us as it is recognized as perspective it can be a problem if measurement where to be done on samples that have depth. So to compensate this instead a lens pair can be used that is distanced at the sum of their focal lengths. This will make the magnification only depend on the on the focal lengths of the lenses used and not the distance to the object [7]. You often say that telecentric systems are space invariant and linear meaning just as stated that the lateral and longitudinal magnifications are constant.

When two lenses form a telecentric system there are two telecentric planes created. As can be seen in fig. 3 they lie on each side of the telecentric lens pair. The special property of these planes are that the position the beams have at their focus between them is defined by the angle at the telecentric planes. So by controlling the angle of the beam in the conjugate telecentric plane it is possible to control the position of the focus point between the lenses. In the figure a focus lens is also included to illustrate that by controlling the focus spot position between the telecentric lenses you also control the position of the focus spot in the object plane. This together with that the magnification only depends on the focal lengths of the lenses makes it a big part of any scanning confocal microscopy system.

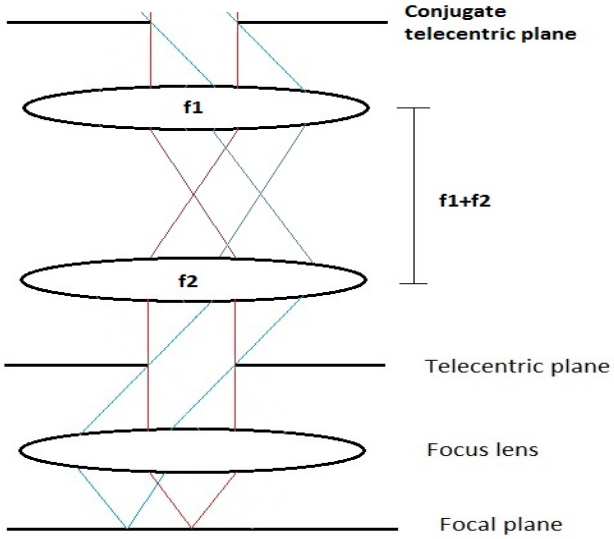

Figure 3: Illustration of how a telecentric system behaves. Observe that the colors of the beams have nothing to do with wavlength of the light.

2.2.4 Chromatic aberrations

The inability for a lens to bring light of different wavelengths to the same longitudinal focus is called longitudinal chromatic aberrations. When longitudinal chromatic aberrations are present it will cause the focus point to have a number of fringes in different colors outside the focus, with the colors of course depending on what light was sent through the lens. But not only that, but depending on what focus spot you chose to look at the different fringes will be in different order and size. This is all pictured in fig. 4.

Chromatic aberrations are due to the difference in refractive index (how fast the light travels in the material), light of different wavelengths have in materials and is therefore often present in thin lenses made of only a single material. There is however lenses that try to compensate for this with the use

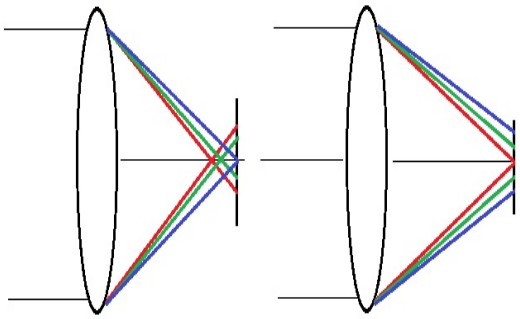

Figure 4: Greatly exaggerated picture showing the effects of chromatic aberration.

of multiple materials, correct curvature and thickness. This was done as early as in the 18th century when Dollond and a number of others made a lens out of crown glass and flint glass that was able to bring the focus spot of blue and red rays together [8].

Another chromatic aberrations are lateral chromatic aberrations which will cause the magnification for different wavelengths to depend on wavelengths as well. Also this chromatic aberration can be compensated for and often is done so in microscopy with a eyepiece that simply has the opposite chromatic magnification than the rest of the system.

2.2.5 Geometrical aberrations

Geometrical aberrations is another type of aberration that rather than having error introduced by the behavior of light with different wavelengths, introduces errors because of the shape of the lens. There are numerous geometricall aberrations that can occur for different reasons, so only the most relevant for this project will be covered here.

One such aberration is the focus field curvature that makes the field where a lens have focus to be parabolic due to the spherical shape of the lens. This is a problem for example in microscopy where you would want to have the whole flat field of view in focus you instead get to chose if you want to have the center or the periphery in focus.

A lens system that is not perfectly aligned can introduce coma aberrations. It is called coma aberrations because of the comet like shape the focus spot will take as the incident angle increases from the optical axis. Why this happens is because of refraction differences between rays passing through the center of the lens and at the periphery. An example of the coma aberration can be seen in fig. 5.

It should be noted that coma aberrations does not have to look the way they do in fig. 5, it can be the opposite way around and the periphery can instead create a small image. It is therefore possible to compensate for this aberration as well with clever optics.

Spherical aberrations are aberrations that take the form of having the focus

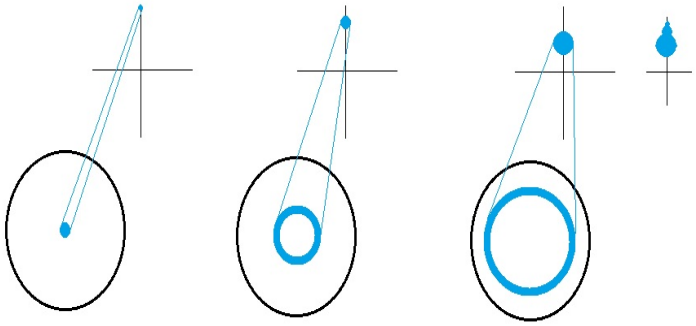

Figure 5: A very crude picture of how coma aberrations can look.

point shift longitudinally for light passing through the lens at the periphery compared to the center. It can be seen in fig.6.

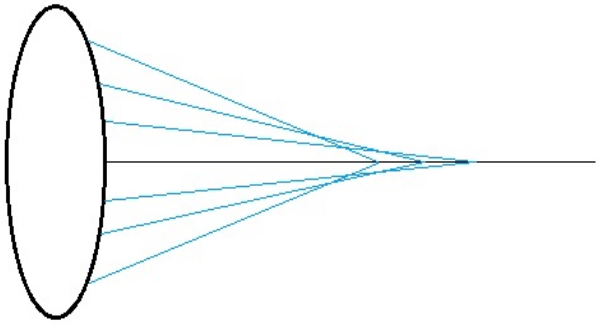

Figure 6: Spherical aberration

2.3 Thermal behavior

A big part of this thesis is the design of a holder for the focus lens and scanning system that sits inside the cryostat. Since the holder itself will be cooled down to single Kelvin values there are some properties concerning solid materials at single Kelvin temperatures that needed to be taken into account and whose basic theory will be covered here.

2.3.1 Thermal expansion and contraction

First of there is thermal contraction and expansion of solids materials. Most materials will expand when heated and contract when cooled. How much the material changes is a property that is measured by the materials thermal expansion coefficient α (K^{-1}). It is important to know that this coefficient varies

for different materials and that it is also temperature dependent.

So to get a figure for how much a solid part of certain size will change in length it's easy. All that's needed is the thermal expansion coefficient α (K^{-1}) for the material, length L_0 (m) of the material and the difference in temperature ΔT (C) [9]. Then a simple linear expansion formula is used:

$$dL = \alpha \cdot L_0 \cdot \Delta T \tag{4}$$

Thou, since the thermal expansion coefficient is temperature dependent, it will need to be integrated for it's different values at different temperatures to get a accurate result:

$$dL = \int_{T_1}^{T_2} \alpha(t) \cdot L_0 \cdot dT \tag{5}$$

The observant reader will notice that the discussion has only been concerning solids and this is important to point out as the above is not true for gases or fluids. This is because solids don't show a big size dependence on reasonable pressure changes which is therefore neglected. This is not true for gases and fluids for which the pressure should be taken into account if not kept constant.

