Creating a Core-Shell Laser Configuration for a Cold Atom Ytterbium Experiment to Increase the Number of Atoms in a Magneto-Optical Trap

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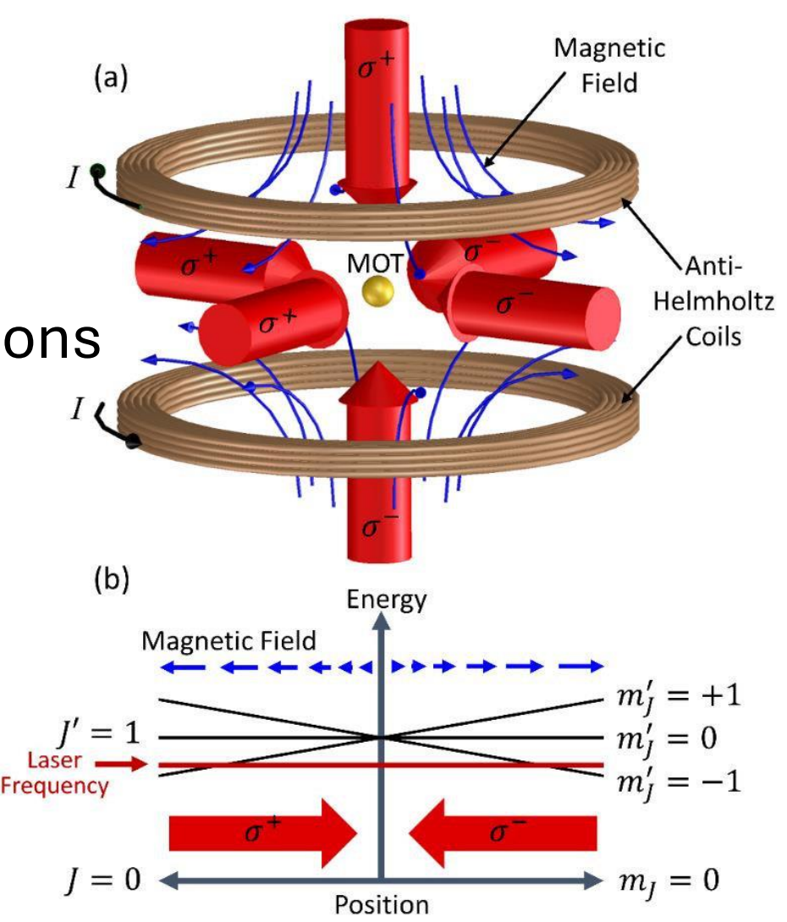
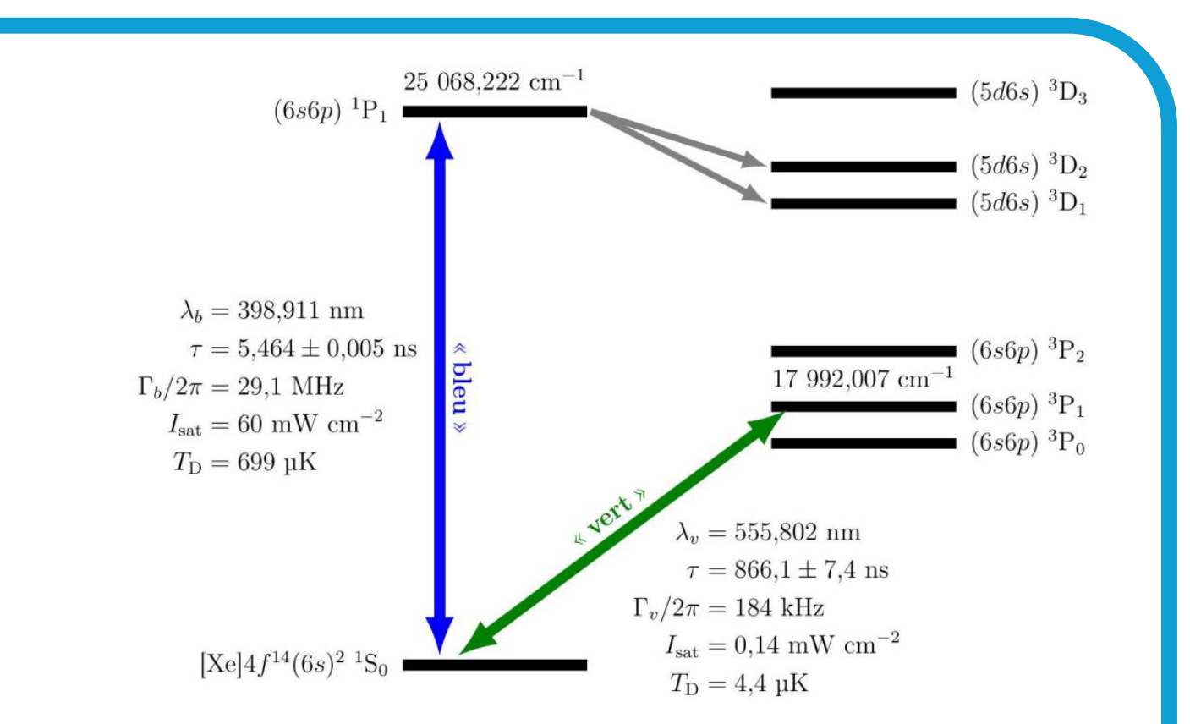
Summary In this internship, I explored two different methods to incorporate a core-shell (CS) configuration into our **laser-cooling experiment with ytterbium**. The current setup is limited by light-assisted collisions (LACs). We use **two different transitions** , the green and the blue to trap as many atoms as possible at low temperatures in our magneto-optical trap (MOT). The **blue transition** is better suited **for loading the trap** with atoms but implies LACs while the **green transition** can achieve **160x lower temperatures**. In the moment, the two transitions are used in quick succession, but we want to combine them by incorporating **a hole in the blue laser** where the green laser propagates through. Then, **LACs cannot happen at the centre of the MOT**, where the atoms accumulate, and due to the higher achievable densities, I computed a three-fold increase in the number of atoms if we decrease the intensity of the blue by 99% in the centre. For the hole creation, two different options, **the SPP and Spot configuration**, are explored. The SPP configuration uses a spiral phase plate (SPP) to change the gaussian beam to a donut-shaped beam profile while the beam propagation is physically blocked. I found experimentally that the Spot configuration can decrease the intensity in the centre by 97-99% while we do not have to worry too much about adjustments in the setup. For the SPP configuration, I can show only numerical results, but also designed a possible setup, where we would achieve 1% intensity in the centre. Due to a more complicated setups with similar results, I **suggest using the Spot configuration**.

