Quantum Guide
Hollow-core fiber atom guide for quantum devices

University of Bonn, Germany
Paul Scherrer Institut, Switzerland
Nicolaus Copernicus University in Toruń, Poland
TU Darmstadt, Germany
Alpine Quantum Technologies, Austria

Introduction/Background/Motivation

- Many quantum technologies are built around the manipulation of isolated atoms in ultra-high vacuum systems. Yet, the source of these atoms generally comes in the form of an "oven" which operates at elevated temperatures and under much higher pressures, leading to increased background gas load and unavoidable contamination of surfaces in the vicinity of the source. In many cases, mitigating the potential contamination results in a much larger device footprint than would technically be required - simply to allow for sufficient differential pumping and isolation between "core" and "loading" sections of an apparatus. The QuantumGuide project aims to fundamentally solve this problem through the development of a fiber-based delivery system for atoms based on laser guiding through a hollow-core photonic crystal fiber.
- Building on established and already demonstrated concepts in this area, we will develop and experimentally verify a framework that allows for a tailoring and performance prediction of the delivery system to specific use cases, which include optical lattice clocks, trapped-ion based quantum computers and quantum simulators. Specifically, we will demonstrate fiber-based delivery of neutral atoms (Ca, Hg, Rb, Sr) to both room temperature and cryogenic experimental platforms, characterizing loading and leak-rates as well as the effective atom temperatures under different operating regimes.
- We further expect our framework and experimental designs to be applicable to a wider range of scientific applications such as the synchrotron and X-ray free electron laser beamlines, available at one of our partner institutions.

Efficient loading of alkaline-earth-metal atoms into fibers

- Almost all fiber-loading experiments to date have been performed with alkali atoms. We will advance to alkaline-earth metal elements, which are employed for optical clocks and ion traps.
- These species have various transitions for laser cooling: very broad transitions for fast and efficient slowing and trapping, and very narrow transitions to reach low temperatures. These elements also offer multiple possibilities for state-selective detection with high sensitivity.
- We will explore the most efficient way to cool, detect, and load strontium and calcium atoms into fibers.

Hollow-core fibers in a cryogenic environment

- Surface ion traps in cryogenic environments offer a path to scalable ion-trap quantum computing.
- Photonic waveguides have been integrated in these devices, enabling the delivery of laser beams through optical fibers fed in from room temperature laser sources.
- We will explore the achievable performance of the QuantumGuide source by investigating the behavior of hollow-core photonic crystal fibers in this context.

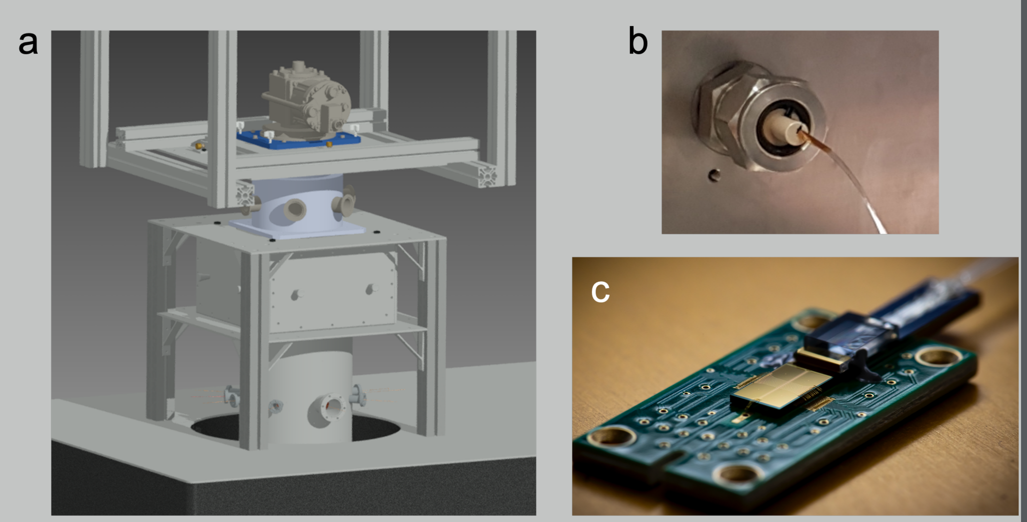

Figure 1:Cryostat assembly (a) hosting a surface ion trap with integrated photonics [1] (c) where laser beams are supplied through a fiber-bundle fed in (b) from room temperature.

