On the back-action of THz measurement on the total current of quantum devices

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INTRODUCTION

Modeling electronic devices is based on fixing an applied voltage and then computing the electrical current. Surprisingly, what means measuring the current is not clear. Most of quantum simulators compute the current without taking into account the back-action of the ammeter on the system. For DC quantum transport one can avoid the computational burden of the back-action [1]. However, at Tera Hertz (THz) frequencies, where the total quantum current (with particle and displacement components) is multi time measured, neglecting the quantum perturbation of the system because of its interaction with the ammeter is not at all justified.

MEASURING THE CURRENT AT THZ

Whenever the interaction between the electrons of the system and those of the ammeter are relevant, a non-unitary operator (different from the Hamiltonian) is needed to *encapsulate* all the *random* interactions of the quantum systems with particles of the ammeter, the cables, the environment, etc. *Which is the operator that determines the (non-unitary) evolution of the wave function when measuring the total current? Is it "continuous" or "instantaneous"? with a "weak" or "strong" perturbation of the wave function?* [2] The answers are certainly not simple. Over the years orthodox physicists have identify the operators, by developing instincts on which are the effect of measurements on the wave function. To the best of our knowledge, no such (THz) current operator has been presented. If we want to extract information of the current at such very high frequencies, taking into account the back-action is mandatory.

A NOVEL APPROACH TO THZ BACK-ACTION

Bohmian mechanics provides a microscopic definition of the interaction between the system and the ammeter in an enlarged configuration space. The conditional wave function [3] of the system, under the approximation reported in [4], evolves as

$$i\hbar\frac{\partial\psi(x_1,t)}{\partial t}=\left[H_0+V\right]\psi(x_1,t) \qquad (1)$$

where $V = V(x_1, \mathbf{X}_2(t), ..., \mathbf{X}_N(t))$ is the conditional Coulomb potential felt by the system and H_0 is its free Hamiltonian. Fig. 1 shows a two terminal device. Because of the large distance between the system and the ammeter we consider only the interaction between the system, x_1, and the near electrons, $\mathbf{x}_2, ..., \mathbf{x}_N$, in the metal surface S_m (see Fig. 2). The total quantum current can be computed as the time derivative of the flux F of the electric field $\mathbf{E}(\mathbf{r}, t)$ produced by all N electrons (system *plus* metal) on the large ideal surface S_L using the relation:

$$I_T(t)=\int_{S_L}\epsilon(\mathbf{r})\frac{d\mathbf{E}}{dt}d\mathbf{s}=\sum_{i=1}^{N}\nabla F(\mathbf{X}_i(t))\mathbf{v}_i(t) \qquad (2)$$

where the flux F depends on each electron position and $\mathbf{v}_i$ is the Bohmian velocity [5], [6].

CONLUSION

Our analysis of the quantum back-action shows that the THz measurement of the total current implies a slightly perturbation of the quantum system (see Fig. 3) and a large fluctuation in the current (see Fig. 4). For high frequencies another source of noise (whose origin is the quantum back-action) appears (see Fig. 4). This new noise cannot be neglected to get accurate THz predictions (see Fig. 5).

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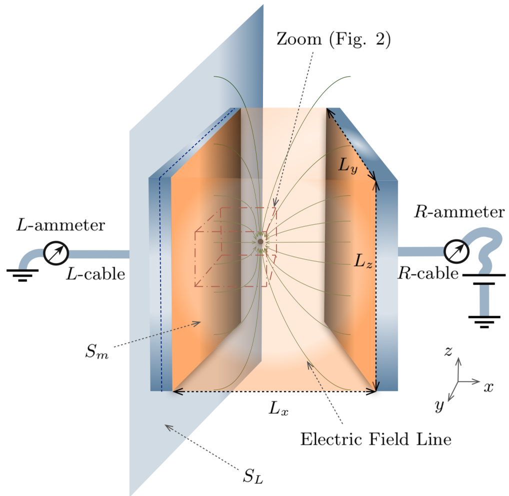

Fig. 1. Schematic representation of a two terminal device. The ideal surface S_L collects all the electric field lines.