The MOT

- 6 beams
- Frequency detuned by Δ
- ➢ Atoms only absorb photons with $\vec{k} \uparrow\downarrow \vec{v}_{at}$
- Helmholtz-coils induce Zeeman-splitting
- ➢ **Cooling force points toward center**
- 2 transitions (green and blue) used



Scheme of the mot [2]



The two transitions and their parameters [1]:

- Γ : Natural linewidth
- I_{sat} : Saturation intensity
- $T_D(\Delta)$: Lowest temperature theoretically obtainable

By how much the intensity must be decreased

Under the assumptions that…

$$N_{max} = \frac{L}{\alpha + \beta \bar{n}}$$

Max. number of atoms
Loading Rate
Avg. atom density
1st order losses **due to background pressure**
2nd order losses **due to LACs**

Previous experiments [1] ,[3] found:
$\alpha \approx 0.5 s^{-1}$
$\beta \approx 1.1 \cdot 10^{-10} cm^3/s$
$L_{max} \approx 3 \cdot 10^9 \, at/s$
$\bar{n}_{green} \approx 1 \cdot 10^9 \, at/cm^3$

…we achieve densities similar to the green MOT,

… β is linear to the I_{blue} at low values

… we want to keep second order losses at the same rate as first order losses,

…the atom density is uniform

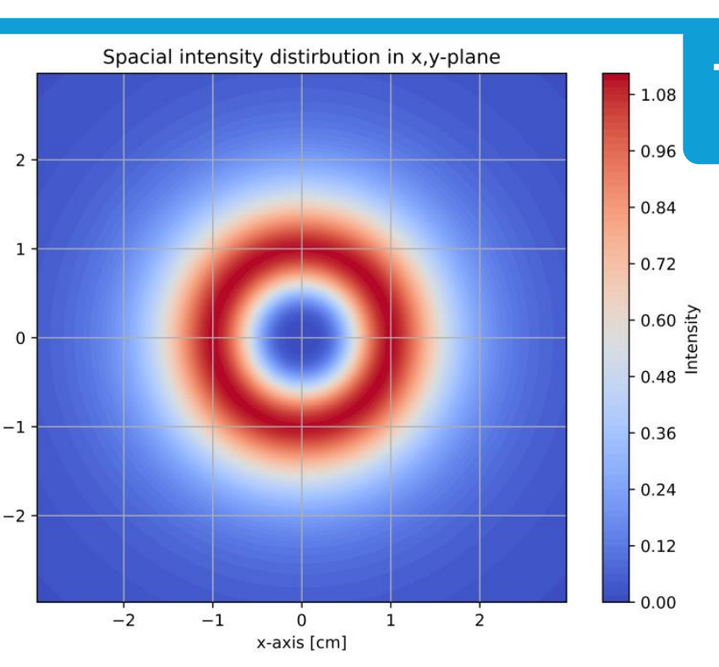
we can triple the number of atoms $N_{max} = 10^9 \, at$ to $N_{max} = 3 \cdot 10^9 \, at$ **if we decrease the intensity by 99%** with a **MOT size** $r_{MOT} = 2 \, mm$.

