Beating Carnot efficiency with Chiral AC driven Conductors

Sungguen Ryu, Rosa López, Llorenç Serra, and David Sánchez

IFISC (CSIC-UIB) Palma de Mallorca – Spain.

sungguen@ifisc.uib-csic.es

Abstract

■ We demonstrate that a chiral conductor driven by AC voltage bias can act as a heat engine with efficiencies much larger than the Carnot limit, and they can also extract work from common temperature baths, violating Kelvin-Planck law.

■ Nevertheless, with a proper definition using information-theoretical approach, entropy production is always positive, and the second law of thermodynamics is preserved.

■ Crucial conditions for achieving efficiency beyond Carnot limit are irreversible entropy production by the photo-assisted electron excitation process due to the AC voltage and the absence of power injection by the AC voltage due to the chirality.

Introduction

■ In macro-scale engines, the 2nd law and Clausius relation dictate that the efficiency should be bounded by the Carnot limit.

■ In micro-scale engines, the system can be driven far out of equilibrium, enabling the efficiencies beyond Carnot limit.

■ A remarkable example is experimental realization of Szilard engine using a quantum dot [J. V. Koski, et al., PNAS (2014].

■ In this direction, a nonequilibrium bath also have merits, as demonstrated by realizing of nonequilibrium demon [R. Sánchez, et al., PRL (2019)] and by using quantum coherence as resource [M.O. Scully, et al., Science (2003)].

■ What is the effect of nonequilibrium bath driven by AC voltage?

■ AC driven quantum conductors have shown remarkable level of control and measurement of electron excitation. However, heat and energy currents are of recent interest.

■ We show that an AC driven quantum device can have efficiencies beyond the Carnot limit.

