PROGRAMME INSTITUTS ET INITIATIVES

Appel à projet – campagne 2021

Proposition de projet de recherche doctoral (PRD)

QICS - Quantum Information Center Sorbonne

Intitulé du projet de recherche doctoral (PRD): MecaFlux

Directrice ou directeur de thèse porteuse ou porteur du projet (titulaire d'une HDR) :

NOM : **Heidmann** Prénom : **Antoine**
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Unité de Recherche :
Intitulé : Laboratoire Kastler Brossel
Code *(ex. UMR xxxx)* : UMR 8552

École Doctorale de rattachement de l'équipe (future école doctorale de la doctorante ou du doctorant) : **ED564-Physique en IdF**

Doctorantes et doctorants actuellement encadrés par la directrice ou le directeur de thèse (préciser le nombre de doctorantes ou doctorants, leur année de 1e inscription et la quotité d'encadrement) : 1, 2020, 100%

Co-encadrante ou co-encadrant :

NOM : **Deléglise** Prénom : **Samuel**
Titre : Chargé de Recherche ou HDR ☐
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Unité de Recherche :
Intitulé : Laboratoire Kastler Brossel
Code *(ex. UMR xxxx)* : UMR 8552

École Doctorale de rattachement : **ED564-Physique en IdF**
Ou si ED non Alliance SU :

Doctorantes et doctorants actuellement encadrés par la directrice ou le directeur de thèse (préciser le nombre de doctorantes ou doctorants, leur année de 1e inscription et la quotité d'encadrement) : 0

Co-encadrante ou co-encadrant :

NOM : **Jacqmin** Prénom : **Thibaut**
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École Doctorale de rattachement : **ED564-Physique en IdF**
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Doctorantes et doctorants actuellement encadrés par la directrice ou le directeur de thèse (préciser le nombre de doctorantes ou doctorants, leur année de 1e inscription et la quotité d'encadrement) :0

Cotutelle internationale : ☒ Non ☐ Oui, précisez Pays et Université :

Selon vous, ce projet est-il susceptible d'intéresser une autre Initiative ou un autre Institut ?
☒ Non ☐ Oui, précisez Choisissez l'institut ou l'initiative :

Description du projet de recherche doctoral ***(en français ou en anglais) :***

Ce texte sera diffusé en ligne : il ne doit pas excéder 3 pages et est écrit en interligne simple.

Détailler le contexte, l'objectif scientifique, la justification de l'approche scientifique ainsi que l'adéquation à l'initiative/l'Institut.

Le cas échéant, préciser le rôle de chaque encadrant ainsi que les compétences scientifiques apportées. Indiquer les publications/productions des encadrants en lien avec le projet.
Préciser le profil d'étudiant(e) recherché.

Objectives: This thesis experimental project aims at demonstrating strong resonant coupling between a long-lived quantum memory in the form of a nano-mechanical resonator, and a qubit. This strongly interacting quantum system will be used to demonstrate an original qubit-assisted cooling scheme, the generation of arbitrary phononic states such as Fock states or Schrödinger cat states, and to perform experimental tests of gravitational collapse models.

Motivation: Controlling the quantum state of a mechanical system is a long-standing scientific goal, with profound implications in both fundamental physics and engineering of hardware for quantum computation and quantum information. From a fundamental perspective, massive mechanical resonators placed in a quantum superposition are promising candidates to study potential deviations from quantum physics induced by gravitational decoherence [1]. On the other hand, mechanical resonators are a unique resource for quantum engineering as they can store fragile quantum states in long-lived mechanical oscillations [2]. Moreover, mechanical resonators could play an important role as quantum transducers, connecting otherwise incompatible quantum systems [3], for example superconducting circuits and optical photons [4], or for sensing spins in a solid state matrix [5]. The field of quantum optomechanics addresses this challenge by coupling a mechanical resonator to a high-frequency microwave or optical cavity. A decade-long quest for low-mass and low dissipation mechanical resonators has led to a new generation of optomechanical systems, where quantum radiation pressure strongly dominates over thermal noise [6]. This has enabled a number of breakthroughs, such as ground-state cooling [7], or the optomechanical generation of squeezed states [8]. However, the standard optomechanical framework suffers a major deficiency: the mechanical and electromagnetic modes are coupled via a linear effective interaction. Their dynamics can thus be entirely captured by a semi-classical model, where the system is described at all times by a positive Wigner function embodying a classical probability distribution in phase space.