The intensity must be decreased by 99%

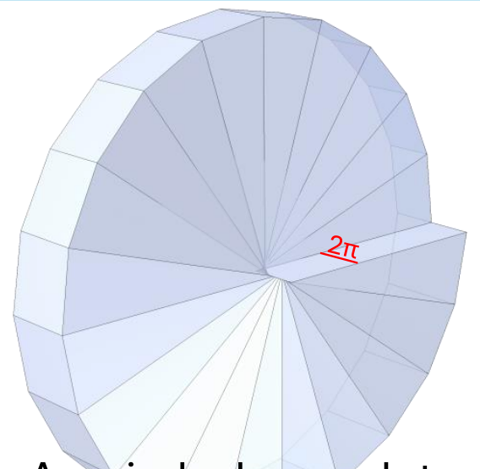
The Spot and SPP configurations

The SPP

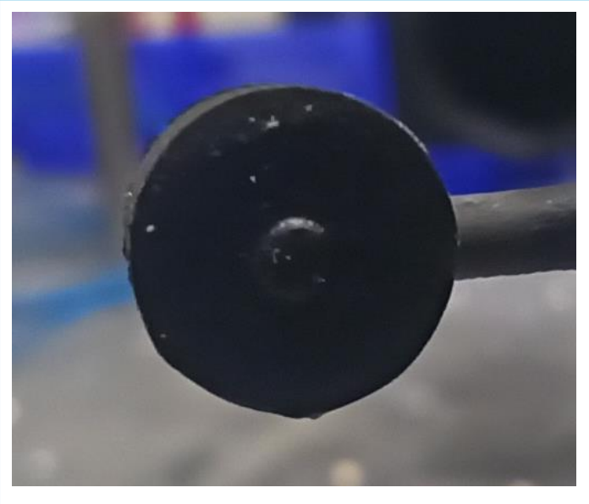
- Adds azimuthal dependent phase
- Periodicity p describes full phases added to energy field distribution
- Needs to get **developed into the far-field image** to avoid inconsistencies in the beam profile
- ➢ Placed in at focal point of a lens, or propagation over a long distance



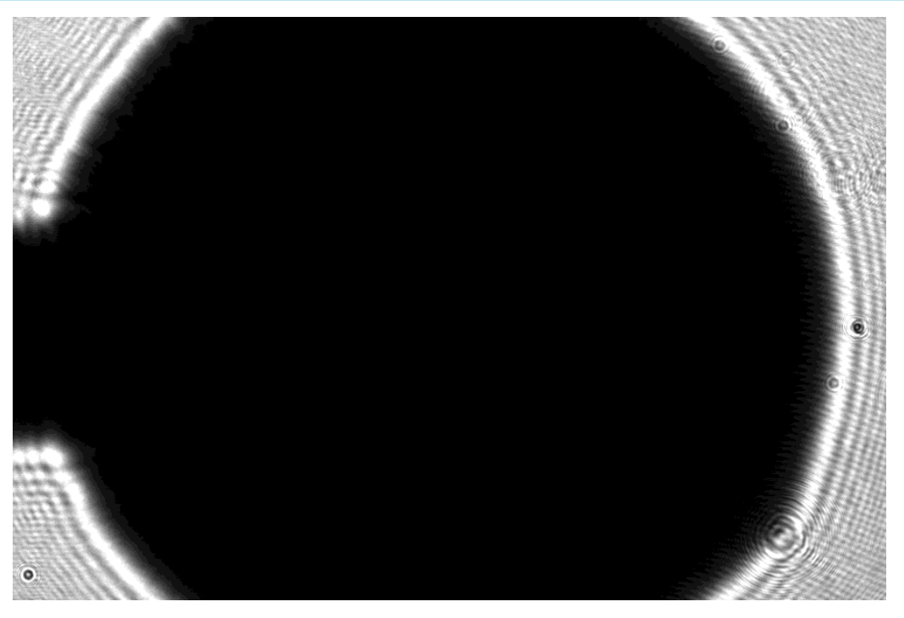
Intensity distribution for $p = 2$ in ff



A spiral phase plate of periodicity of p=1



The Spot, where $d_{spot} = 6mm$



Intensity of the Spot at 10 cm from camera

The Spot

- A round plate in center of the beam or a painted circle on a two-inch glass plate
- No diffraction patterns
- ➢ **Close-field image** of Spot; placed in front of MOT
- Distance to MOT and Spot size varied for optimal configuration

The SPP Configuration

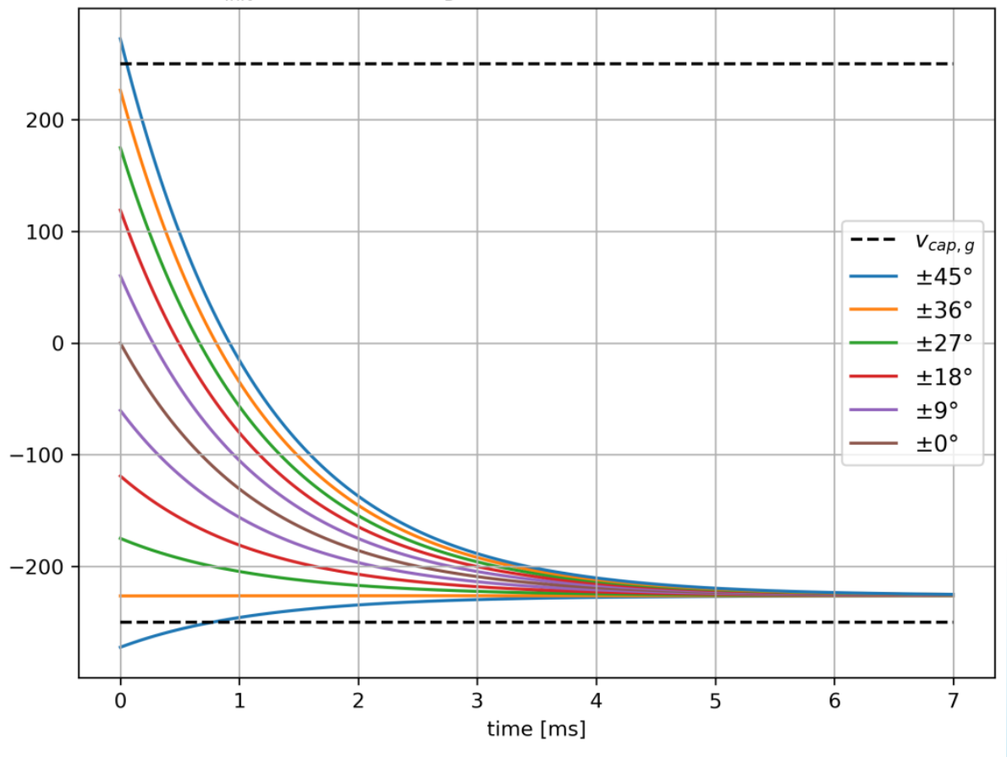
- Goal: Imbalance induced drift speed stays below capture velocity of the green
- For the SPP no sharp intensity drop-offs
- ➢ $I_+(\vec{r}) = (1 + \epsilon(\vec{r}))\, I_-(\vec{r})$

