Voltage pulse unveils a far away perturbation

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Abstract

Here we present the unveilling of dynamical interferences in a Fermi liquid by a voltage pulse propagating through a quantum wire. Time-dependent simulations were performed with the open-source Python package Kwant and its extension Tkwant.

INTRODUCTION

MODEL

We consider a N sites one dimensional wire connected to two semi-infinite leads. We model the system by the following tight-binding Hamiltonian:

$$\mathbf{H} = -\gamma \sum_i c_i^\dagger c_{i+1} + \sum_i w(t)\theta(-i) c_i^\dagger c_i + \sum_i V_{QPC}(i) c_i^\dagger c_i \tag{1}$$

The scattering region will be indexed by $i \in [\![1, N]\!]$, whereas left (right) lead sites are indexed with $i \leq 0$ ($i \geq N+1$). The voltage pulse is modeled by the second term, with $\theta(x)$ being the Heaviside function and $w(t)$:

$$w(t) = V_P e^{-2((t-t_0)/\tau)^2} \tag{2}$$

V_P being the amplitude, τ the width and t_0 the starting time of the perturbation. We introduced a Quantum Point Contact (QPC) which consists in a filtering potential barrier:

$$V_{QPC}(i) = V_0 e^{-((x-x_0)/\xi)^2} \tag{3}$$

V_0 being the amplitude, ξ the width and x_0 the position of the QPC. The time-dependent peturbation can be absorbed by the gauge transforming leading to a redefinition of the hopping parameter the left lead where the pulse is applied and the scattering region:

$$\gamma \to \gamma e^{-i\phi(t)} \tag{4}$$

with:

$$\phi(t) = \frac{e}{\hbar} \int_{-\infty}^{t} w(u) du \tag{5}$$

SIMULATION

Tkwant allows to evolve the states in time. The density is obtained by integrating over the energy of all onebody states:

$$n(i,t) = \int \frac{dE}{2\pi} f(E) |\psi(i,E)|^2 \tag{6}$$

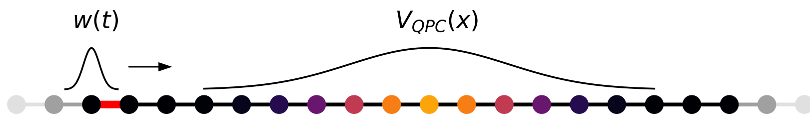


FIG. 1: A schematic of the system. The wire is connected to two semi-infinte leads. The site color reflects the QPC's voltage amplitude. The time-dependent hopping parameter is displayed in red (here $L = 18$, $V_0 = 1$, $x_0 = L/2$, $\xi = 3$).

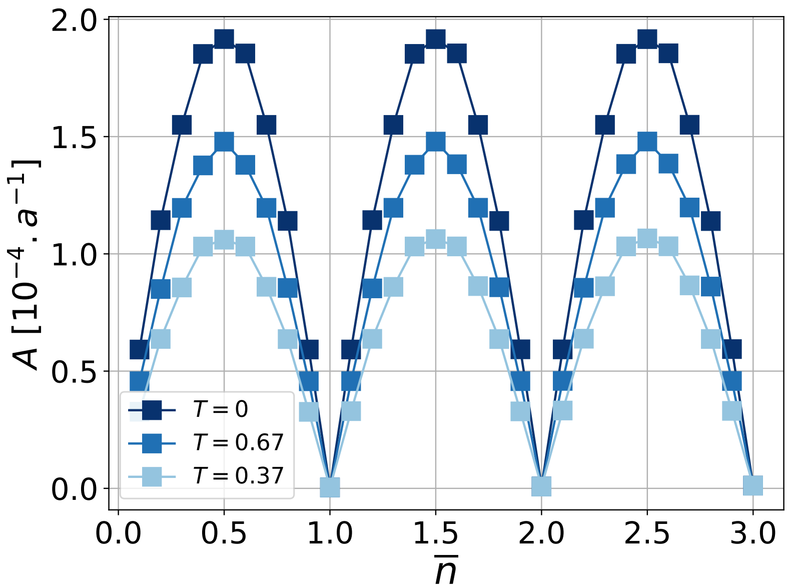


FIG. 2: The oscillation amplitude A vs the injected charge *overlinen* for different values for transmission T. Here the parameters were: $W = 1$, $L = 3000$, $\xi = 50$, $\tau = 500$, $t_0 = 1200$. For $T = 0$, $V_0 = 3$, $\xi = 50$, for $T = 0.67$ ($T = 0.37$), $V_0 = 0.4$ ($V_0 = 0.24$) and $\xi = 1$.

