INNOVATION RADAR QUESTIONNAIRE

PROJECT	
Project number:	**820404**
Project name:	**Integrated Quantum Clock**
Project acronym:	**iqClock**

1. INNOVATIONS

SUMMARY OF PROJECT INNOVATIONS *(mandatory)*

Please see the instructions below regarding good vs. poor innovation titles.

1	Comb-stabilized suite of lasers for cold-atom quantum sensors
	Frequency combs are precision instruments essential for time dissemination with optical atomic clocks. At the same time, they provide frequency stabilization for all laser systems required for trapping, manipulating, and interrogating ultra-cold atoms inside a suitable ultra-high vacuum system. Conventionally, these systems are stationary. Here, however, a transportable, rack-based system has been developed by Toptica without any compromise in performance when compared to stationary systems. This has been made possible through a consistent, drawer-based layout and smart design choices for stabilizing these drawers.
2	Transportable clock laser as precision frequency reference
	The clock laser is the essential flywheel in the contemporary system design of optical atomic clocks. It serves the purpose of extracting a frequency reference signal from the reference atom species. The system is very sensitive to environmental factors, in particular to temperature variations and mechanical vibrations. Hence, it is a significant challenge to build this narrow-linewidth laser and its dedicated optical reference cavity in a robust and transportable fashion. Here, the system developed by Toptica is contained in a stabilized and thermally isolated box and an accompanying rack-mountable drawer. Overall, the clock laser design provides a compact layout and improved robustness for a transportable optical lattice clock.
3	Fiber cable for stable, low-loss, near-universal wavelength delivery
	Laser wavelengths for cooling and atom manipulations should be delivered to atom traps stably by polarisation-maintaining optical fiber. Typically one needs to guide multiple different wavelengths throughout the visible spectrum and extending slightly into the UV and NIR. However, step index optical fiber cannot transmit over broad bandwidths in the visible, and therefore are a limiting technology for quantum technologies. NKT has developed a micro-structured fiber and replaced the usual air holes with a doped glass. This therefore achieves broadband transmission and allows the fiber end to be polished into a connector without an end-collapse. This represents a valuable innovation, as this broadband fiber can now be pigtailed with, for instance, FC/APC and interface with another fiber without the need for free-space coupling.

4	Highly-stable rack-mountable light distribution system
	The generation, manipulation, and interrogation of ultra-cold atom samples serving as quantum reference requires sophisticated timing and modulation of optical signals (laser light). The light distribution system created by UoB provides a flexible, rack-mountable drawer design with optimized mechanical stability. The drawers can house all necessary optical and acoustic/electronic-optical modulators required for the operation of cold-atom based quantum sensors.
5	Transportable atomics package for generation of ultra-cold trapped atoms
	Optical atomic clocks for out-of-lab operation require robust subsystems. A central system is the atomic package, which comprises an ultra-high vacuum system, including an atom source and a trapping chamber with user-defined optical access, as well as coil systems and monitoring equipment. The modular subsystem developed by Te2v considers thermal management, shielding of laser light, and convenient interfacing with the other subsystems of an optical atomic clock.
6	UHV-compatible ultra-black coatings for quantum sensors
	Stray radiation within the containment chamber for ultra-cold atoms is a problem because it reduces signal quality from the ultra-cold atoms that serve as “quantum probes”. The ultra-black coatings developed by ACKTAR are capable of absorbing a large share of the stray radiation at the relevant optical and infrared wavelength used in common cold-atom based quantum sensors and thus help to improve measurement precision.
7	Computer control system for cold-atom quantum sensors
	Cold-atom based quantum sensors require a number of control and interface systems for operation. The computer control system created by Te2v provides all the means required to operate complex sensors such as an optical atomic clock. It includes provisions for analogue and digital input and outputs, frequency modulation, and special interfaces such as high-voltage outputs to operate ion pumps. The control system includes an embedded computer which runs software that allows users to build user-specific operation sequences, tailored to the quantum sensing task.
8	UTC-rack with low-noise frequency down-converter for precision time dissemination
	When developing state-of-the-art timing facilities, it is important to have a facility based on proven technology for benchmarking the performance of the novel system. The capability to interface such existing technology with the optical atomic clock technology developed in iqClock and elsewhere is crucial. Hence, Chronos’ frequency converter provides the means to ‘translate’ the output of an optical frequency comb referenced to an optical atomic clock to signals compatible with existings timing and network infrastructure.
9	Transportable telecom network simulator for evaluation of optical frequency references
	Testing timing equipment in real-world use cases requires a safe ‘sandbox’ for performing the initial demonstrations. The compact (half-rack), transportable network simulator created by BT is a helpful device for running the first test prior to a larger field trial. The compactness allows its operation with a number of laboratory based facilities which, in turn, is a convenient and efficient way to establish baseline performance measurements informing on the next step of a larger-scale system demonstration.
10	Continuous ultracold atom sources for atom interferometers and optical clocks
	UvA has developed continuous strontium sources with high phase-space density. 87-Sr can be continuously provided in a narrowline magneto-optical trap [Phys. Rev. Research **3**, 033159 (2021)], 88-Sr as a high phase-space density beam [Phys. Rev. Applied **12**, 044014 (2019)] and 84-Sr as quantum degenerate gas [arXiv:2012.07605, accepted by *Nature*].

	These continuous Sr sources will make possible a new generation of ultracold atom sensors, in particular improved atom interferometers and continuously operating passive (traditional) and active (superradiant) Sr clocks. Continuous operation promises increased measurement bandwidth and can help to achieve higher accuracy. Superradiant clocks use a different operating principle than traditional optical clocks, which should make them less sensitive to vibrations and more suitable for operation in adverse environments, such as on moving platforms. Real-world applications may thereby come closer, e.g. in geodesy, network synchronization or navigation.
11	Electronics framework for optical atomic clocks
	UMK has developed an open-source hardware and software ecosystem for optical atomic clocks. We provide PCB schematics and fabrication files for manufacturing the most important electronic systems together with the required software. The boards are designed for an active bad-cavity superradiant strontium clock and a passive optical lattice strontium clock, but they can be easily adapted to other atomic species optical atomic clocks or ultra-cold atoms' systems like magneto-optical traps or Bose-Einstein Condensate set-ups.
12	Open-Source Numerical Framework for Simulating Quantum Systems
	Numerical simulation of quantum systems is not only memory and computing time intensive task but usually requires complex coding and testing. Nevertheless in different implementations it is mostly a finite set of generic operators to be implemented and time evolutions to be solved. UIBK provided a user-friendly and well tested generic implementation for a quantum simulation framework, which can be easily generalized to various hardware platforms besides cold atoms and cavities. First add-on packages on ion quantum gates are already developed in other groups.
13	Nanoscopic Structure for Creating Coherent Light
	UIBK showed that a rather small well controlled array of quantum emitters can be the generic basis for a future minimalistic generation of nano optical devices. While the concrete technical implementation is still open (tweezers, quantum dot arrays or molecules in DNA origami setups) we could show that subwavelength coherent light sources, single photon sources or even controlled photon pair sources are in principle in range of this technology.