$$v_{imb}(t) = \left(\sin(\alpha) v_{init} + \epsilon \frac{v_a v_\Gamma}{v_a \epsilon + v_\Gamma} \right) \exp\left(- a_{imb} t \frac{v_a \epsilon + v_\Gamma}{v_a v_\Gamma} \right) - \epsilon \frac{v_a v_\Gamma}{v_a \epsilon + v_\Gamma}$$

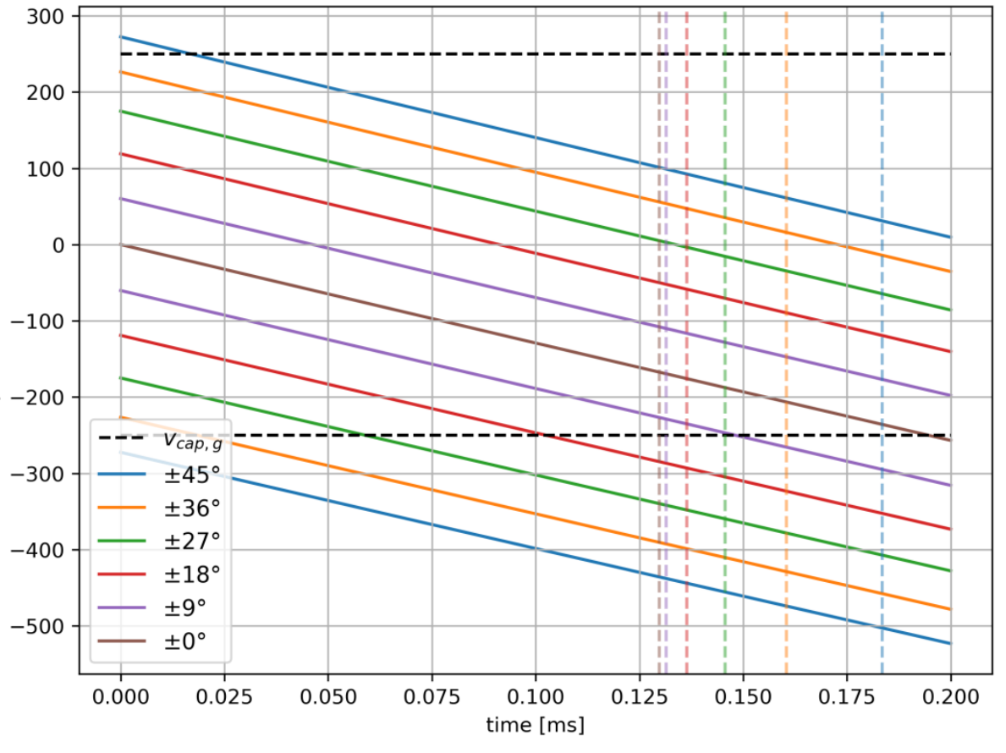
- To weigh low intensity regions, we multiply by s/s_{sat} to get the condition:

$$\frac{|I_-(\vec{r}) - I_+(\vec{r})|}{I_{max}} < 0.3 \text{ in outside region}$$

Finding adjustment conditions



The velocities for different angles $\alpha \angle \vec{e}_r, \vec{v}$ of speed in the imbalance region for $\epsilon = 0.3$. The velocity converges towards a terminal value



The velocities for different angles $\alpha \angle \vec{e}_r, \vec{v}$ for ΔL_Spot<50 µm. The dashed line corresponds to the time spent in the offset area for each α