We define the injected charge $\overline{n}$ as:

$$\overline{n} = \int I(t)dt \tag{7}$$

By using the Landauer-Bttiker formula $I = eV/h$, we obtain the following definition of $\overline{n}$:

$$\overline{n} = \frac{eV_P\tau}{h}\sqrt{\frac{\pi}{2}} \tag{8}$$

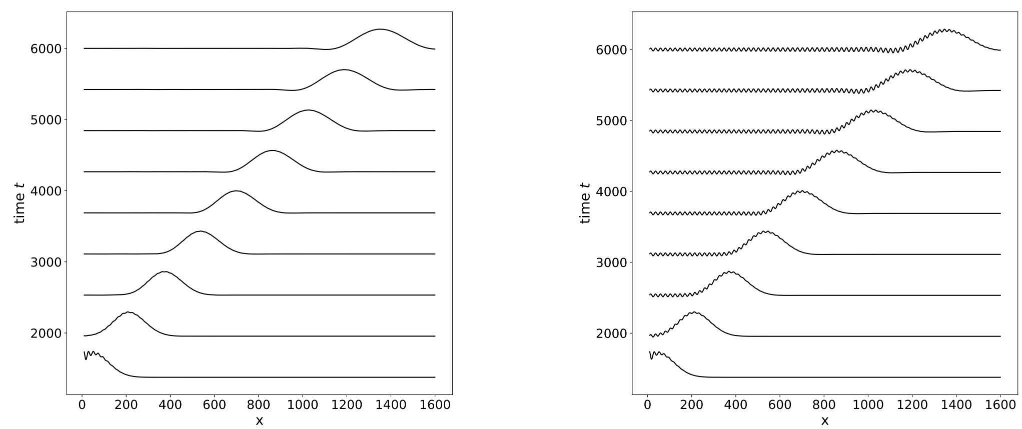
INTERFERENCES

For one-dimensional chain, the scattering states have the simple form:

$$\psi(x,t) = \frac{1}{\sqrt{v(k)}} e^{ikx-iEt} \tag{9}$$

In our case, the QPC reflects the incoming states, and we obtain the following wavefunction:

$$\Psi(x,t) = \frac{1}{\sqrt{v(k)}} e^{ikx-iEt} + r\frac{1}{\sqrt{v(k)}} e^{-ikx-iEt} \tag{10}$$



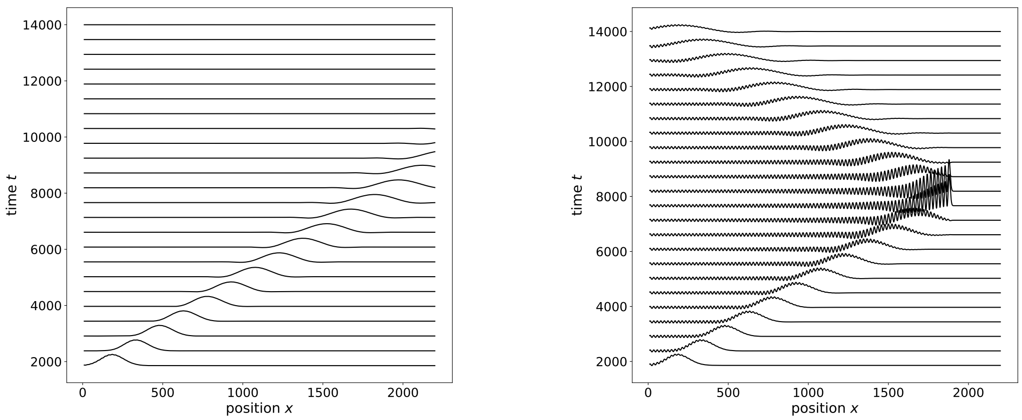
(a) (b)

FIG. 3: The charge density as a function of time t and position x (a) without (b) QPC. The parameters were $\overline{n} = 0.01$, $\tau = 500$, $t_0 = 1200$, (a) $V_0 = 0$ (b) $V_0 = 3$, $\xi = 50$, $E_F = 2.02$.

This leads to destructive interferences. However, as the voltage pulse progagates, the incoming state phase shift dynamically:

$$\psi(x,t) = \frac{1}{\sqrt{v(k)}} e^{ikx-iEt+i\phi(t)} \tag{11}$$

which unveils the presence of interferences by changing the phase differences between the incoming and reflected states by $\phi(t \gg \tau) = 2\pi\overline{n}$.



(a) (b)

FIG. 4: The charge density as a function of time t and position x (a) without (b) QPC. The parameters were $\overline{n} = 0.01$, $\tau = 500$, $t_0 = 1200$, (a) $V_0 = 0$ (b) $V_0 = 3$, $\xi = 50$, $E_F = 2.02$.