2.3.2 Thermal conductivity

All bodies of material at different temperature will strive to reach thermal equilibrium. How fast a material can transfer heat in order to achieve this is often measured by its thermal conductivity coefficient k (W/(mK)). Heat transported through a solid is mainly by either phonons (lattice vibrations) or electrons. Further, for materials that have proven to be good thermal conductors at low temperatures, which are of interest in this project, the main mechanism for heat transport is by electrons. So basically, materials with good electrical properties are good at transporting heat at low temperatures or to make it simpler, different metals are good at conducting heat at low temperatures.

To measure materials low temperature thermal conductivity is not a simple task. Therefore when concerning metals where the thermal conductivity at liquid helium temperatures is mostly governed by electrons, most often the thermal conductivity is given by its electrical properties. This since it's easier to measure the electrical resistance. The value for the measured resistance is often given by the so called residual resistivity ratio RRR [10], which is a ratio between the materials resistivity at room temperature ρ_{293K} (Ω) and at the temperature of interest ρ_T (Ω):

$$RRR = \frac{\rho_{293K}}{\rho_T} \tag{6}$$

With the resistivity it's then possible to get the thermal conductivity through Wiedemann-Franz law [11] where L ($W\Omega/K^2$) is the Lorenz number, T (K) the temperature and σ (Ω) the electrical resistance:

$$k = LT\sigma \tag{7}$$

As mentioned earlier, the heat transfer in solids takes place because of all the connected bodies try to reach thermal equilibrium to each other. The rate of which heat can be conducted between two bodies will obviously depend on

the geometry of the bodies. Bodies with bigger cross section area will be able to transport more heat than smaller bodies can. However, how much heat that will flow through it depends not only on the geometrical shape of the bodies but also on the temperature difference. A simple method for calculating how much heat that will be transferred is to first transfer each solid body into a thermal resistance value R_T (m^2K/W) according to Eq. 8 [12], where l is the length of the body, A the cross section area of the body in the flow direction and k the thermal conductivity coefficient.

$$R_T = \frac{l}{kA} \tag{8}$$

Each body can thereafter simply be thought of as resistors in an electrical circuit where the voltage would be the temperature difference and current the thermal power.

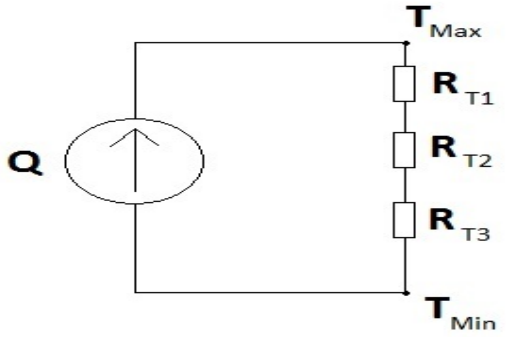

Figure 7: Equivalent schematic for thermal resistance conversion calculation in the form of a circuit diagram.

Then the amount of thermal power Q_{TH} (W) that can be transferred by the solid body can be calculated using ohms law via Eq. 9 , where ΔT (K) is the temperature difference and R_{tot} (m^2K/W) is the total thermal resistance of the solid.

$$Q_{TH} = \frac{\Delta T}{R_{tot}} \tag{9}$$

2.3.3 Increasing thermal conductivity

As mentioned earlier good thermal conductors at single Kelvin temperatures are metals. The best are actually copper, aluminum and silver. But one of the most frequently used is copper. Therefore, throughout the cryogenic community a number of methods have been invented to increase the thermal conductivity of the already high thermal conductive copper. It is done via annealing in different conditions. The major difference is the atmosphere in which the samples are being annealed. Some examples that was found in the literature [13] [14] are vacuum, nitrogen and oxygen. Here only the basic principles of oxygen annealing will be covered since that's what was used in this project.

As mentioned earlier, for metals and so copper, at single Kelvin temperatures it is the electrons that conduct the heat. So in order to increase the thermal conductivity, a good start would be to make sure the electrons have the best conditions possible to be able to this. It's been pointed out in literature [13] that major hampering of the electrons ability to move freely and so conduct heat efficiently is the scattering of the electrons caused by impurities. So it is this that oxygen annealing aims to improve on.

But the first step is of course to get a sample that you want to use with as high purity as possible [14] as it will have less impurity centers that can scatter the electrons to start with. Then what the oxygen annealing does, is it oxidizes the internal impurities by diffusing oxygen into the sample and when the oxygen hits an impurity the oxidation can take place. Although, the process is not that simple and there are a number of conditions that must be satisfied.

First off, in order to get the internal oxidation to happen the oxygen must diffuse faster in the copper then the targeted impurities. If not so then the oxidation will only take place at the surface. This is achieved by doing the annealing at temperatures close to the melting point of the copper. A temperature of about 1000C is often found in the literature [13] to work fine.

Secondly it's important that the oxide layer on the copper decomposes so the oxygen easily can diffuse into the copper. This is done by controlling the oxygen pressure and is found by others [13] to be around 10^{-5} Torr. This will allow for internal oxidation of impurities without the scale formation on the surface.

And lastly, to get oxidation throughout the whole sample the correct annealing time must be applied. As discussed by Ficket [13] the time for the oxygen to diffuse in copper is a good theoretical base for getting a good approximation of the annealing time needed. With Eq. 10 where t (s) is time, d (cm) is depth and K (cm^2/sec) is a proportionality constant, good values for the annealing time required can be found:

$$t = \frac{d^2}{K} \tag{10}$$

The proportionality constant K is hard to estimate and temperature dependent but at the stated conditions 4x10^{-6} cm^2/sec is a good estimation [13]. The difficulty in determining the constant comes from a product in the constant between the saturation solubility and diffusivity of oxygen in copper.

3 Method

3.1 Design of the optical system

3.1.1 Introduction to the basic optical setup

When this thesis project started a basic suggestion for how the system could look had already been made by one of the supervisors of this project, Jenny Karlsson. The suggestion can be seen in fig. 8.

The basic concept of the setup is simple. The 370nm laser is focused by the blu-ray lens inside the cryostat to excite the ions. The fluorescence is then collected by the blu-ray lens (objective lens) and transmitted through the beam splitter. In order to keep the noise ratio low and not get any of the 370nm excitation laser light into the detectors some kind of filter is suggested (F1) after

the beam-splitter. Since the fluorescence light will have a longer wavelength this needs to be a lowpass filter. After the filter the beam is then focused by L2 to one of the detectors, using flip mirrors to switch between them.

The most important parts of the suggested setup were the use of a confocal microscopy setup and the use of a blue ray lens. The use of the confocal microscope approach (focusing light through the pinhole PH1 fig. 8) is easy to understand with all of its benefits in the increased resolution. The blue ray lens however is not so obvious. Due to major optical aberrations created by the optical window of the cryostat and the fact that the ions need to sit below the surface in the host crystal to not be disturbed by the environment, puts high demands on the objective lens. So lets summarize what characteristics are required by the objective lens:

- Be able to take care of aberrations created by the cryostat window
- Be able to take care of spherical aberrations created by having to focus below the surface of the crystal.
- High numerical aperture for high light collection and small focus spot
- High transmission for wavelengths of 370-450nm

All points are somewhat met for by the blu-ray lens. The first item on the list is completely compensated for by putting the lens inside the cryostat. This is possible due to the short focal length and small size of the lens. By putting the lens inside the cryostat and so not having the cryo-window between the objective lens and sample, all spherical aberrations will be eliminated that would have been created by the cryo-window.

The blu-ray lens itself is designed to read blu-ray-discs which have a 0.1mm cover layer [15]. Therefore the next item on the list is also compensated for by the lens. The next point is definitely acceptable as the NA of the blu-ray lens in air is 0.85, which is quite high.

