Bachelor and master theses in the group of Carsten Klempt (Institute of Quantum Optics)

Who are we?

The group of Carsten Klempt at the Institute of Quantum Optics works in the field of non-classical atom optics. We create Bose-Einstein condensates of neutral atoms and prepare them in non-classical quantum states, so called entangled states. Our goal is to have unprecedented views onto their characteristic features, and to employ them into interferometric sequences to surpass the so-called standard-quantum-limit.

Our experiments are laboratory-filling setups consisting of many subsystems. You will find large assemblies of optical elements to prepare the needed modes of coherent laser light, and to guide this light onto the atomic ensemble in our vacuum chamber. Multiple pairs of coils are used to create the desired magnetic environment, and radio-frequency and microwave pulses are employed to manipulate the quantum mechanical state of the BEC. At the end of each experimental sequence, the final state gets detected by illuminating the ensemble and collecting the light on a highly sensitive camera.

What topics do we offer?

For your Bachelor or Master thesis, our group offers topics in the fields of optics, electronics, programming/simulating, and much more. Come and ask! (write an E-Mail first ☺)

What do you need?

For the theoretical background, you should bring a basic understanding of quantum mechanics, e.g. from a lecture like “Introduction to Quantum Theory”. The lecture “Quantum Optics” describes quite nicely (the theory of) our field of work, but is not required.

For the practical work, you will learn the skills you need here at the institute.

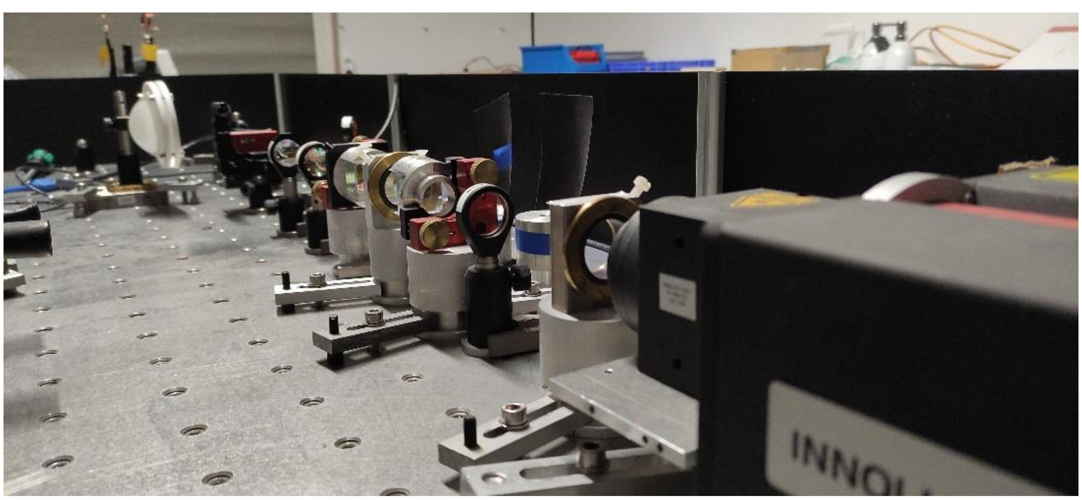


Figure 1 Impressions from our "student's lab"

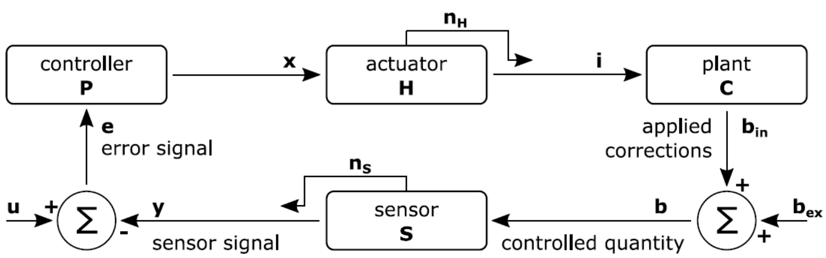
Specific topics

Improving an optical dipole trap by designing, constructing and benchmarking a multi-stage laser intensity stabilization (Bachelor or master thesis)

After the first stages of trapping and cooling, the atomic ensemble is loaded into an optical dipole trap. It yields a confining potential, whose depth is proportional to the laser power. This depth will get sequentially lowered over many orders of magnitude to establish evaporative cooling (the hottest atoms escape the trap, while the colder ones remain inside, thus lowering the average temperature). Finally, this will lead to Bose-Einstein condensation.

Noise on the laser power will heat the atoms. An inaccuracy between the actual and the desired laser power will make it hard to set up the best evaporation sequence. A drift in the power over hours and days will limit the runtime of the experiment, before adjustments need to be made.

This is why an active stabilization scheme (aka feedback control system) is used to monitor and automatically adjust the laser power. The current system uses the same settings for all needed orders of magnitude of the laser power (from several Watts to 100µW), and we believe that improvements can be made by extending it by a “low-laser-power” mode.



