【Grant-in-Aid for Transformative Research Areas（B）】

A Study of innovative efficiency improvements in the generation and utilization of energy through quantum effects（Pioneering and realizing innovative methods to improve the efficiency of energy generation/utilization through quantum effects）

Principal Investigator	The University of Electro-Communications, Graduate School of Informatics and Engineering, Assistant Professor TAJIMA Hiroyasu　Researcher Number : 60757897
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Purpose and Background of the Research

●Outline of the Research

In recent years, it has been confirmed that quantum effects can significantly improve the performances of information processing such as computation and communication. If similar performance improvements are possible in the generation and utilization of energy, it could be the key to solving energy problems and developing new technologies to realize a sustainable society. However, due to the huge gap between energy generation/utilization and information processing, it is unclear whether such performance improvements are possible for energy devices. We will solve this problem from theoretical and experimental perspectives in this transformative research area. More precisely, we will establish the "realization of drastic performance advantage in quantum devices compared to classical devices (i.e., quantum advantage)" in terms of both energy generation and consumption. Moreover, we will clarify the fundamental limit of performance improvement, and realize it at the laboratory level.

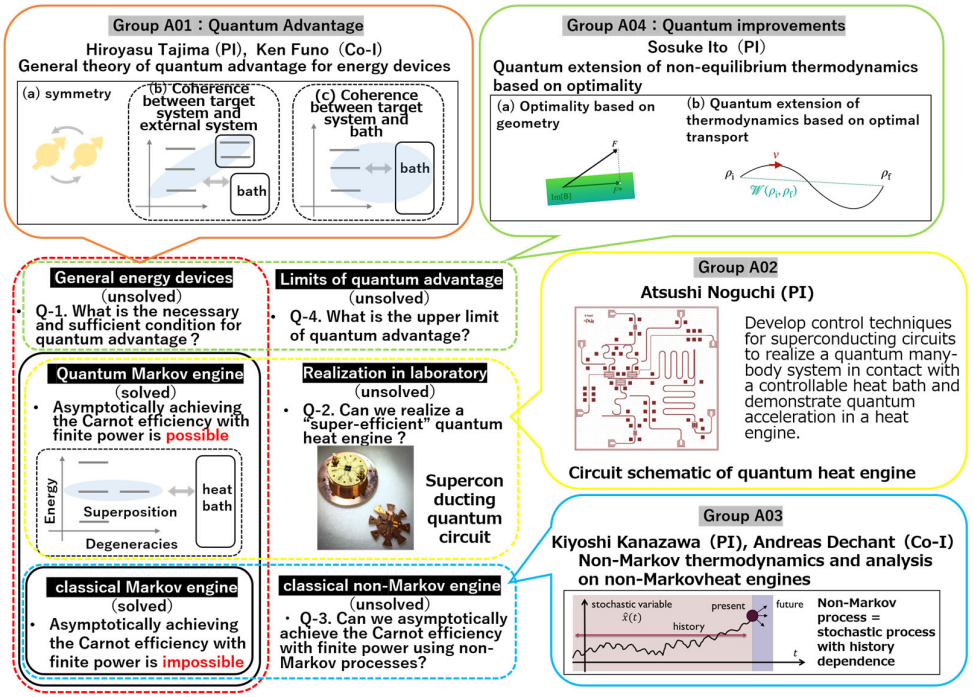

Figure 1. schematic image of the research area

●Background and how to Achieve the Goals (Figure 1)

This transformative research area is based on the theoretical breakthroughs that occurred in non-equilibrium physics in recent years. In this field, the second law of thermodynamics was refined. As one of its applications, a tradeoff between the efficiency and power of heat engines was clarified, which shows that the Carnot efficiency cannot be attained in a Markovian classical heat engine, as long as it works with a finite speed and produces non-vanishing power (Shiraishi-Saito-Tasaki, PRL 2016). On the other hand, it was recently shown by A01 group members that heat engines asymptotically achieving the Carnot efficiency with finite power can be constructed in quantum Markovian systems (Tajima-Funo, PRL 2016). While this result suggests a quantum advantage with respect to energy generation, questions Q1~Q4, shown in Figure 1, remain: **Q1**: Is such a quantum enhancement possible for other energy devices? **Q2**: Can we realize the quantum advantage of heat engines in a real system? **Q3**: Can we reproduce the effects of quantum enhancement by classical non-Markovian effects? **Q4**: Is there any quantum enhancement in heat engines stronger than the above result? If possible, what is the upper limit? To solve these questions, we organize four groups, A0 to A3.

Expected Research Achievements

●Specific goals in the research area and in the groups A01-A04

The goals of the research area : To achieve theoretical and experimental breakthroughs for energy devices using quantum effects. More specific goals to be achieved are as follows :

①Establish a general method of performance improvement by quantum effects for general energy devices
②Realization of quantum advantage of heat engines in laboratory
③Theoretical check of the possibility for the simulation of quantum enhancement by a classical non-Marvkov process
④Finding a stronger quantum improvement and proving its optimality

Goal of group A01 : : Establish a theory of quantum enhancement for energy devices in general and elucidate quantum effects that lead to performance enhancement.

Goal of group A02 : To establish all-coupled superconducting qubit control techniques and combine them with the development of controllable heat baths to realize ultra-high performance quantum heat engines.

Goal of group A03 : To analyze the thermodynamic limit following non-Markovian classical stochastic processes and verify the classical reproduction of quantum cooperative phenomena.

Goal of group A04 : To improve and optimize the theory of quantum enhancement for energy devices by combining techniques developed in the field of optimal transport and information geometry.

●Expected impacts

Our ultimate goal is to realize a society in which quantum effects can be used to solve energy problems and other "non-information technology" problems. Quantum effects have improved the performance of many devices in the past, but they have been limited to information-related technologies such as communication, computation, and sensing. However, the real world faces many issues that cannot be directly addressed by the improvement of information-related technologies. Our ultimate goal is to develop a quantum approach to solve a wide range of global issues, in particular, the energy problems.

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