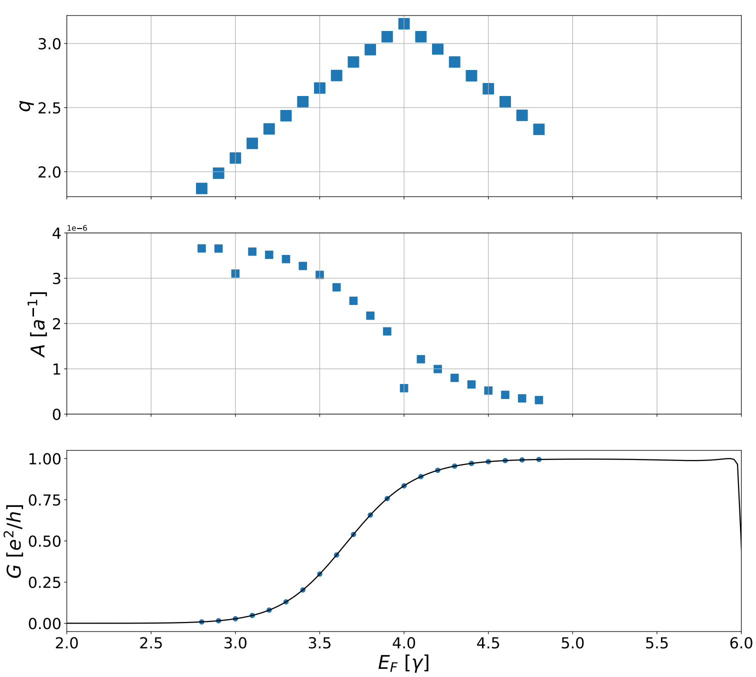


FIG. 5: $L = 4000$, $V_0 = 1.7$, $\xi = 2.1$

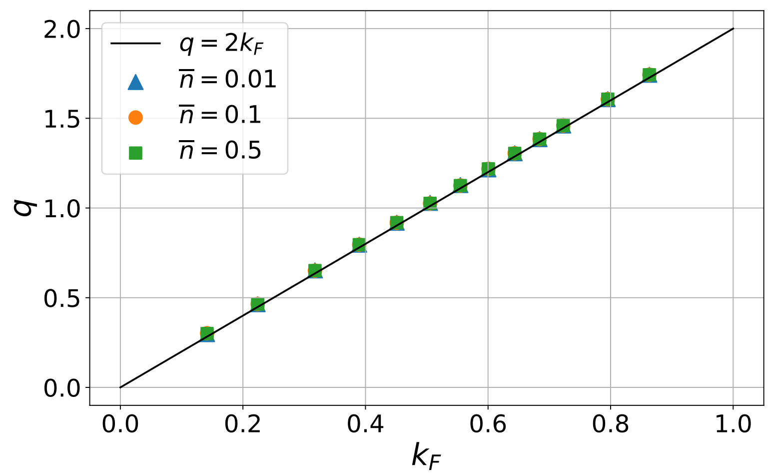


FIG. 6: The oscillation wavevector q for different k_F and $\overline{n}$ values. Here the parameters were: $L = 3000$, $V_0 = 3$, $\xi = 50$, $\tau = 100$, $t_0 = 1200$.

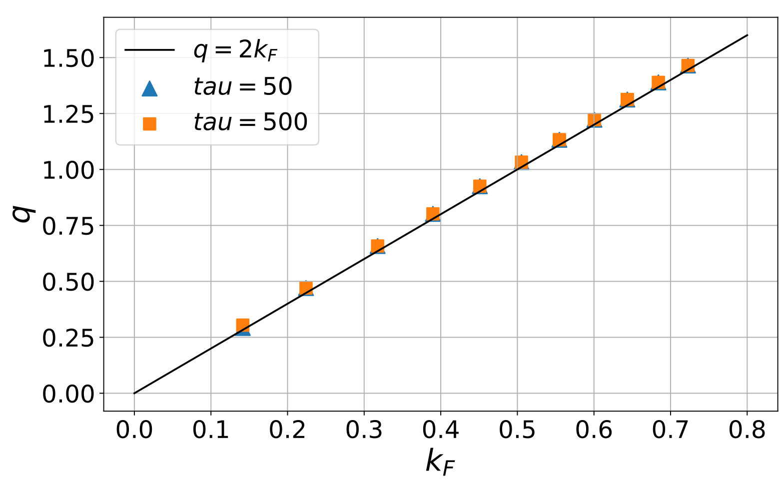


FIG. 7: The oscillation wavevector q for different k_F and τ values. Here the parameters were: $L = 3000$, $V_0 = 3$, $\xi = 50$, $\overline{n} = 0.01$, $t_0 = 1200$.