Setup

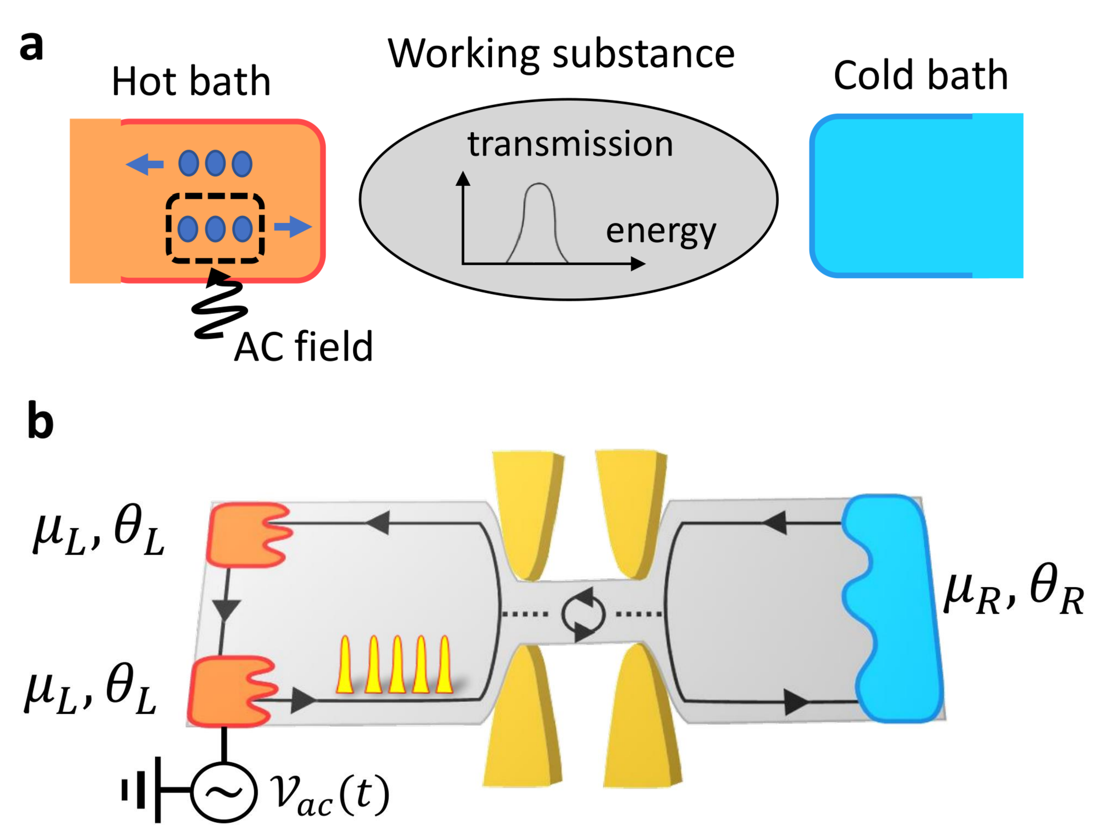
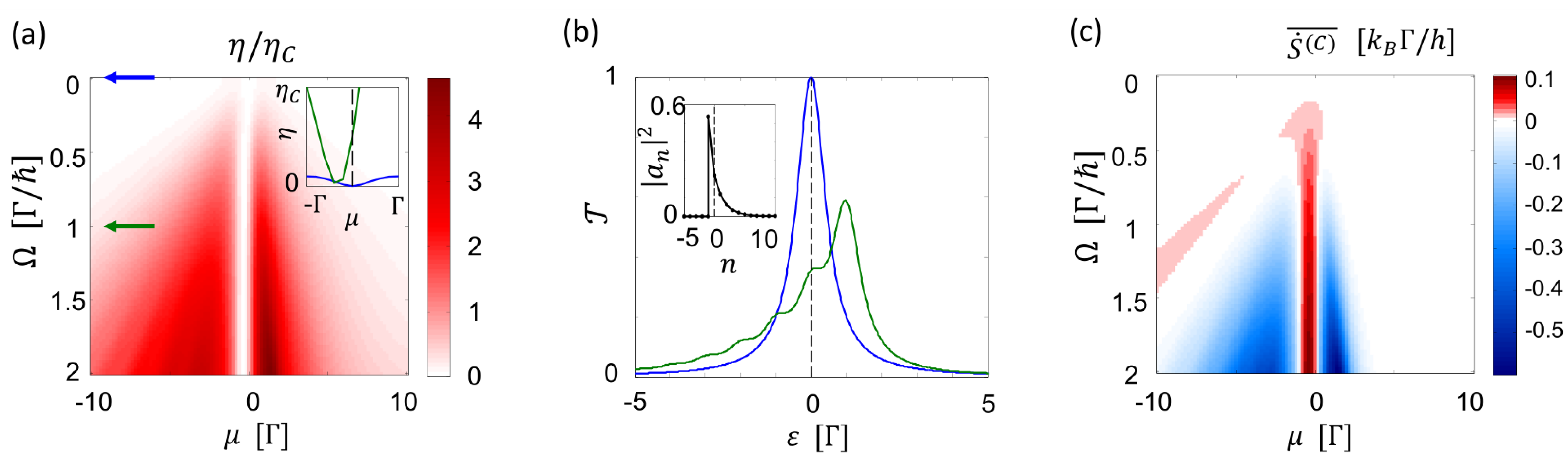


Fig. 1. **Setup**.
(a) Schematic of periodically driven chiral engine. In the hot bath, an AC field is selectively applied only to the electrons directed towards the working substance. This selective application completely avoids any AC input power, allowing a high efficiency in contrast to nonchiral cases.

(b) An implementation using a chiral conductor with a localized energy level. A time-dependent AC voltage $V_{ac}(t)$ is applied only to the lower left reservoir, hence realizing the selective AC driving. Edge channels from left and right reservoir are tunnel coupled to the localized state. The hot left reservoirs (cold right reservoir) have temperature $\theta_{L(R)}$ and chemical potential $\mu_{L(R)}$.