The Spot Configuration

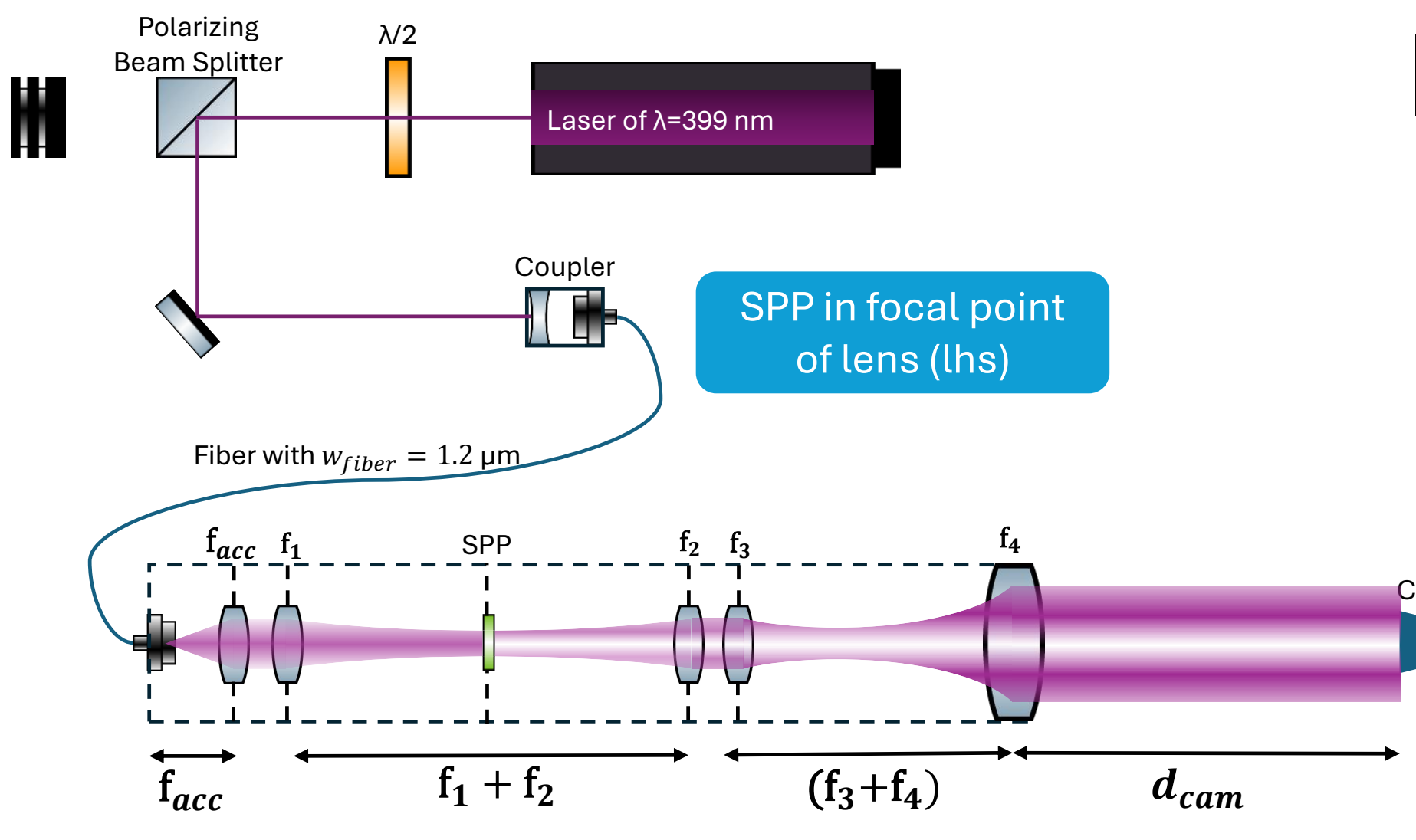
- Goal: Imbalance induced drift speed stays below capture velocity of the green
- Sharp Intensity drop-off in offset region:
- ➢ $I_-(\vec{r}) = 0$