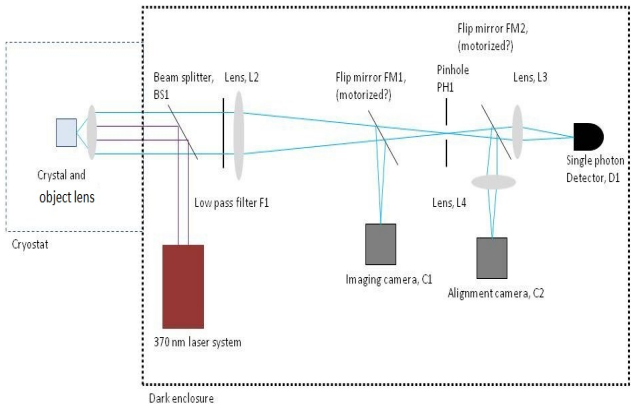

Figure 8: Basic setup made by supervisor Jenny Karlsson.

The last item on the list cannot be answered for certain as no exact plots for the transmission has been found. But the lens is designed for 405nm light [15] so it is kept in mind but assumed to not be a problem.

Going on with the setup the purpose of the imaging camera C1s is to get a widefield view of the sample without having to scan. For this to be possible, the excitation light from the laser needs to somehow be spread across the sample and not focused by the blu-ray lens.

Next in fig. 8, if the beam is not steered down to the first camera C1 it would pass through the pinhole. The idea behind the second camera C2 was to make this whole process easier.

Last, the beam could be directed to the lens L3 and focused on the single photon detector. The single photon detector just as the second camera C2 only looked at a single point in the sample and the idea was to be able to get a high resolution (relatively) image by scanning the sample and taking measurements in each point.

3.1.2 Choosing scanning method

A big part that was missing from the basic setup presented in the previous part was how the sample would be scanned. In confocal microscopy there are two methods for scanning the sample that are being used. The concepts are simple, either you move the sample or you direct the beam. Here follows a number of requirements that is put on both scanning approaches:

- A high accuracy set by the diffraction limit of the blu-ray lens. At 370nm the diameter is calculated by Eq. 1 to be 217nm. So an accuracy around 0.3μm would be acceptable
- Scan an area of $100\mu m^2$
- Scan the sample sufficiently fast, steps of 1μm at a 100Hz is acceptable
- Be able to repeat the position with an accuracy close to twice the diffraction limit.

Moving the sample is pretty straight forward, you put the sample on something that can move the sample with the accuracy that you want. Though in this case since the space inside the cryostat is very limited and that it has to work at liquid helium temperatures, this is not an easy task.

There are a number of companies that provide so called nanopositioners that can move the sample at nanometer scales. With the extreme environment and size restrictions only one company was found that could meet the requirements, a German company called attocube and their nanopositioner series ANP/Res. In fig. 9 it is shown how each positioner moves. So to get a movement of the sample in a two dimensional plane two nanopositioners are stacked on each other, one X-led and one Z-led positioner, and the sample put on top.

The other approach, steering the beam is a bit more complicated. By using mirrors whos tilt angle can be controlled, the beam path can be controlled. Usually the mirrors can only be tilted around a single axis and so two mirrors would be needed to move the beam along the two axes in a plane. This is done by having the laser beam hit the first mirror at its rotation axis and it is very important that it is centered at the mirrors axis or else the beam would get

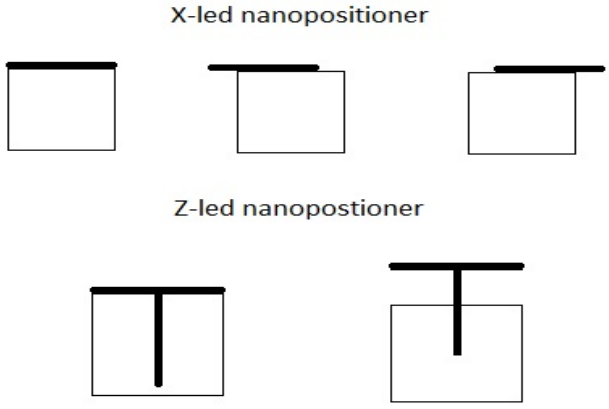

Figure 9: Nano-positioner movement.

translated as the mirror is rotated. If the first mirror is setup as described it is then possible to steer the beam towards the next mirror and have it move along that mirrors axis. If setup this way the two mirrors will then be able to control the beam in two axes without any translations as the angle increases.

If the beam steering is done as described and the beam goes directly into the focus lens there will be aberrations in the form of focus field curvature. This can be fixed by using a telecentric system. So if a pair of lenses is set up as in fig. 3 there is a conjugate telecentric plane before the intermediate optics of the focus lens. If the scanning mirror is placed with its pivot point (center of rotaion) in it, the aberrations mentioned will be gone [7].

As mentioned earlier to be able to scan in two axes the use of two single axis mirrors needs to be used. Now there is only one conjugate telecentric plane to be used so there are a couple of different solutions. One way is to use a mirror that can tilt in two axes but no such mirror was found during this project with good enough accuracy to be considered. Another way is to get two single axis mirrors and place one in the conjugate telecentric plane and then create another telecentric plane by placing another pair of telecentricly placed lenses between the mirrors. Since keeping a low photon loss level of the optical system is one of the main requirements of the system this was also never considered. This leaves the simplest solution and what seems to be the most common. It is simply to have the two scanning mirrors placed as close as possible around the conjugate telecentric. Many of the scanning mirrors that were considered even had associated mounts for just this purpose.

To make the decision of which scanning method should be implemented was not an easy task. There are pros and cons for each method and keeping the project in a reasonable budget also was important, so a thorough evaluation had to be done since precision at this level comes with a price.

The mirror approach puts much more pressure on the optical system compared to moving the sample. The main reason being that it cannot be kept axially but have to have angles to the optical axis introduced. This fact increases the chance of introducing geometrical aberrations through misalignment

and chromatic aberrations could cause problems for the telecentric system if not corrected properly by its lenses. There is also the increased number of optical elements in the detection path which is a problem since as mentioned, one of the big goals of the system is to keep photon losses low in the detection path to be able to detect the already weak signal from the single ion.

The moving sample approach is definitely the best approach from a pure optics perspective. The optical components are kept to a minimum and the whole system is kept axially. One problem with it and also the biggest tradeoff that had to be made is the speed of it. The scanning can be done much faster with the mirror approach. But the real problem and one that had to be thoroughly investigated was the possibility to implement it at all in the coldfinger-cryostat. To figure that out a model of the whole cryostat with the design of a holder for the nanopositioners was done in solidworks. Details of that whole process is covered in the next part of the report. Suffice it to say, the model shows promise and there is a backup plan for using a liquid helium cryostat instead of the coldfinger cryostat should problems arise, so it was found that its possible to implement the moving sample approach.

In the end the method for scanning the sample was moving the sample. Although a bit more pricey and with some uncertainties with the cryosystem, it is in the end for the purpose of detecting single ions the better choice.

3.2 Designing of the holder for the cryostat

When the decision was made that a model of the cryostat was needed, the first order of business was to measure the cryostat since no good schematics of it was available, neither from the manual or by contacting the manufacturer. The model of the cryostat can be seen in fig. 10 and was made using solidworks. Most of the dimensions could simply be measured using a caliper. As can be imagined the inside diameter was a little tricky to measure and required a special toll that was borrowed from the machine department.