State of the art: The most direct approach to go beyond this linear regime is to exploit the resonant coupling between a mechanical mode and a superconducting qubit to control the mechanical quantum state [2, 9–11]. However, in spite of recent breakthroughs, such as the demonstration of multi-phonon Fock states [2], it is restricted to GHz resonators, with short coherence times. Extending such schemes to MHz mechanical resonators would open intriguing perspectives, as ultra-coherent mechanical systems recently developed in the optomechanics community have demonstrated unprecedented force sensitivities [12], and lifetimes in the minute range [13–15]. The main difficulty stems from the large frequency difference between the mechanical resonator and the superconducting circuit, typically operating at GHz frequency. Many routes have been pioneered, but none of them proved fully satisfying: either the qubit coherence properties are poor [16], or the fidelity of the mechanical mode state is very small [17].

Approach followed in this thesis project: We propose a resolutely new approach that will enable full quantum control of a mechanical resonator operating in the 3-30 MHz range and with a lifetime >10 s. This parameter regime makes it an appealing candidate for quantum sensing, quantum information storage, and experimental tests of quantum gravity. We will overcome the frequency gap between this mechanical object and superconducting quantum circuits by coupling the former to a strongly non-linear circuit: the fluxonium qubit [19]. At a particular bias point, this circuit presents a low-frequency qubit manifold which is protected simultaneously against flux noise and energy relaxation. This new qubit paradigm has recently outperformed the transmon architecture [20], which constitutes the current quantum computing standard. Eventhough the qubit manifold lies well below the frequency range accessible with standard microwave components, the rich level structure of higher qubit excited states allows for its efficient readout, reset, and manipulation. Opportunely, the frequency of the qubit manifold in the heavy fluxonium regime [20, 21] naturally matches the mechanical resonance frequency of the ultracoherent mechanical membranes envisioned here. The large capacitive shunt of the heavy fluxonium is also perfectly compatible with a capacitive coupling scheme.

Mechanical resonator implementation: The mechanical resonator which is at the heart of this project is a softly-clamped [14] silicon-nitride membrane developed at LKB [15] with an ultra-low dissipation rate of $\Gamma<(30\ \ /s)$ [22]. The mechanical modes are well localized within the defects of a phononic bandgap that is directly etched in the 100-nm thick Si_3N_4 membrane, and can be engineered to present an anti-symmetric vibration pattern. We have recently demonstrated that the membrane could serve as the electrode of a planar capacitor by depositing a metallic pad on the mechanical antinode [22].

Qubit implementation: The fluxonium qubit is composed of a Josephson junction (JJ) shunted by an extremely large inductance. This inductance cancels charge carrier noise across the JJ, and together with a large capacitive shunt and the JJ, result in a system with transitions in the MHz range with very good coherence properties. The large inductance will be implemented with on arrays of JJs [19].

PhD candidate work: The PhD candidate would first have to estimate the coupling between the qubit and the mechanical mode. As the qubit transition has a low frequency, prior to any protocol implementation, the qubit needs to be actively set in its ground state. For this purpose, GHz-range transitions to higher qubit excited states can be used to evacuate the system's entropy into an effective zero-temperature bath [20]. Then he will investigate and implement qubit-assisted cooling, to set the mechanical mode in its ground state. Finally, he will use these higher frequency qubit transitions to prove readout of the dressed qubit-resonator system [20]. An additional scientific aim will be the quantum manipulation of the membrane and perform tests of gravitational collapse models.