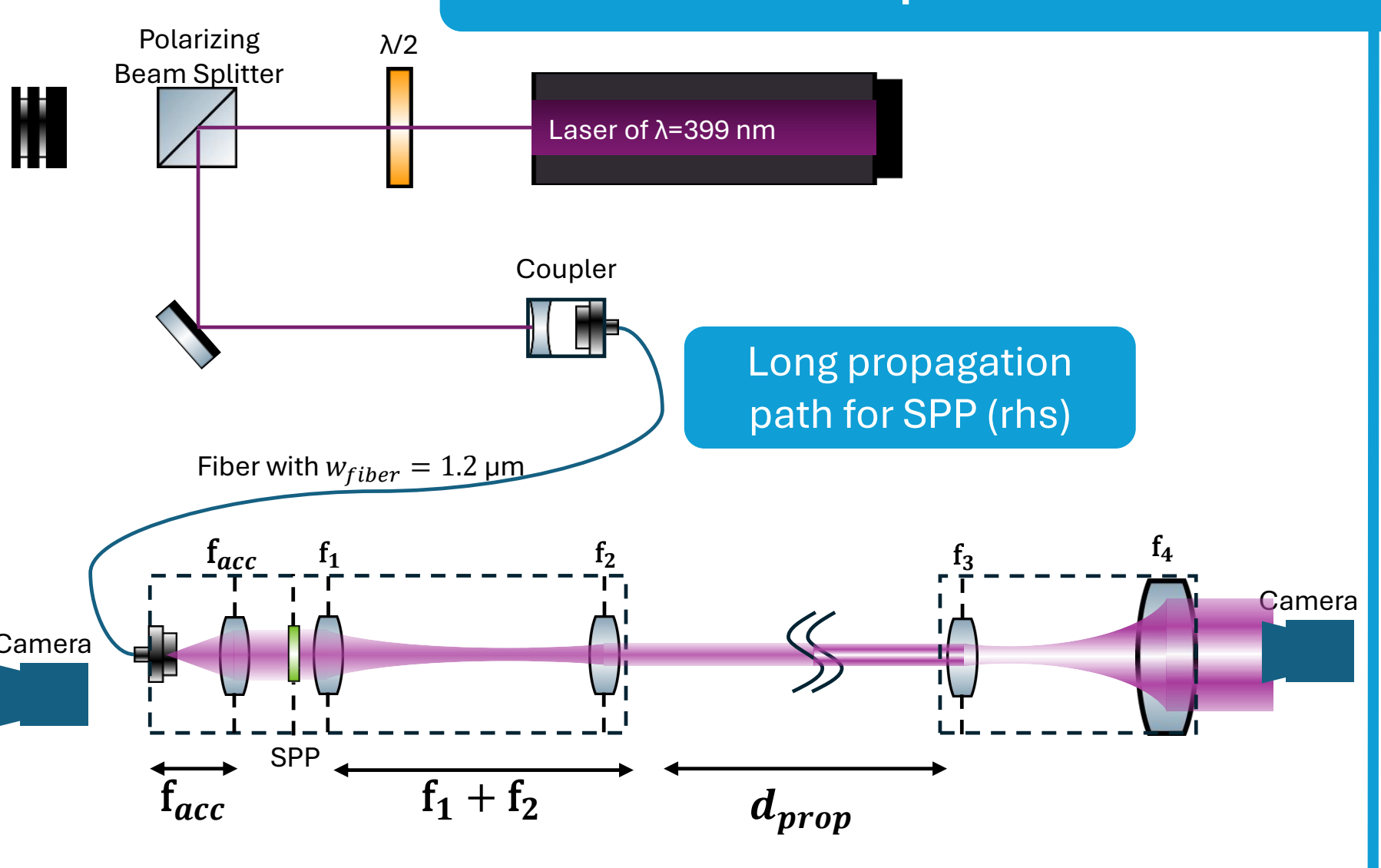
$$v_{offset}(t) = (v_\Gamma + \sin(\alpha) v_{init}) \exp\left(- \frac{a_{imb}}{v_\Gamma} t \right) - v_\Gamma$$

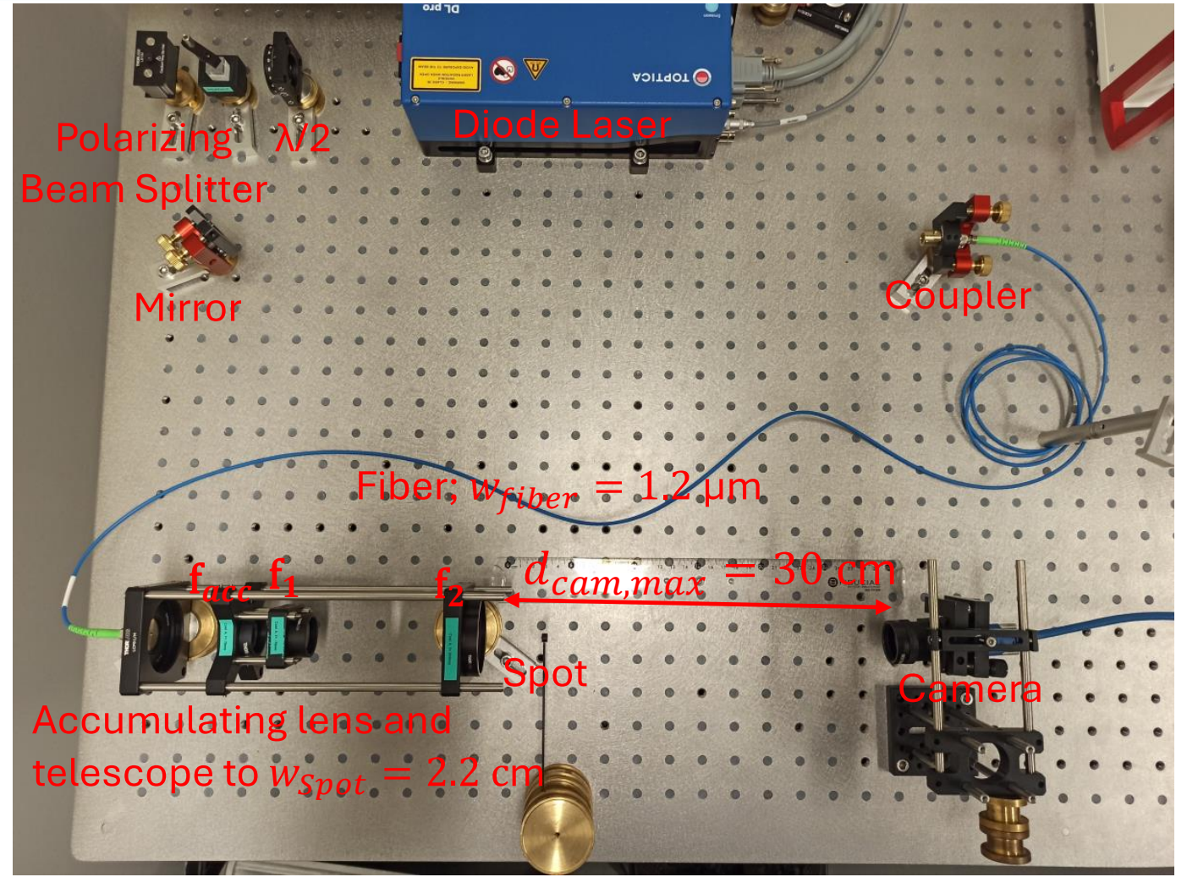
- Initial velocity at typical value for blue trap