Extending fiber lengths to the meter scale

- So far, cold atoms have been transported through hollow-core fibers of lengths below **30** cm. The transport distance was limited by atomic collisions within the fiber, variations of the guiding potential, and heating.
- Despite no radial access to detect atoms inside the fiber, spatially-resolved detection and determination of loss rates was recently demonstrated [2].
- We will employ spatially-resolved detection to identify and minimize loss rates within the fiber through a combination of baking, in-fiber cooling, and controlled acceleration to advance the transport distance into the regime of meters.

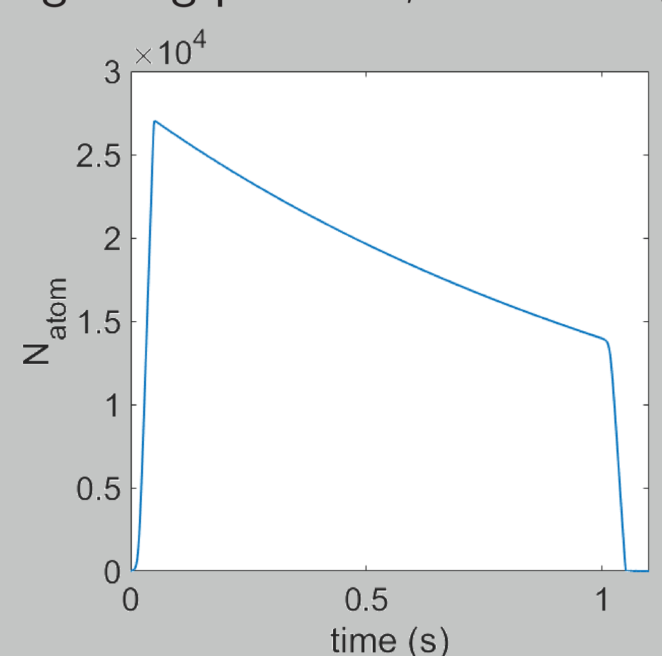

Figure 2:Simulation of the number of atoms inside a hollow-core fiber of **1** m length vs time for optimized loss rates.

Atoms on demand

- **Pulsed source.** A pulsed source of fiber-guided atoms can be generated by time-dependent loading or by time-dependent acceleration and deceleration of atom bunches within the fiber.
- Continuous source. A continuous flow that can be tuned in flux rate can feed e.g. an active optical clock or a Ramsey-Bordé-type clock (see Fig. 3).
- **Acceleration of atoms within the fiber.** Tuning the frequency difference of two counter-propagating modes of a light field allows for the creation of a moving optical lattice that acts as a conveyor belt.