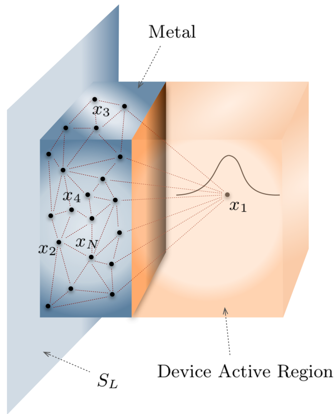

Fig. 2. Zoom of the red region in Fig. 1. It is schematically depicted the coulomb interaction (dashed lines) and the conditional wave function (solid line) defined in Eq. (1).

References

[1] X. Oriols and D.K. Kerry, *Quantum transport beyond DC*, Journal of Computational Electronics **12**, 317 (2013).

[2] F. L. Traversa, G. Albareda, M. Di Ventra, and X. Oriols, *Robust weak-measurement protocol for Bohmian velocities*, Physical Review A **87**, 052124 (2013).

[3] D. Dürr, S. Goldstein, and N. Zanghì, *Quantum equilibrium and the origin of absolute uncertainty*, Journal of Statistical Physics **67**, 843-907 (1992).

[4] X. Oriols, *Quantum trajectory approach to time-dependent transport in mesoscopic systems with electron-electron interaction*, Physical Review Letter **98**, 066803 (2007).

[5] G. Albareda, D. Marian, A. Benali, S. Yaro, N. Zanghí and X. Oriols: *Time-resolved electron transport with quantum trajectories*, Journal of Computational Electronics, **12**(3), 405-419 (2013).

[6] D. Marian, X. Oriols, and N. Zanghì, in preparation.

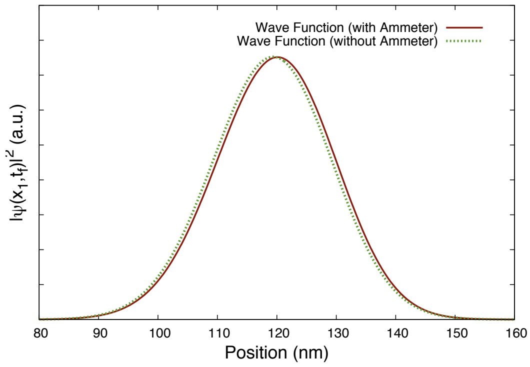

Fig. 3. Comparison at the final time of the simulation (t_f) of the modulus square of the conditional wave function (solid line) evolving according to Eq. (1) and the wave function without ammeter (dashed line), i.e. considering a Schrödinger evolution in a time independent potential $V(x_1)$ computed as a mean field.

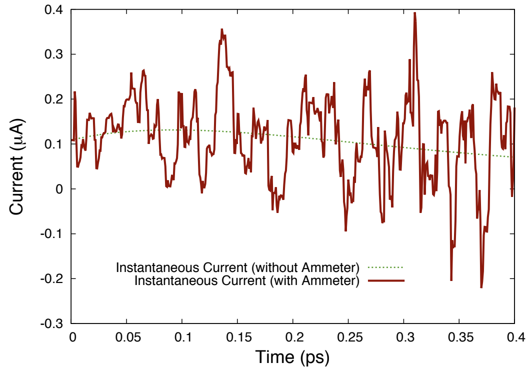

Fig. 4. Value of the total current. With solid line is reported the instantaneous value of the total current calculated from Eq. (2) (with ammeter) and with dashed lines obtained from a mean field simulation for particle x_1 alone (without ammeter).

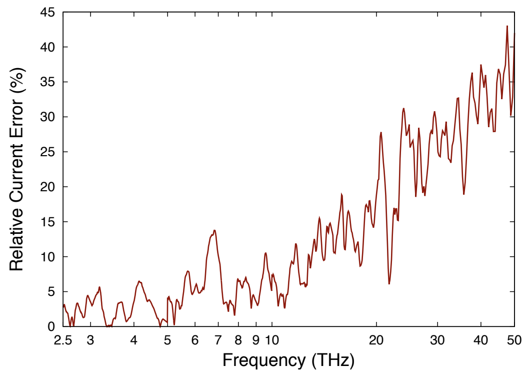

Fig. 5. Relative error for the total current as a function of frequency ($f = 1/T$) calculated as $|\overline{I}_T(t) - \overline{I}_T^{x_1}(t)|/|\overline{I}_T^{x_1}(t)|$. The $\overline{I}_T(t)$ is the mean temporal current at the considered frequency taken from Eq. (2) (with ammeter) and $\overline{I}_T^{x_1}(t)$ is mean temporal total current obtained from a mean field simulation (without ammeter).