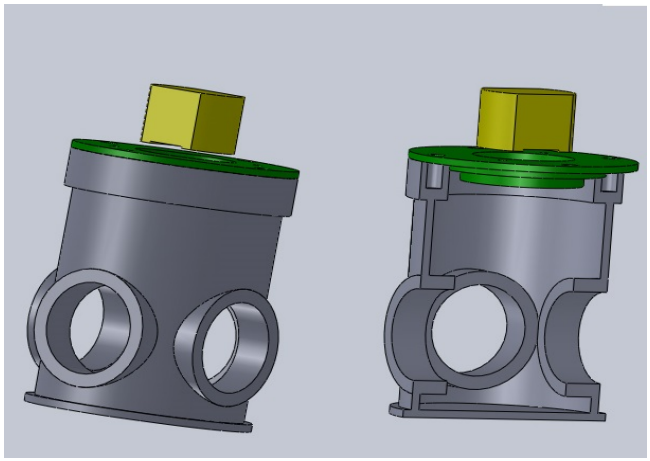

Figure 10: Model of the cryostat.

With the model of the cryostat available the next step was to find a design

for a holder of the scanning system. The requirements of the scanning system had been set to be able to scan in a plane, but the focus also had to be able to be adjusted. So by making simple dummies of three attocubes and playing around with them inside the cryostat model it was soon realized that the only configuration that would work was the one seen in fig 11. Setup this way meant that the plane scanning would be done by moving the sample in two directions and adjusting the focus depth by moving the lens in one direction.

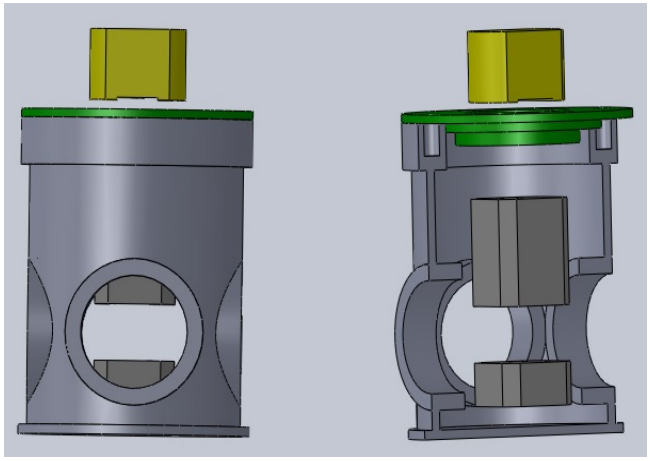

Figure 11: Model of the nanopositioners position.

The next big design question was how to design the thermal bridge. It was very soon realized that the thermal bridge and the entire holder went hand in hand and had to be designed together. This was very tricky and a lot of considerations had to be taken into account. They are presented here:

- The most important requirement was to have a high enough thermal conductivity between the sample holder hand the coldfinger of the cryostat (have a good enough thermal link)
- Since the sample was going to be moved the thermal link also had to be flexible
- Since the attocubes had to be put the way shown in fig. 11 some kind of platform to place the bottom attocube on needed to be included in the design
- It should be as convenient as possible to remove the sample and replace it

The first point on the list was as stated the most important one and absolutely had to be met. To get as high thermal conductivity as possible a design with as big crossection area of the thermallink as possible should be used. It was therefore quickly decided that the thermal link would look something like in fig. 12. Between the sample holder placed on the attocubes and the thermal link extended from the coldfinger of the cryostat thin copper links would then be soldered to complete the link. Since joints between different pieces have a much higher thermal resistance [16] than if the two pieces where one solid, in order

to keep the thermal resistance down for the thermal link, the number of joints should be kept to a minimum. In the design one joint between the coldfinger and the thermal bridge is unavoidable. So the first design idea was to make the whole thermal link and holder of the scanning system in one single piece. This could not be done, as restrictions on the diameter of the link were set by the diameter of the high purity copper rod of which the link would be made. Therefore some kind of detachable design had to be made. The final thermal link design can be seen in fig. 12. As can be seen a adapter piece is connecting between the coldfinger and thermal link. This adapter would also serve as a connector for the platform which can be seen attached to the thermal link in fig. 13. The platform design was more straight forward. The only real concern was stability and is why the holder has been designed as a corner.

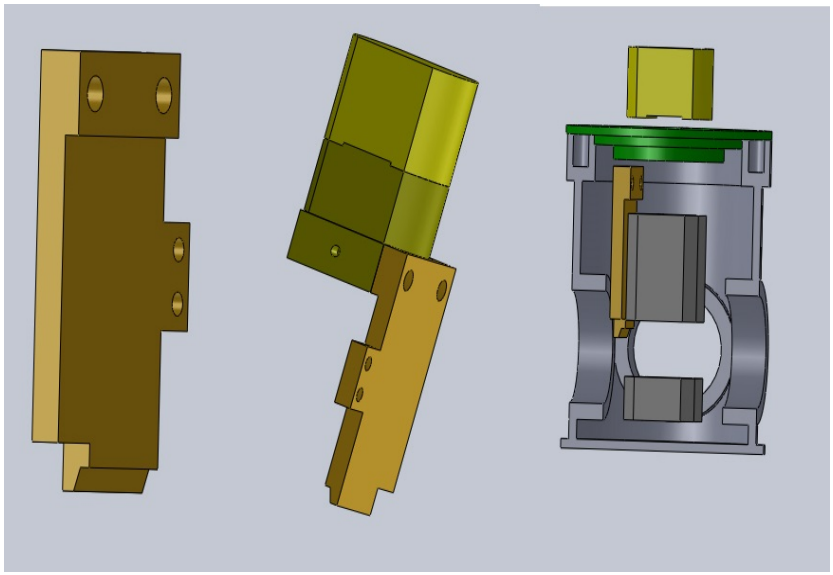

Figure 12: Thermal bridge design.

If fig. 13 is inspected it can be seen that the attocubes that are holding the sample will be attached to holder. This is a deliberate decision and comes from the consideration that it should be easy to change the sample. The procedure for changing the sample is to first remove the old and then the new sample is fastened to the sampleholder with a special kind of glue that needs to be heat treated. Since the thin copper links between the thermal link and sampleholder will be soldered together there will be no way of separating the sample holder from the thermal link. So in order to not break the delicate copper links when the sample shall be removed the whole system of sampleholder, thermal link, platform and attocubes will be removed as seen in fig. 13.

The sample-holder design is really all about fitting it in the narrow space that is available between the sample-holder and lens-holder as seen in fig. 14. To be more precise it is to make room for the copper links and screws of the lens holder.

For the lens-holder the same design considerations have been made concern-

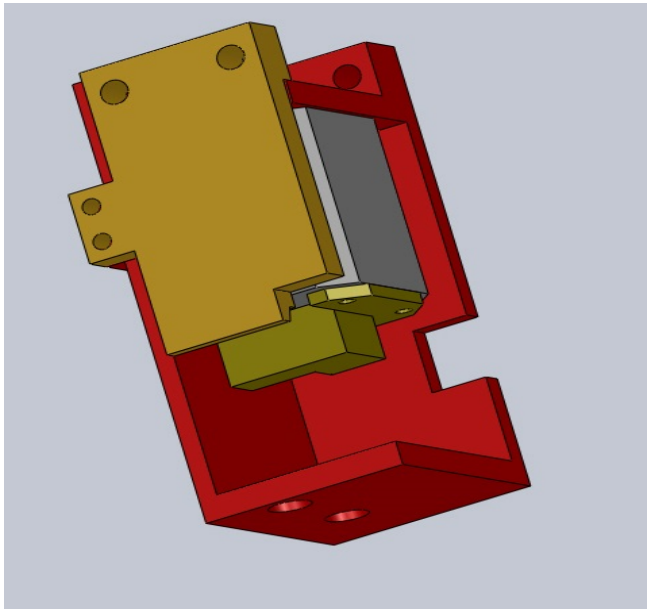

Figure 13: The pieces that are removed during sample swap.