$$\Delta L_{Spot} < 50 \text{ µm}$$

Setups that could fulfill the conditions





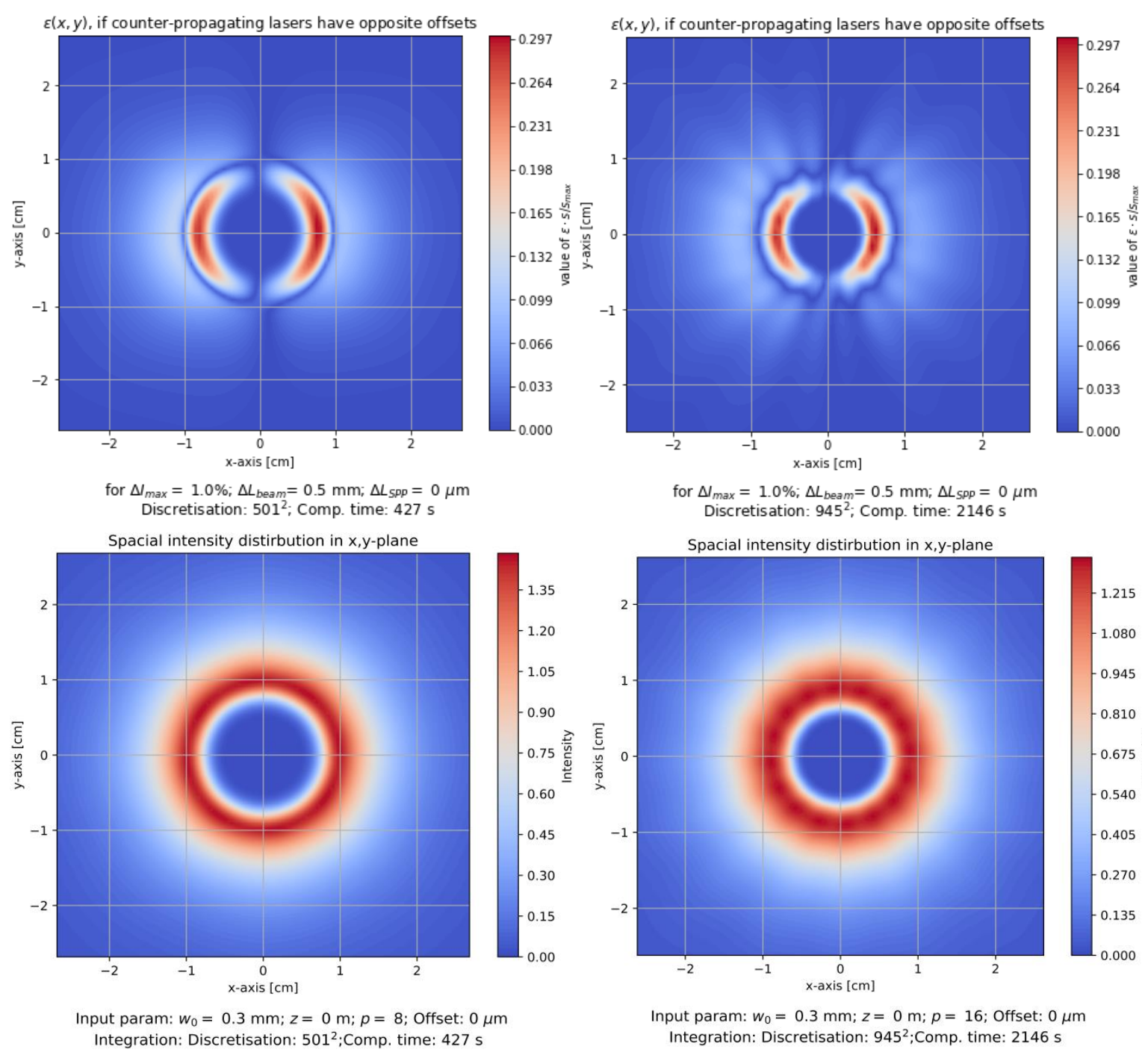


The experimental setup to measure the beam profile

Measurements of beam profile for $r_{Spot} \in \{1.5\, mm, 2.25\, mm, 3\, mm, 4\, mm\}$ for different distances $d_{cam} < 30$ cm to see if 99% intensity reduction is achievable in center