General sketch of a closed control loop. Every block stands for a linear single input-single output device. The signals are drawn as arrows. The electric noise contributions of the actuator and the sensor are depicted as well, and are to be understood to add up to the device's *output*.

The goal of the thesis is to design a multi-stage, analog control system for stabilizing the power of a laser beam. Is shall be able to switch smoothly between a high-power mode and a low-power mode.

This requires to extend or redesign the given PID-controller, which is why you should have a great interest in understanding, designing and testing analog electronics. You will learn how to use different measurement devices to benchmark your own test setup. For this, linear control theory is used.

If you are interested and want to learn more, contact quensen@iqo.uni-hannover.de.

Designing and testing of microwave antennas to selectively drive atomic hyperfine transitions (Bachelor or master thesis)

The optical ground state of Rubidium is split into two hyperfine levels (“F=1” and “F=2”) that are separated by 6.8GHz. Each hyperfine level is further split into Zeeman states (different quantum numbers “m_F”), when a nonzero magnetic field is present. We can prepare the atomic ensemble in one of these states, or in a superposition of multiple ones, by using coherent microwave pulses that drive transitions between the hyperfine levels.

To generate the required electronic microwave signals, we combine the flexibility of a direct digital synthesis (DDS) device with a self-designed “microwave chain” for frequency mixing and amplification. This way, the pulses can be controlled in frequency, amplitude and phase.

Finally, the electric signal is send to a microwave antenna, which generates an oscillating electro-magnetic field at the position of the atomic ensemble.

The effect of the oscillating field on the atoms depends on all its parameters, i.e. frequency, amplitude, phase and polarization. The polarization determines which hyperfine transitions (“σ+”, “σ-“ or “π”) are primarily driven.

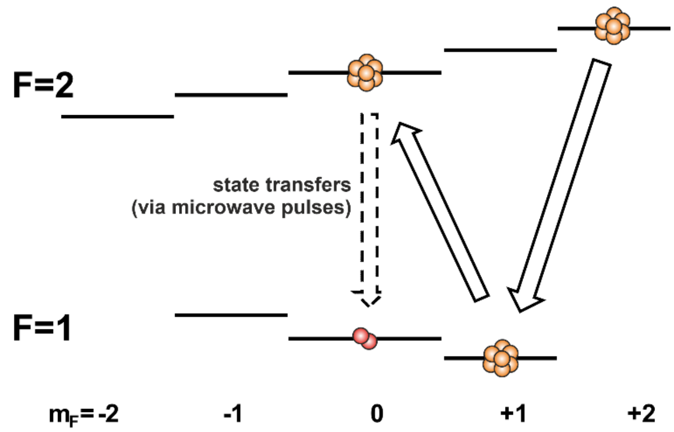


Figure 2 Sketch of a short microwave pulse sequence for preparing the atomic ensemble in a desired state.

In our current setup, we cannot dynamically control the polarization. Thus, the antenna is chosen in such a way, that the microwave field couples sufficiently well to all three kinds of transitions. This, however, has the disadvantage that often “cross transfers” occur, e.g. the |F=1, m_F=0> -> |F=2, m_F=+1> transition gets driven while we do a transfer on |F=1, m_F=+1> -> |F=2, m_F=0> (because the required frequencies are very similar). This can be a problem, when the interferometric sequence requires to have multiple energy levels populated at the same time.

The goal of the thesis is to design and test new microwave antennas, in order to either generate a static, well-defined field polarization (antenna with one electric input) or to generate a dynamically controllable field polarization (antenna with two electric inputs).

If you are interested and want to learn more, contact cassens@iqo.uni-hannover.de.

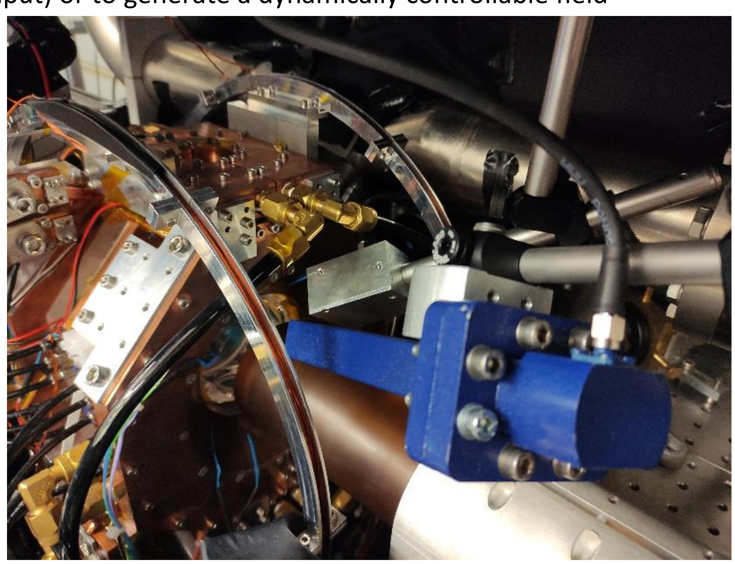


Figure 3 Two directional microwave antennas (blue and aluminum), pointing at the vacuum chamber where the atomic ensemble is created.