The PhD candidate will develop skills in: finite element analysis (both in the mechanical and electromagnetic domains), microfabrication in clean rooms of the Paris area, optical characterization of silicon nitride resonators and microwave experiments in a cryogenic environnement. He will work in close collaboration with the Quantic team of LPENS (Zaki Legthas), the teams of Emmanuel Flurin and Hélène Lesueur at CEA, and the Alice&Bob spinoff of ENS.

Adequation between the project and the call: This quantum information project falls into the "Hardware and foundational aspects" category of the QICS call.

PhD advisors: Antoine Heidmann (DR), head of the Quantum Optomechanics group at LKB, will be the PhD director. Samuel Deléglise (CR) would be the co-director, and Thibaut Jacqmin (MCF) would be the second co-director. Antoine Heidmann pioneered the field of optomechanics twenty years ago, and will be the reference for optomechanics. Samuel Deléglise has a strong experience in CQED and optomechanics. The last five years he started to perform experiments with superconducting circuits and built many strong collaborations with groups specialized in that field. These collaborations lead to important scientific results [18]. He also originated CryoParis the "Plateforme cryogénique de Sorbonne Université" where the experiments performed during this thesis will be implemented. This platform has now a fully equipped Bluefors dilution cryostat. Thibaut Jacqmin has been working in close collaboration with Samuel Deléglise for the past six years. He has a strong experience in clean room micro-fabrication, optical characterization of mechanical samples and FEA simulations. He contributed to the state of the art phononic crystal resonators that were recently demonstrated in the group and that will be at the heart of this project.

Owing to their extreme aspect ratio and large tensile stress, ultracoherent membranes are very delicate objects that require precise control at every step of the microfabrication process. LKB is one of a handful labs in the world able to interface such systems with superconducting circuits. Moreover, our consortium gathers some of the best experts in high-impedance circuits (LPENS, Zaki Legthas) and hyperinductances (CEA, Emmanuel Flurin, Hélène Lesueur). Finally, we have unrestricted access to cutting-edge superconducting deposition equipment that will enable us to achieve state-of-the-art dissipation in these hyperinductances.

The publications authored by the advisors and related to the project are [15, 18, 22, 23].

[1] M. Carlesso et al., NJP 20, 083022 (2018)
[2] Y. Chu et al., Nature 563, 666 (2018)
[3] M. Wallquist et al., Physica Scripta T137, 014001 (2009)
[4] R. W. Andrews et al., Nature Physics 10, 321 (2014)
[5] D. Rugar et al., Nature 430, 329 (2004)
[6] M. Rossi et al., Nature 563, 53 (2018)
[7] E. Verhagen et al., Nature 482, 63 (2012)
[8] D. Mason et al., Nature Physics 15, 745 (2019)
[9] A. D. O'Connell et al., Nature 464, 697 (2010)
[10] Y. Chu et al., Science 358, 199 (2017)
[11] P. Arrangoiz-Arriola et al., Nature 571, 537 (2019)
[12] D. Hälg et al., Phys. Rev. Applied 15, L021001
[13] A. H. Ghadimi et al., Science 360, 764 (2018)
[14] Y. Tsaturyan et al., Nature Nanotech.12, 776 (2017)
[15] E. Ivanov et al., Appl. Phys. Lett. 117, 254102 (2020)
[16] J. J. Viennot et al., Phys. Rev. Lett.121, 183601 (2018)
[17] A. P. Reed et al., Nature Physics 13, 1163 (2017)
[18] R. Lescanne et al., Phys. Rev. X10, 021038 (2020)
[19] V. E. Manucharyan et al., Science 326, 113 (2009)
[20] H. Zhang et al., Phys. Rev. X 11, 011010
[21] N. Earnest et al., Phys. Rev. Lett.120, 150504 (2018)
[22] T. Capelle, PhD thesis, Sorbonne Université (2020)
[23] T. Capelle et al., Phys. Rev. Applied 13, 034022 (2020)