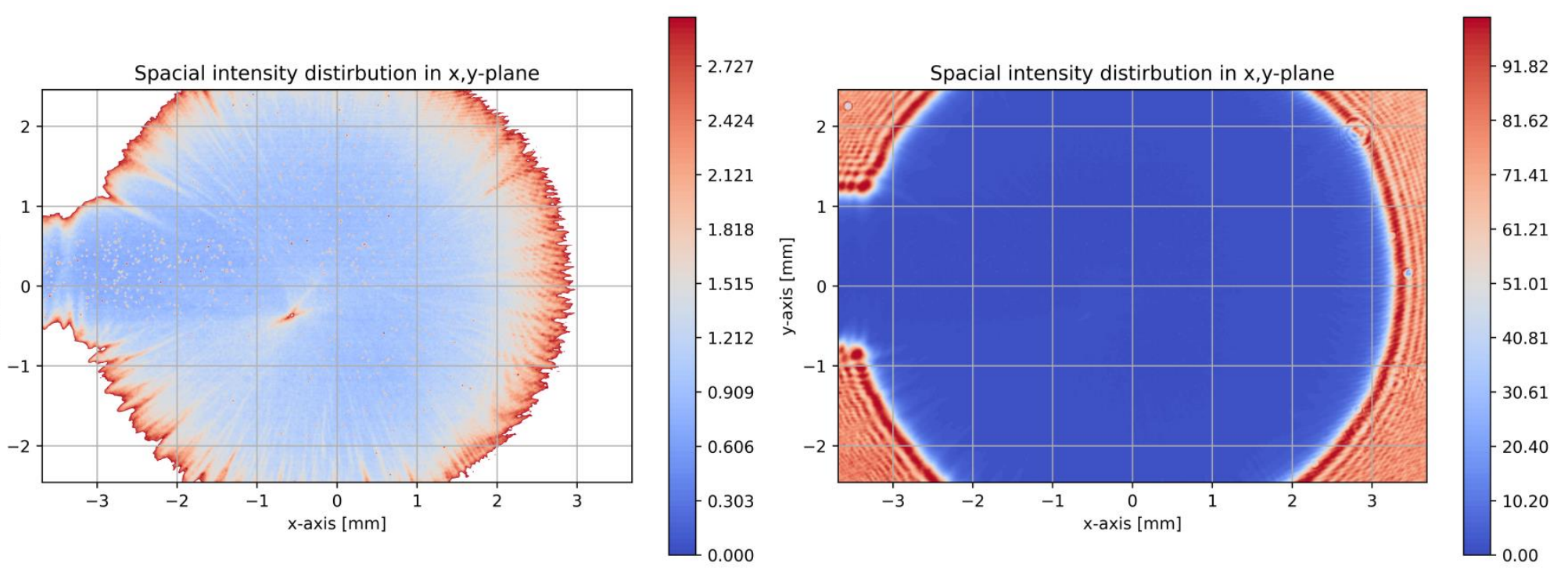
$$\mathbf{f}_{acc} = 75\, mm,\ \mathbf{f}_1 = -75\, mm,\ \mathbf{f}_2 = 200\, mm$$

Parameters for the Setups/ The beam profile



- Condition $\frac{|I_-(\vec{r}) - I_+(\vec{r})|}{I_{max}} < 0.3$ fulfilled at alignment error at SPP of $\Delta L_{SPP} = 10$ µm for $w_{SPP} = 300$ µm
- $\boldsymbol{w_{SPP} = 300}$ **µm not achievable with lhs setup**
- ➢ Rhs setup with $d_{prop} = 50$ cm:
- **Two possible setups for rhs** without f_1 and f_2 :
  - $p = 8,\ f_3 = 30\, mm,\ f_4 = 300\, mm$
  - $p = 16,\ f_3 = 60\, mm,\ f_4 = 300\, mm$

- **True 1%-intensity not achievable**
- Diffraction pattern on edge of plate
- "Stripes" of higher intensities ($\approx 3\%$) leaking into low-intensity region
- Diffraction speckles even at small d_{cam}
- **For** $\boldsymbol{r_{Spot} = 3\, mm}$ **and** $\boldsymbol{d_{cam} < 10}$ **cm stripes don't leak in** $\boldsymbol{r > 2\, mm}$



The measured relative intensities in % for $r_{Spot} = 3\, mm$ and $d_{cam} = 10$ cm on different scales. The high-intensity centered spot (left) appears in every measurement at the same spot and can therefore be ignored

Conclusion

- **Small margin of error for both configurations**
  - $\Delta L_{Spot} < 50$ µm ; $\Delta L_{SPP} < 10$ µm
  - Lense errors and impurities of SPP are not taken into account
- **Effectiveness of SPP and Spot hard to compare**
  - Comparing numerical with experimental results
  - SPP configuration works in theory, the Spot practically
  - Hole size of SPP configuration for high p might be too large
- **SPP configuration more complicated to implement**:
  - More parts
  - Higher alignment requirements
  - Takes up more space

The Spot configuration is better suited for the atom cooling experiment

Bibliography

[1] Lettelier, H., t.b.defended 2024, *Piegeage magnéto-optique de l'ytterbium sur la transition* $´^1S_0 \rightarrow ^1P_1$, Ph.D. thesis, Universite Côte d'Azur.
[2] Mcclelland J. J. et. al, 2015,*Bright focused ion beam sources based on laser-cooled atoms,* Applied Physics Reviews
[3] Alvaro Mitchell, t.b.def. 2024*, Refroidissement laser de l'ytterbium sur la ligne d'intercombinaison pour des expériences sur la localisation de la lumière*., Ph.D. thesis, Institut de Physique de Nice
[4] Vortex Photonics, visited last 15.06.2024, https://vortex-photonics.de/vortex-lenses-spiral-phase-plates.html
[5]Dalibard, J., 2014, *Lecture on Laser cooling of atomic gases, English version* (Collège de France).