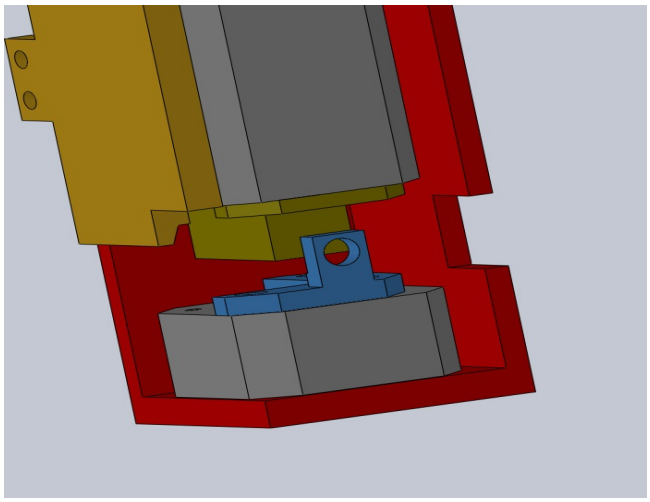

Figure 14: Sample and lens holders.

ing space improvement as the sample holder. For the holder of the lens itself a very simple design has been designed as can be seen in fig. 15, mainly because of the lack of space that limits the design possibilities. The design puts quite high demands on when the lens will be glued to the holder. A small misalignment around the vertical axis can be compensated for by the elongated screw hole, but other than that there is no compensation available.

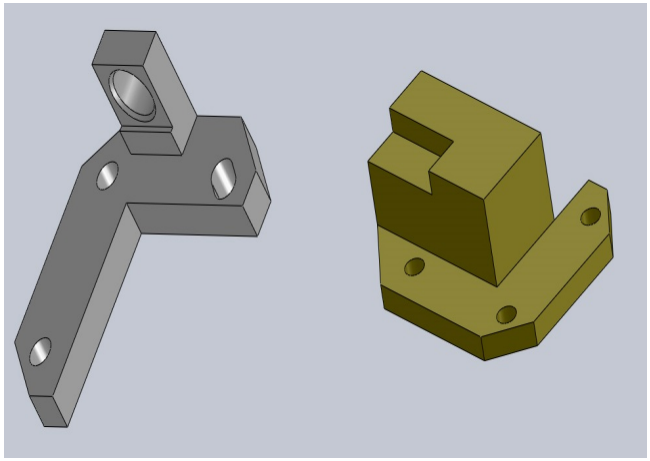

Figure 15: Close look at the designs of the holders.

3.3 The annealing procedure

As mentioned in the previous section an important requirement of the thermal link was to be able to conduct enough heat. How much heat that is, is hard to estimate. First it was assumed that if the thermal link could conduct 1W of heat it would be more than enough. So to calculate how much heat the thermal link could carry the thermal resistance method presented in the theory part was used. So to specify the target was to get 1W of heat conduction with no bigger temperature difference than 0.5K. In fig. 16 the amount of heat that can be transported by the thermal link is calculated with values for the thermal conductivity of high purity copper at 3K (5N, 99.999% pure) taken from [14] and thermal resistance value for the joints from citethermResCoppJoint. The calculations are for using six 18*0.2*3mm copper links.

As can be seen by the graph in fig. 16 only about 20mW of heat would be transported by the thermal link at a temperature difference of 0.5K. This is not nearly good enough so investigations of how the thermal conductivity could be raised was done. It was soon realized that the best results of increasing the thermal conductivity was by oxygen annealing the copper. A simple procedure of heating the copper up to close to its melting point in a vacuum pumped system and allow for a small oxygen leak. How it works is described in the theory. With the thermal conductivity of oxygen annealed copper [14] the amount of thermal power conducted by the thermal link was calculated to be according to fig. 17.

This, although not close to 1W, was considered an acceptable figure by comparing approximations of what other companies that have similar solutions had done. So it was decided that if the oxygen annealing could be done, then the design for the thermal link would work.

Thanks to collaboration with the solid states physics department, the oxygen annealing could be realized in their labs using their ovens and equipment. The whole setup can be seen in fig. 18.

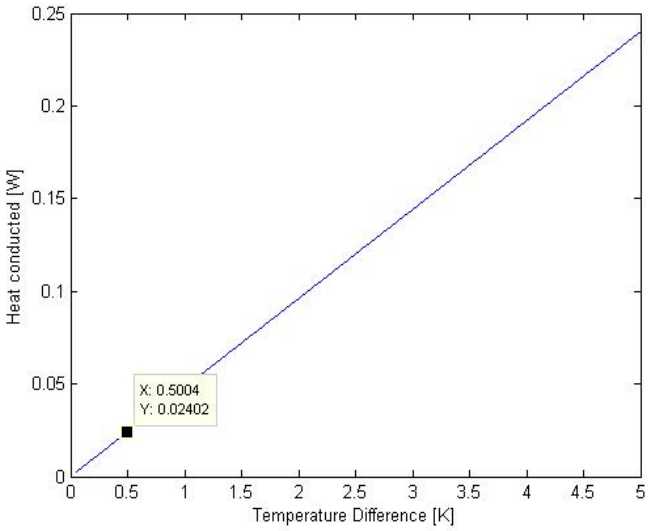

Figure 16: Heat conductivity for the thermal link with high purity copper.

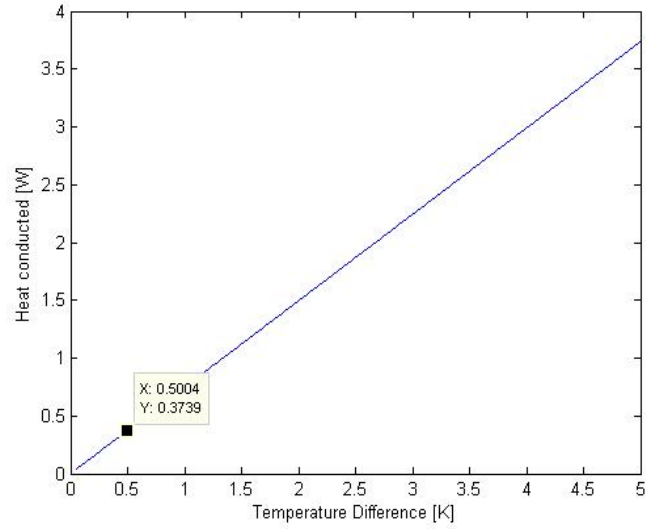

Figure 17: Heat conductivity for the thermal link with high purity copper.

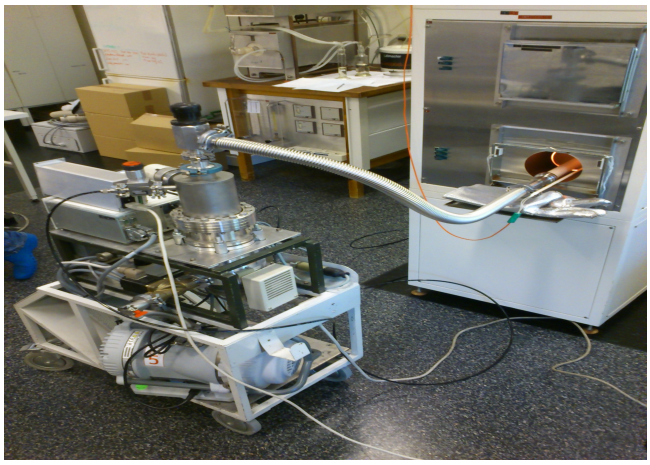

Figure 18: Oxygen annealing system.

