On the Role of Current-Voltage Correlations on the Electric Power Consumption of Electronic Devices

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I. INTRODUCTION

In Landauer's work "Irreversibility and Heat Generation in the Computing Process"[1] it was argued that computing machines inevitably involve devices which perform logical functions that do not have a single-valued inverse. This logical irreversibility is associated with physical irreversibility and requires a minimal heat generation typically of the order of kT for each irreversible function. This dissipation serves the purpose of standardizing signals and making them independent of their exact logical history. Commonly known as Landauer's principle, this seminal paper has led to considerable interest in the study of reversible computing. Recently, physical experiments have tested Landauer's principle[2,3].

Landauer's principle can be argued in terms of the first and second laws of thermodynamics for an overall closed system. However, much less is known about the role of the thermodynamic laws in open quantum systems far from equilibrium[4–6], for example nanoelectronic devices. Typically, the concept of entropy production in nanoelectronic devices is discussed in terms of heat generation. In this conference, we will focus on the role played by the *local* electrical power (i.e. the rate at which kinetic energy is generated or subtracted from a particular region of the space) on the *local* generation of heat. The electric power is usually understood as a (mean field) observable defined as the product of the current by the (mean field) voltage drop,

$$P_{mf}(t) = \langle I(t) \rangle \langle V(t) \rangle. \tag{1}$$

with $\langle ... \rangle$ denoting the quantum ensemble average. We will show that a proper treatment of the many body problem can actually induce the breaking down of this definition for open quantum systems. Even while overall electric power of the total system can be still defined as the standard product $P_{mf}(t)$, individual parts of a system may violate this definition.

II. OBERVIEW OF THE PROBLEM

The openness of quantum electron systems has been studied extensively in the literature, but few works are devoted to discuss its effect on the computation of electric power. Here, we provide a novel expression for the accurate estimation of the electric power in nanoscale open systems deduced from a many-particle electron transport formalism that goes beyond the standard mean field approximation[7,8]. Surprisingly, we show that the usual expression of the electric power in the device active region, i.e. $P_{mf}(t)$ is inappropriate when dealing with systems with strong (time-dependent) Coulomb correlations. Once such correlations are taken into account, a much more complex recipe is needed to compute the electric power in the active region.

In order to go beyond the mean field approximation, we formulate the problem in terms of the correlation between the (Bohmian) velocity of the i-th electron $\mathbf{v}_i(t)$ and the electrostatic force $q_i \mathbf{E}_i(t)$ made by the rest of electrons of the whole (closed) system on it. It can be shown that the exact mean electric power, P_{corr}, associated to the $N(t)$ electrons enclosed in an open system reads:

$$P_{corr} = \sum_{i=1}^{N(t)} q_i \langle \mathbf{v}_i(t) \mathbf{E}_i(t) \rangle_T, \tag{2}$$

Only when the electric filed acting on the ith particle is roughly equal to its mean field value, i.e. $\mathbf{E}_i(t) \approx \mathbf{E}_{mf}(t)$, expression (2) for an open system becomes equal to (1). Let us notice that, although the electric power defined in (2) refers only to those $N(t)$ electrons in the open system, its value is clearly affected by all the M particles composing the whole closed circuit. Since energy is continuously entering and leaving an open system through the interaction among carriers inside and outside its spatial limits, it is of critical importance to properly model the boundary conditions through which the dynamics of electrons within and outside the open system become correlated[9].

III. CHALLENGES

Given the above result, we will provide new insights into the use of electron Coulomb correlations to manipulate the *local* heat generation of a given device. More specifically, we will address the following question:

> Can we design electron-electron Coulomb correlations to manipulate the way in which energy is dissipated along different regions of a circuit?

The answer to this question could be quite relevant considering the fact that power consumption is one of the main drawbacks that electronics must affront when scaling down any new technology[10]. Moreover, from a theoretical point of view, the results of this work shed new light into how many-body interactions could affect the thermodynamic limits of computing machines.

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