Efficiency enhancement by chiral AC voltage driving



Parameters: $\theta_L - \theta_R$= 0.1θ, $k_B\theta$= 0.25 Γ. The AC voltage profile is periodic Lorentzian pulses carrying an electron charge per period, with vertical offset. The temporal width of each pulse is 0.05×2π/Ω. DC potential bias is chosen for maximal power generation.

Fig. 2. Efficiency enhancement beyond Carnot limit by AC voltage driving.
(a) Efficiency when tuning the AC frequency Ω and the average chemical potential μ. Inset: Plot near μ = 0 for Ω = 0 (blue) and Ω = Γ/ℏ (green), showing a photo-assisted thermoelectric heat engine.
(b) Photo-assisted transmission probability $\mathcal{T}$ of an electron of energy ε incoming from the left reservoir for Ω = 0 (blue) and Ω = Γ/ℏ (green). Inset: the photo-assisted transition probabilities $|a_n|^2$, whose asymmetry induces electron-hole asymmetry.
(c) The entropy production rate defined by Clausius $\overline{\dot{S}^{(C)}}$, i.e., sum of heat current into the reservoirs divided by their temperatures. It is negative when the efficiency is larger than the Carnot efficiency.

Departure from Clausius relation

■ We find that the entropy production $\dot{S}$ defined by information-theoretical approach is always non-negative.

$$\overline{\dot{S}} = \frac{k_B}{h}\sum_{\alpha=L,R}\int d\mathcal{E}\Big[-\sigma[f_\alpha(\mathcal{E})] + \sigma[f_\alpha^{(\text{out})}(\mathcal{E})]\Big]$$