Here is a list of the equipment used in the annealing system:

- A turbo pump for creating the desired pressure
- A 1 meter long tube with one end closed, made of alumina that will contain the samples and be placed inside the oven. Inner diameter of 27mm
- Adapter between the alumina tube and pumping system tube. The adapter made the connection air tight with the use of a o-ring
- Oven
- Needle valve for controlling the oxygen leak
- Pressure sensor
- Temperature sensor

The annealing process is done in the following order and all references to different valves are made to 19:

1. Clean the copper pieces. In this project acetone and optical tissue was used to clean the pieces
2. Put the pieces inside the alumina tube and connect it to the pumping system
3. Shut the furnace valve V2 and open the oxygen V1. Then start the pumping and empty the tube between V1 and the oxygen source V3.
4. When the tube between V1 and V3 is empty V1 is once again closed and V2 opened to start pumping the alumina tube.
5. When the pressure is closing in on $5 \cdot 10^{-6}$Torr the oven can be turned on.
6. When both the temperature has reached 1000C and the pressure $1 \cdot 10^{-6}$ torr the valve V1 shall be opened to get the pressure to $5 \cdot 10^{-5}$ torr.

7. Then the copper pieces are annealed for the time calculated by Eq. 10

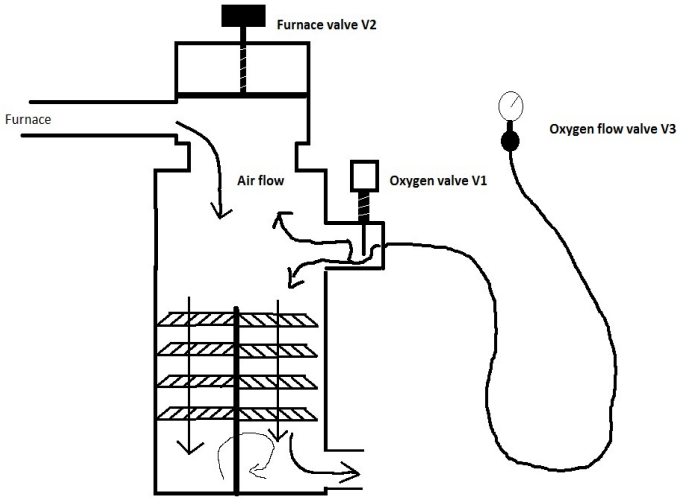

Figure 19: Heat conductivity for the thermal link with high purity copper.

The exact timings of the procedures done in this project are presented in fig. 20 21.

Annealing of three 1 inch diameter 5N copper pieces
Total length of copper pieces 15cm

Date	Time	Pressure	Temp.	Furnace prog	Needle valve	Remarks
	hh:mm	mbar	°C		to O2	
########	08:00	atm	RT	RC0	closed	start pumping
	11:00	6.2*10-6	RT	RC10	closed	start heating
	12:15	9.7*10-6	725,0	RC10	closed	outgas
	13:07	2.3*10-5	####	RC10	closed	outgas
	13:25	1.5*10-5	####	RC10	closed	outgas
	14:00	1.0*10-5	####	RC10	closed	outgas
	14:15	8.0*10-6	####	RC10	closed	
	14:16	1.3*10-5	####	RC10	opened	adjust
	14:56	1.3*10-5	####	RC10	opened	
	17:10	1.2*10-5	####	RC10	opened	adjust
	17:11	1.3*10-5	####	RC10	opened	
########	08:16	1.1*10-5	####	RC10	opened	adjust
	08:17	1.3*10-5	####	RC10	opened	
	11:50	1.2*10-5	####	RC10	opened	adjust
	11:51	1.3*10-5	####	RC10	opened	
	15:30	1.4*10-5	####	RC10	opened	adjust
	15:31	1.3*10-5	####	RC10	opened	
########	07:52	1.2*10-5	####	RC10	opened	adjust
	07:53	1.3*10-5	####	RC10	opened	
	09:30	1.3*10-5	####	RC10	opened	
	15:43	1.3*10-5	####	RC10	opened	
June 20,2013	09:45	1.3*10-5	####	RC10	opened	3 days in O2
	14:20	1.3*10-5	####	RC0	opened	stop heating
	14:21	1.7*10-6	####	RC0	closed	
	15:28	1.7*10-6	593,1	RC0	closed	
	leave for weekend and remove on Monday 24/6					

Notes;

1. Ramp up temperature - rate around 10°C/min (M/S)
2. O2 quality is N5.2
3. Pipe between regulator and needle valve was vacuum pumped before filling up O2.
4. Needle valve must be open 2.8 to 3.1 revolution to obtain pressure 1*10-5mbar
5. Ramp down temperature - rate around 5.7°C/min

Figure 20: Exact annealing procdure for big 1inch cylinders.

Oxygen annealing of 22*0.2*3mm 5N copper clamps

Time	Pressure	Temperature	Furnace prog	Needle valve	Remarks
hh:mm	mbar	°C		to O2	
09:15	atm	RT	RC0	closed	start pumping
12:00	6.4*10-6	RT	RC10	closed	start heating
12:45	3.7*10-6	450	RC10	closed	
13:39	3.3*10-6	1011	RC10	closed	
13:40	1.3*10-5	1011	RC10	opened	
14:05	1.3*10-5	1008	RC10	opened	25 min in O2
15:06	3.7*10-6	635	RC0	closed	stop heating
15:50	3.9*10-6	465	RC0	closed	
16:25	4.1*10-6	360	RC0	closed	
17:00	4.3*10-6	271	RC0	closed	
leave for weekend and remove on Monday 17/6					
07:45	6.2*10-6	RT	RC0	closed	
07:47	atm	RT	RC0	closed	stop pumping
					& ventilate
Notes;					
1. Ramp up temperature - rate around 10°C/min (M/S)					
2. O2 quality is N5.2					
3. Pipe between regulator and needle valve was vacuum pumped before filling up O2.					
4. Needle valve must be open 2.8 to 3.1 revolution to obtain pressure 1*10-5mbar					
5. Ramp down temperature - rate around 5.7°C/min					

Figure 21: Exact annealing procedure of small copperlinks.

3.3.1 The implemented optical system

From the basic setup made by Jenny Karlsson to the final setup implemented in this project apart from small changes there where two major parts that needed to be added. The first one already covered was the scanning system. The second mentioned in the basic setup introduction was a way to illuminate a bigger part of the sample. This could be solved in two ways. Either a lens is put between the laser and the beamsplitter so that the blu-ray lens will not focus the incoming light from that laser but instead spread it. The second approach is to steer the laser light to hit the sample from the side. Both approaches can be seen in fig.22.

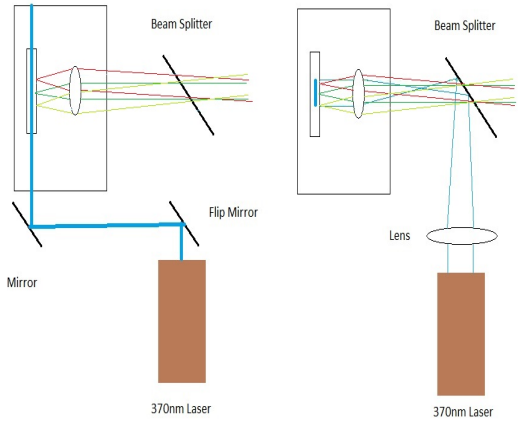

Figure 22: Two different widefield illumination choices.

The design with steering the beam from the side was chosen (left setup in fig.22). It seemed like the simpler solution at the time and not much thought was put on it. The complete setup that was finally implemented can be seen in fig. 23. The setup was coarsely aligned.

As seen in the figure a number of smaller changes was made. First the two mirrors M1 and M2 needed to be implemented to linearise the system by making the beam completely horizontal and parallel to the optical tables screw holes (the aim was to keep the beam aligned with the screw holes and have right angles everywhere). The next two mirrors in one of the possible beampaths FM1 and M3 are there as just described to get a widefield illumination of the sample.

The next component is instead of a beamsplitter that would just let through a portion of the beam whatever the wavelength, is a dichroic beamsplitter. Since the dichroic beamsplitter also acts as a filter the filter in the basic setup can be skipped.

