

Master 2 Internship / PhD Proposal:

Optimizing a Single-Shot Quantum Measurement in Finite Time

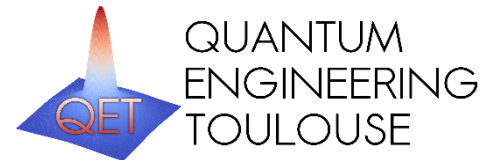
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Thesis possibility after internship: **YES (funding acquired)**

Context and scientific premise: Quantum sensing is one of the most advanced areas of quantum technologies, and has already resulted in practical applications [1]. Theoretically, detection limits may be improved and optimized by relying on quantum entanglement and/or large amounts of data [2]. A more practical goal however, is to maximize the amount of information that may be extracted from a single measurement in a finite amount of time, optimizing the usage of resources. This is the objective pursued in this project, which combines quantum optimal control and estimation theory based on Fisher information. For the estimation of a given parameter, we seek to derive control fields that will maximize the accuracy of a single-shot measurement in a finite time, by ensuring the classical Fisher information is maximized, reaching its quantum limit, and to demonstrate them experimentally.

By characterizing speed limits for such realistic protocols, and including robustness against relevant noises, this project aims to provide operational bounds for multi-parameter quantum sensors, and control strategies that will be transferable to other platforms.

Experimental platform and objectives: We plan an implementation on Bose-Einstein condensates, which provide a macroscopic quantum object that can be manipulated in optical lattices of various dimensionalities and geometries. Both the depth of the periodic trap structure and its position can be manipulated by precise modulation of the intensity and phase of laser beams. The project builds upon recent proof-of-principle experiments on state-to-state controlled preparation that we performed in a one-dimensional lattice [3,4], and which support the feasibility an extension to higher dimensionalities.

A first experimental objective is to demonstrate such optimal controls in the measurement of an unknown vector force in 2D. Such a force can be applied through magnetic or optical field gradients, or as an inertial force in an accelerated lattice. Besides ensuring the maximization of Fisher information, the control field design will have to mitigate the deleterious effect of the quasimomentum width (velocity dispersion) of the condensate (resulting from its finite size) and possible fluctuations of experimental parameters. This will require the progressive extension of control protocols to more robust realistic ones.

This initial force sensing demonstration will further open the way to rotation measurements (either directly driven on the experiment or alternatively emulated with artificial gauge fields [5,6]), and to the precise measurement of the atom-atom interaction strength parameter [7].

Methodology: On the theoretical and numerical side, the guiding idea is to synthesize control fields that drive the classical Fisher information to saturate the quantum bound in a finite time.

The design of practical control fields will have to account for hardware constraints (bounded amplitudes, phase and intensity slew-rate limits, and finite actuator bandwidths) together with robustness with respect to auxiliary parameter fluctuations.

We intend to initially employ gradient-based quantum optimal control (GRAPE/Krotov variants) alongside reinforcement learning to explore the control landscape. As in previous project, we expect the PhD student to gain hands-on experience and autonomy in the numerical techniques.

The experimental implementation will rely on the expertise of the UT group in cold atom manipulation, in the recently built lab space that ensures stability for complex experimental setups, with local engineering support in specialized optics and hardware interfacing. The setup development will ensure that modulated controls can be fully characterized and monitored at every stage. The collective wavefunction of the Bose-Einstein condensate allows for single-shot readout either of spatial or momentum distributions.

References

- [1] C. L Degen et al. Rev. Mod. Phys. 89, 035002 (2017).
- [2] P. Asenbaum et al. Phys. Rev. Lett. 125, 191101, (2020); R Gautier, et al. Science Advances 8, eabn8009 (2022).
- [3] N. Dupont et al., PRX 2, 040303 (2021).
- [4] E. Flament et al., PRR 7, 033069 (2025).
- [5] J. Dalibard, et al. Rev. Mod. Phys. 83, 1523 (2011).
- [6] Y.-J. Lin, et al. Nature 462, 628 (2009).
- [7] E. Dionis, et al. Front. Quantum Sci. Technol. 4, 1540695 (2025).