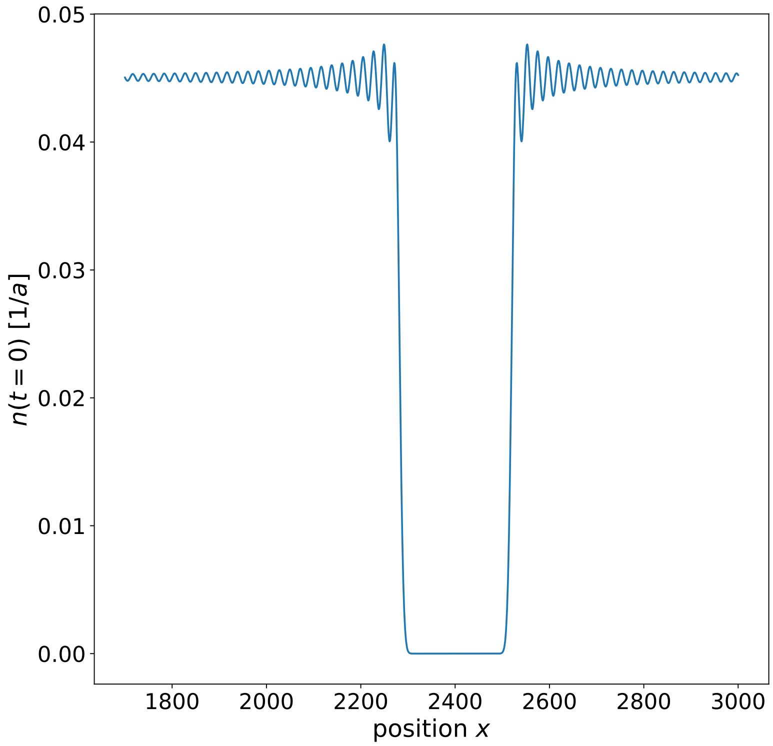


FIG. 8: Density n at t=0 for $\overline{n} = 0.01$, V_0 =3, $E_F = 2.02$. We observe oscillation on both side of the QPC.

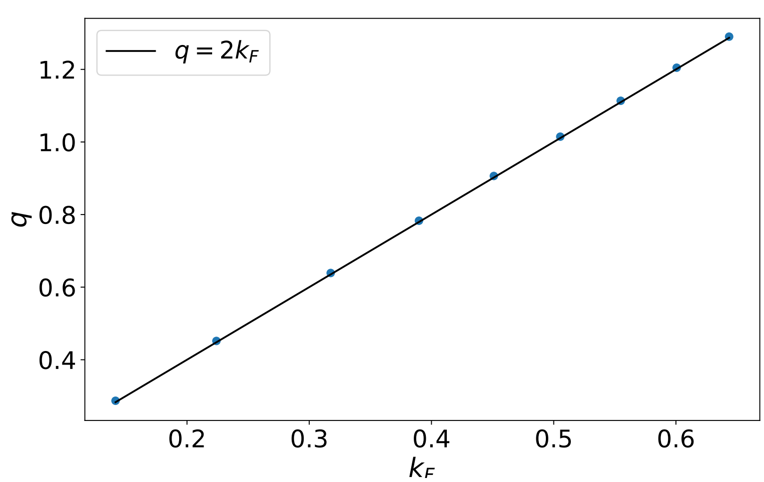


FIG. 9: Oscillation wavevector q of the oscillation at t=0 at differents k_F values. There is a perfect match with the line $q = 2k_F$.

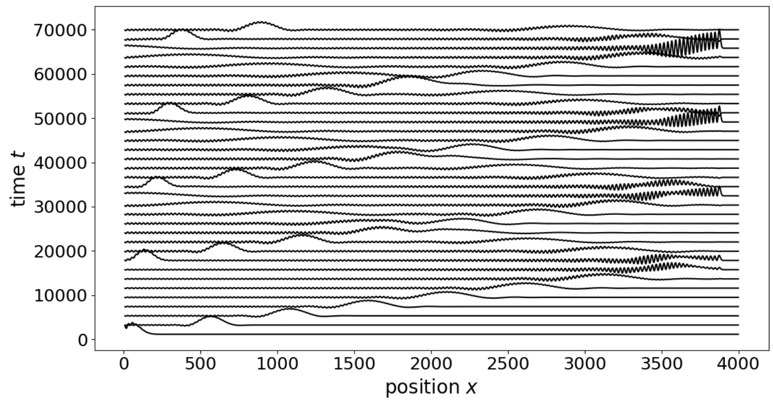


FIG. 10: For $V_0 = 3$, $\overline{n} = 0.01$, $E_F = 2.015$, we send a new pulse everytime a pulse reaches the QPC. In some region, the oscillation seems to be quasi-stationnary.