After the dichroic beamsplitter another flip mirror is used to possibly steer the beam down to the widefield camera. Here a separate focus lens have been added to be able to control how big part of the sample should be imaged by the camera. Simple calculations using Eq. 3 was used to determine the lens. The same goes for the lens infront of the PMT with the adition of adding two

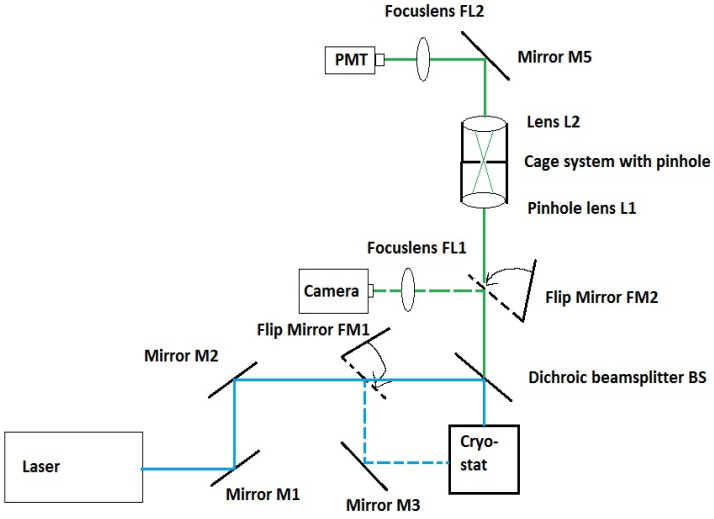

Figure 23: The end design of the optical system.

magnifications together.

The last part of the setup not mentioned is the cage system containing the pinhole and two lenses. The lenses are so called achromatic lenses that are compensated to have the same focal length over the wavelength interval of interest. Since all the light passing through this part will be along the optical axis this is the only real aberration that needs to be compensated for in order to get as much light through the pinhole as possible to have low losses in the detection path of the PMT.

4 Results

Unfortunately due to the time of the project running out nothing have been tested. Therefore the only results that can be presented are a detailed description of the whole system that has been built to simplify the continued work on the setup.

4.1 Complete setup

In fig. 24 the whole actual setup can be seen. It has only been coarsely aligned and not put to any real tests.

The mirrors M5 and FM2 are of the type E02 and their transmission spectrum can be seen in fig. 25.

The mirrors M1, M2, M3 and FM1 are all broadband mirrors and in the detection path so their exact transmission is of no real interest. In fig. 26 the transmission spectra for the dichroic beamsplitter can be seen. The lenses FL1 and FL2 are simple spherical lenses with the corresponding focus lengths

Figure 24: The complete optical setup

35 and 25.4mm. The lenses L1 and L2 are both achromatic lenses with the corresponding focus lengths of 40 and 50mm.

Further to be able to align the system a number of translators have been included. Both of the focusing lenses FL1 and FL2 are mounted in lens mounts that can adjust the lens position both horizontally and vertically. Further they are both placed on top of a z-translator that allows for help focusing the lens on the detectors.

In the cage system the first lens in the detection path have a mount that can be moved along the optical axis to easily find the right distance to the pinhole. The pinhole can be moved both vertically and horizontally to be able to find the focus of L1.

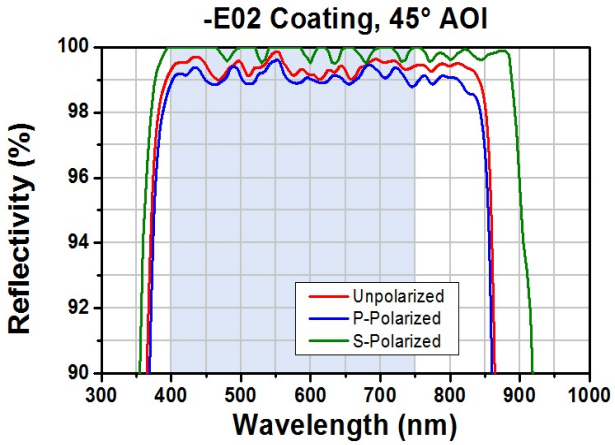

Figure 25: Transmission graph for the dichroic mirrors E02.Figure from [17]

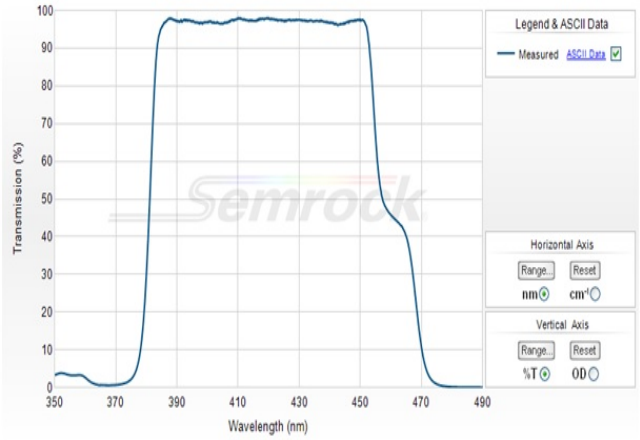

Figure 26: Transmission graph for the dichroic beam splitter brightline from semrock. Figure from [18]

4.2 Cryostat holder

Since most of the parts designed for the cryostat was going to be made with the oxygen annealed copper, they have not been manufactured yet. So whether the design is a success is unkown. But the design is finished and as soon as the annealing is done it can be sent for manufacturing. The complete model of the cryostat with the holder and scanning system can be seen in fig. 27 and fi. 28.

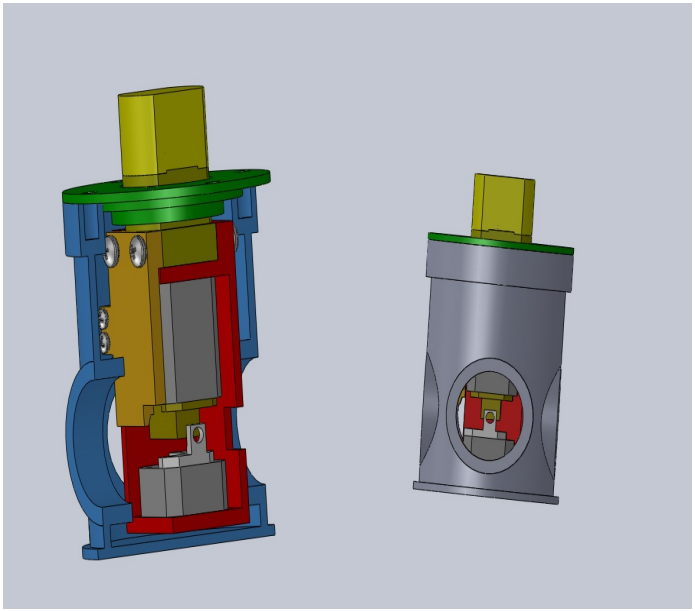

Figure 27: Complete model of the system inside the cryostat

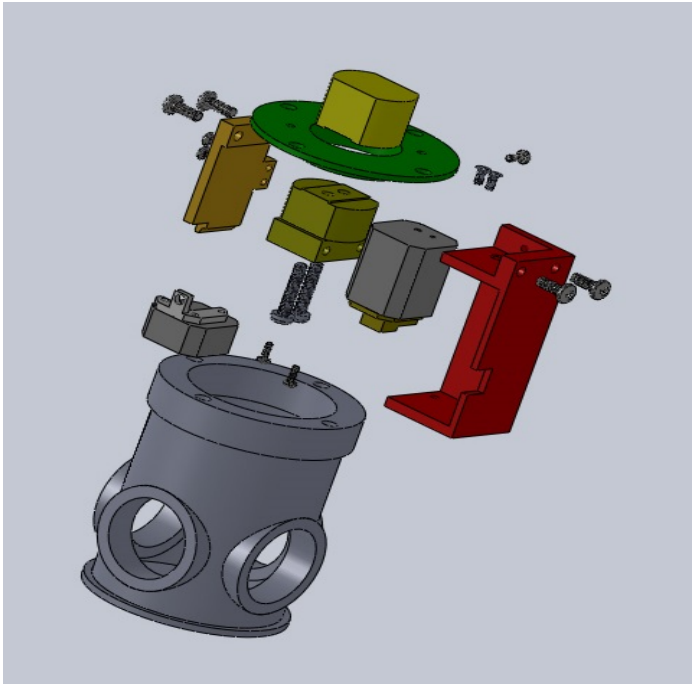

Figure 28: Exploded complete model of the system inside the cryostat

4.3 Oxygen annealing

A system for oxygen annealing of copper have successfully been built over at solid state physics with the capability to fit pieces of 1 inch in diameter. It was able to keep the pressure and temperature that had been determined by literature. Unfortunately due to a pressed time schedule for access to the lab and oven and it coinciding with midsummer, the big pieces could not be annealed as long as had been calculated by Eq. 10 (72 hours instead of 110). The annealing of the small copper links that will connect the sample holder and thermal link went completely according to plan. Also they got really soft from the annealing which is a very welcome fact for making the link between the thermal link and sample holder flexible enough for the nanopositioners to be able to move it. The small copperlinks can be seen in fig. 29.