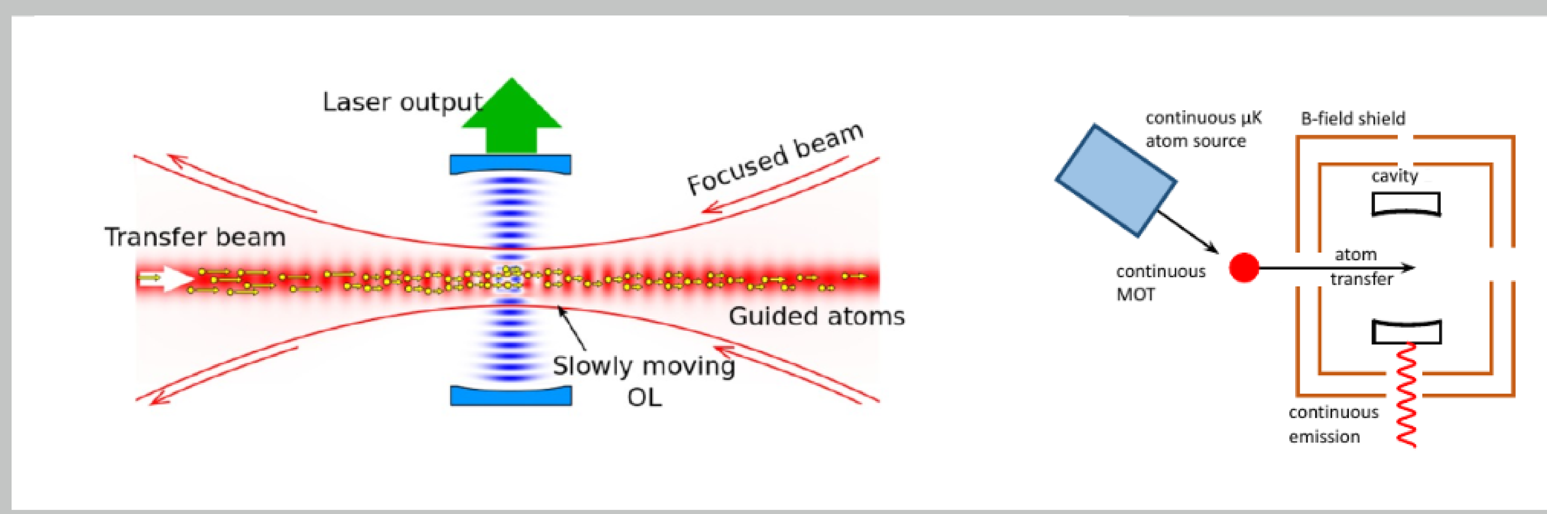

Figure 3:Left: conceptual scheme of a continuous superradiant laser. Right: realization of a continuous superradiant laser under construction at UMK.

Demonstrator

- A proof-of-concept setup that allows for controlled loading of a quantum processing unit with neutral atoms or ions.

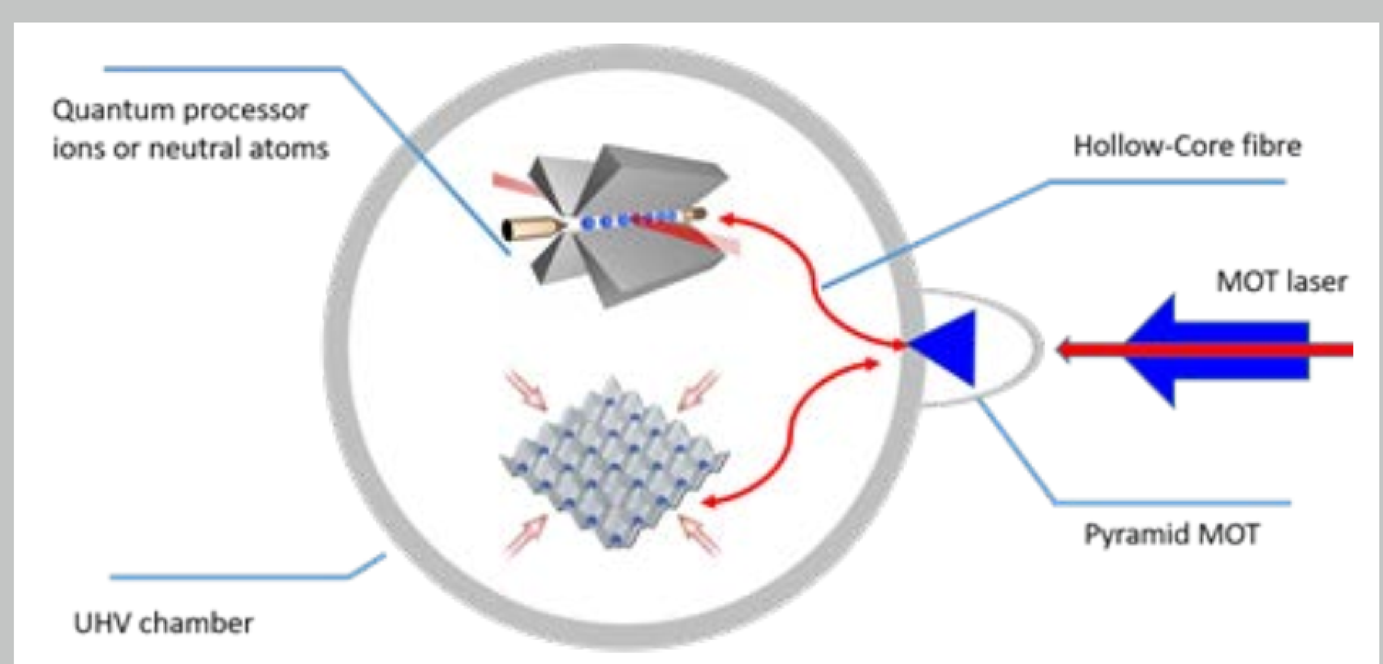

Figure 4:Concept of a pyramid MOT which is attached to a vacuum chamber. A dipole laser can transfer ultracold atoms through the hollowcore fibre towards quantum processors such as trapped ions or optical lattices for neutral atoms. The pyramid MOT could also be placed further away from the UHC chamber.

References

1. K. K. Mehta *et al.*, Integrated optical multi-ion quantum logic, Nature **586**, 533 (2020).
2. T. Peters *et al.*, Loading and spatially resolved characterization of a cold atomic ensemble inside a hollow-core fiber, Phys. Rev. A **103**, 063302 (2021).

Contact: stellmer@uni-bonn.de, marcin.w@umk.pl