Utilizing machine learning to improve the precision of fluorescence imaging in a cold-atom experiment (Master thesis)

At the end of each experimental sequence, we illuminate the atomic ensemble with (near-) resonant light, and collect the emitted fluorescence light on a highly efficient CCD camera device. The results are images (up to 1024x1024 pixels), with each pixel a measure the number of photons that were emitted from a specific position. Examples can be seen below (the color-mapping illustrates the photon counts per pixel).

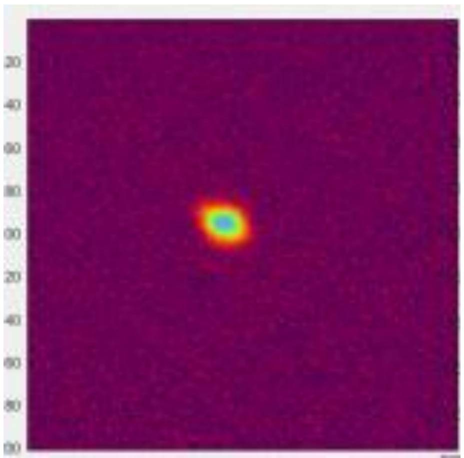


Figure 4 Detection MOT (Magneto-Optical-Trap) image

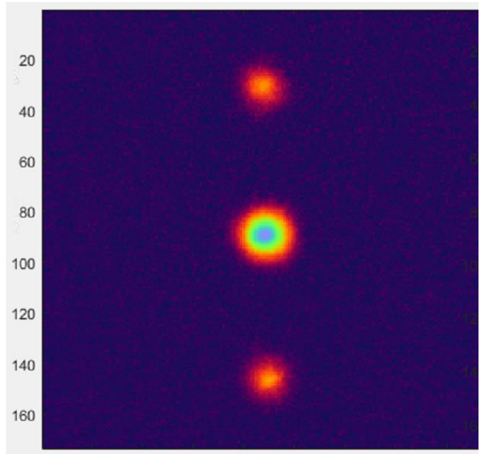


Figure 5 Fast illumination (100µs) of a Stern-Gerlach separated superposition state

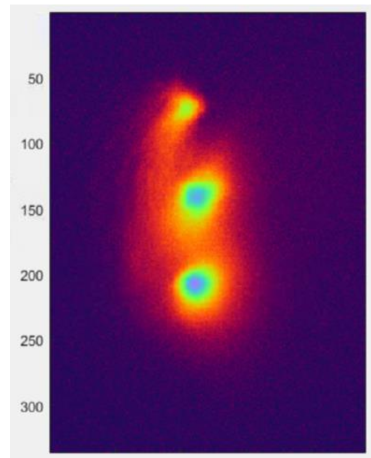


Figure 6 Long (5ms) molasses illumination

The sum of all photon counts from one of the visible “atom clouds” is a measure of how many atoms populated a specific energy-state. From this information, many observables of interest (e.g. the total atom number and the z-component of the total spin) can be calculated.

In our experiments, we are interested in surpassing the standard quantum limit in an interferometric sequence, or showing quantum features of the atomic states that often hide behind the *exact* atomic population number. We are thus interested in increasing our detection precision as much as possible.

For the evaluation of the CCD camera images, other research groups have already demonstrated that machine learning can be utilized to improve this precision beyond what is possible by just adding photon counts in a specific area. For example, background-image estimation (how much signal comes from other sources than the atoms, e.g. stray light or electronic noise) can be performed with a deep neural network.

The goal of the thesis is to program advanced image evaluation techniques to increase the detection precision in a cold-atom experiment. You should be interested in machine learning, optimization algorithms and neural networks. You should be able to write your own programs in python.

If you are interested and want to learn more, contact quensen@iqo.uni-hannover.de.

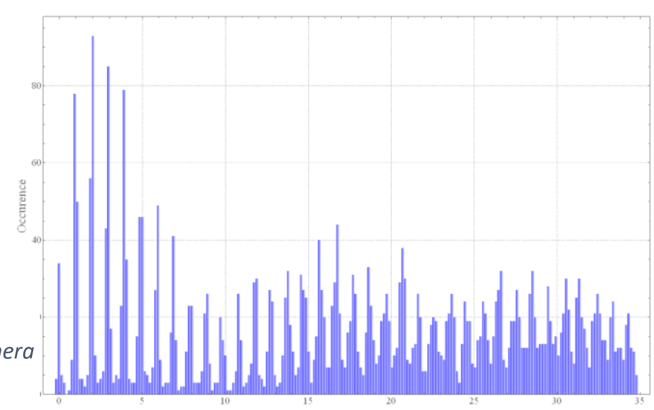


Figure 7 Histogram of photon counts in a measurement series of atomic ensembles with few atoms. Distinct peaks demonstrate the capability of accurately count single atoms.
Can a machine learning algorithms help to (even) better evaluate the camera images and decrease residual noise? (decrease the width of the peaks)