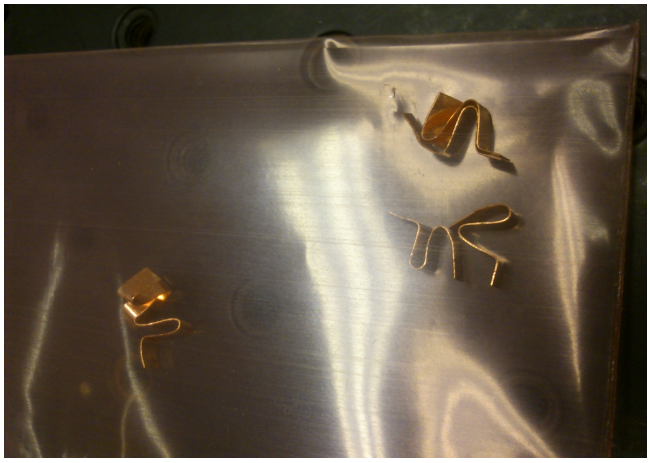

Figure 29: Oxygen annealed copper links that will connect the sample holder and thermal link

5 Discussion and continued work

Here follows a discussion of the work that has been done and for future work that needs to be done to finish the setup.

5.1 The optical setup

The main goal this whole project is to detect single ions. To be able to do that many requirements have to be met. For the optical setup this means as mentioned to have minimum attenuation of the signal in the detection path and to be as close to the diffraction limit as possible. To keep the attenuation of the of the signal as low as possible a minimum number of optical elements should be used. Looking at the setup created this demand is to satisfactory and other then being able to skip the mirror M5 in fig. 23 had there been more space I cannot see how it could be efficient. To get as low attenuation as possible in this setup is now more about being able to align it as good as possible.

A suggestion for making that easier is to get a xy-translator for the PMT. Its quantum efficiency is very much tied to how much of the detector is illuminated. For best performance with 100% of its maximum quantum efficiency, a beam diameter of as small as 50μm should hit the detector. Sure it would be possible to fine adjust the beam using the mirror M5 and the focusing lens since they can be tilted and translated but would be so much easier to just have them aligned to keep the beam close to the optical axis and then let the positioning of the PMT find the beam. Another suggestion to improve upon the system would be to get a z-led translator for the dichroic beamsplitter. Again with the purpose of having the beampath parallell to the optical tables sides and so keeping the whole system using right angles. If implemented the aligning of the system up to the cryostat would be as easy as to first linearise the system with the two linearising mirrors (M1 and M2) and then when you have a beam with the correct hight and with right angles all that needs to be done with the beamsplitter is to make sure the beam hits it with 45°. Unfortunately a mistake in the design was realized during the writing of this report. It concerns the focus lens FL1 in fig. 23 for the camera. Since the camera will be used to image a widefield view, in order to minimize geometrical aberrations caused by the light not traveling along the optical axis, this lens should be placed at the sum of it and the blu-ray lens to create a telecentric system. This cannot be realized with the current system as the sum of their focus lengths is far too short and would place the focus lens somewhere around where the beamsplitter is situated. So the current setup for the widefield camera will not work and needs to be reconfigured in a another way using different focusing lenses.

5.2 Holder design

The holder and thermal bridge design is pretty much complete but there are a few things that should be said about the continued work. The first step will be to have the whole design manufactured, using the oxygen annealed copper for the thermal link parts. Since the thermal conductivity still is far from the value that was set at the beginning, everything that can be done for keeping the sample cool should be done. Therefore it should definitely be considered to gold plate the sampleholder and so make it less susceptible to absorb heat radiation. This could greatly help out lowering that value for how much heat the thermal bridge have to be able to conduct. Secondly, the joint between the adapter piece and the thermal link should also be considered to be gold plated since as stated in [16] this is the best surface two joints can have to get the best thermal conductivity. The joints should also be screwed together using brass screws [19] since the thermal expansion coefficient of brass will make it contract more than the copper and so tighten the joint further increasing the thermal conductivity of the joint. Lastly the copper links that has been annealed needs to be soldered to the thermal link and sample holder. It is important that the solder is hard solder (highest purity of silver solder) and not soft solder as that would have a terrible effect on the thermal conductivity [20]. One thing that needs to be said about the design is the force that the nanopositioners can handle. Since the annealing of the copper links softened them quite much it should not be a problem to get the attocubes to move with all of them attached. However care should be taken here and it should from time to time be tested that the attocubes actually are able to move the sampleholder in a correct way. This

since as the links will bend they will start to build up stress. The stress will make them harder and so a greater force would be needed to bend them. The attocbues can take a very limited force along their axis and work properly so it should be kept in mind. The tests should be easy to do since the attocubes have a sensor to detect their movement.

5.3 The oxygen annealing procedure

As stated in the result the annealing system worked very well. The next step should be to measure how big impact the procedure actually had on the thermal conductivity of the copper. There is plenty of copper over for the big pieces so cutting a piece from them to be measured can easily be done. Although it might be interesting to cut parts from different depths of the big pieces to see if the oxidation really has penetrated the whole sample or if it needed to be annealed longer as foretold by the literature. Unfortunately the small copper links are at a minimum number for the design and none can be spared for measuring. This was definitely a blunder to not have an extra piece for measuring on.

6 Conclusion

In this project a design for an optical system with the aim of detecting single ions have been produced. The optical system includes a scanning confocal microscopy approach, set to increase the resolution as much as possible. The system has not yet been tested so whether it works or not remains to be investigated. A thorough model of the cryostat has been created to aid in the design of a holder for the scanning system inside the cryostat. The holder also includes a flexible thermal link that will keep the sample cool by conducting heat to the cryostats coldfinger. To get enough heat conduction for the flexible design of the thermal link, a lot of research into different methods for increasing the thermal conductivity of high purity copper was done and small tricks of how to best design your thermal link. It resulted in an oxygen annealing system which increased the thermal conductivity by internal oxidation of the copper and softening the small pieces of the thermal link responsible for its flexibility and so further increased said property. How well it worked remains to be tested, but the system delivered on the requirements set up in the literature so hopes are good.

7 Acknowledgement

First I'd like to thank my supervisor Jenny Karlsson who has done her uttermost to smoothly introduce me to the basics in the quantum physics field. A special thanks to my other supervisor Stefan Kröll and Lars Rippe with whom I have had a number of discussions where they have helped me take the right design decisions. I would also like to thank Diana Serrano for great help in answering my questions I've had about the oxygen annealing procedure. I also want to thank the whole quantum information group for being very helpful and always eager to answer any questions I have had. And last a big thanks goes to Sören, Høakan and Mariusz over at solid state physics, without their help with

constructing the annealing system, this whole project would have had to take a whole other approach.

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