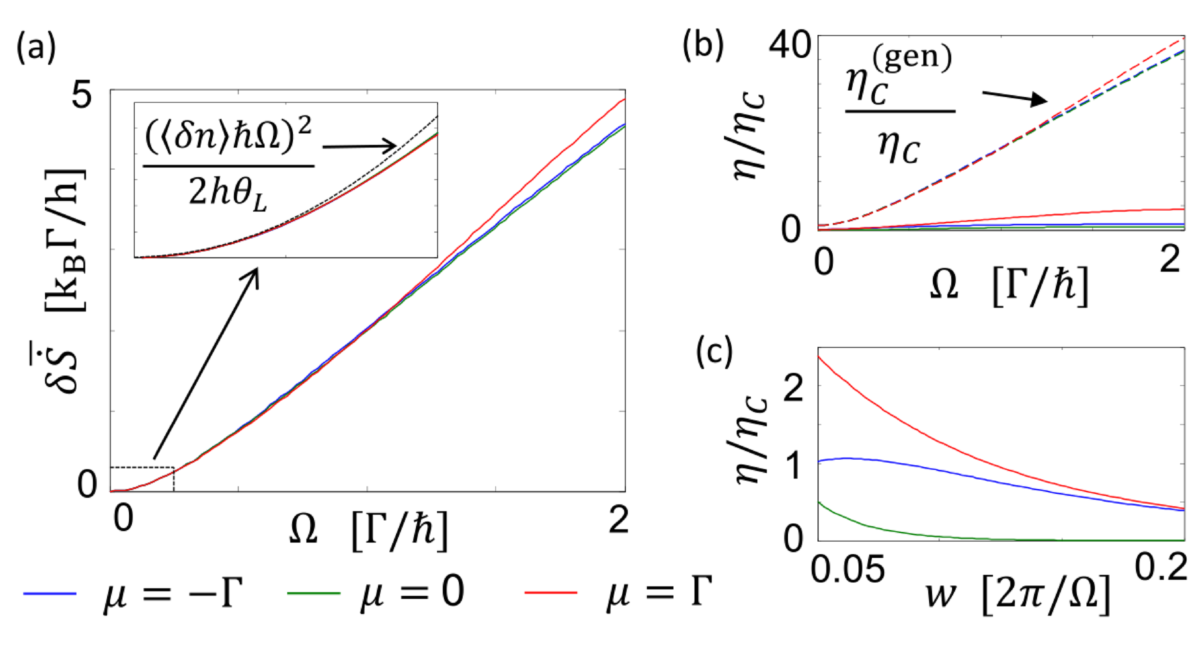


Fig. 3. Departure from Clausius relation. (a) Deviation of the entropy productions $\delta\overline{\dot{S}} \equiv \overline{\dot{S}} - \overline{\dot{S}^{(C)}}$ from Clausius relation, in the situation of Fig. 2. Inset: Slow-driving regime, $\Omega \in [0, k_B\theta/\hbar]$, showing that the difference is determined by the photon numer uncertainty $\langle\delta n\rangle$ (dashed line) **(b)** Efficiency in comparison with a new upper bound determined by positivity of entropy production $\overline{\dot{S}}$ (dashed lines). **(c)** Efficiency when tuning the temporal width w of the Lorentzian pulses, while fixing $\Omega = \Gamma/\hbar$. The more the pulses are squeezed, the more the efficiency is enhanced, due to larger photon number uncertainty.

Power generation from isothermal baths

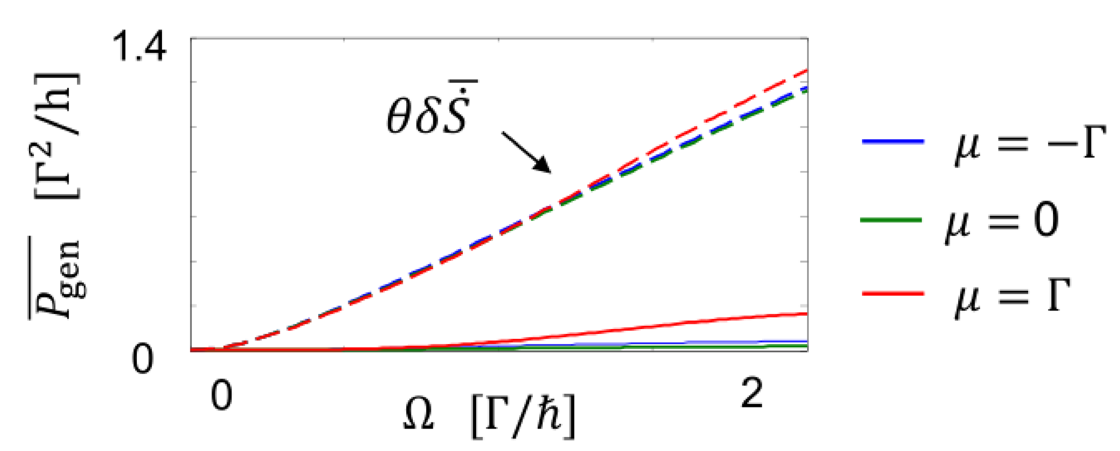


Fig. 4. Power generation from isothermal baths.
The power generation is allowed upto $\theta\delta\overline{\dot{S}}$ (dashed lines) when the AC driving induces additional entropy production, $\delta\overline{\dot{S}} > 0$. Here, $k_B\theta = 0.25\Gamma$.

Conclusion

■ We demonstrated photo-assisted thermoelectric engine, extracting work even beyond Carnot limit.

■ The entropy production defined by information-theoretical approach is always non-negative, while one defined by Clausius is not.

■ The difference between the two entropy productions was determined by photon number uncertainty in the low frequency and linear regime.

■ The ac voltage plays a role of the nonequilibrium demon recently suggested, which only induce nonequilibrium without energy injection.

■ Our system have a merit that it does not need a fine tuning, as the energy injection is always zero regardless to ac voltage profile.

Reference: Sungguen Ryu, Rosa López, Llorenç Serra, and David Sánchez. Arxiv:2104.11149, Accepted in Nature Communications.