DIGITALLY ENHANCED QUANTUM
TECHNOLOGY MASTER

Laser Cooling and Magneto-Optical Traps: From Classical Response to Real Atoms

Heidelberg Center for Quantum Dynamics, University of Heidelberg

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Course Overview

This course introduces the principles of laser cooling and trapping of neutral atoms, culminating in the experimental realization of a Magneto-Optical Trap (MOT). The central goal is to build a complete understanding of the MOT starting from classical light–matter interaction and directly connecting to a real experimental platform.

The course combines theoretical foundations, numerical simulations, and hands-on laboratory work, providing a coherent bridge between fundamental physics and modern quantum technologies.

Learning Objectives

After completing the course, students will be able to:

- Explain light–matter interaction from the Lorentz model to quantum optical forces
- Derive and interpret radiation pressure and Doppler cooling mechanisms
- Understand the physical principles underlying MOT operation
- Analyze experimental data from cold atom systems
- Connect theory, simulation, and experiment in quantum systems

Course Structure

1. Classical Light–Matter Interaction (Lorentz Model)

- Driven harmonic oscillator, radiation damping, steady-state response
- Induced dipole moment and polarizability
- Real and imaginary parts: dispersion and absorption

2. Optical Forces and Laser Cooling

- Radiation pressure and scattering force
- Doppler effect and optical molasses
- Doppler cooling limit
- Spatially dependent forces in magnetic fields

3.Semi-classical approach Beyond the Lorentz Model

- AC Stark shift and dressed atom picture
- Spontaneous emission and fluorescence
- Sub-Doppler cooling mechanisms

4. Magneto-Optical Trap (MOT)

- Zeeman effect and magnetic field gradients
- σ^+/σ^- polarization
- Position-dependent restoring force

5. Experimental Realization (The student MOT experiment)

- Laser systems and frequency stabilization
- Vacuum systems and atomic sources
- Magnetic coils and field control
- Imaging and detection

6. Data Analysis

- Fluorescence signals and atom number
- Loading curves and system dynamics
- Dependence on detuning and experimental parameters

Teaching and Learning Activities

- Interactive lectures and guided derivations
- Simulation exercises (optical forces, cooling dynamics)
- Hands-on laboratory work with a real MOT setup (minimum 5 hours)
- Data analysis and interpretation tasks

Workload and DigiQ Points

Total workload: $\sim$40–50 hours (lectures, simulations, laboratory, assignments)
Equivalent to: **2 DigiQ points** (1 point per 20–25 hours)

DigiQ Qualification (Augmentation Types)

- **A – Module:** Interactive use of theoretical and simulation modules (Lorentz model and optical forces)
- **F – Physical Augmentation:** Hands-on MOT experiment accessible to DigiQ students
- **E – Shared Materials:** Lecture notes, simulations, and experimental resources shared within the network

Accessibility and Integration

The course is designed as a modular, hybrid offering that can be integrated into existing MSc programs. Experimental infrastructure is available for visiting students, enabling direct connection between DigiQ coursework and laboratory experience.