Letter

Dissipative dynamics of a fermionic superfluid with two-body losses

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We study the dissipative dynamics of a fermionic superfluid in the presence of two-body losses. We use a variational approach for the Lindblad dynamics and obtain dynamical equations for Anderson's pseudospins where dissipation enters as a complex pairing interaction as well as effective, density-dependent, single-particle losses which break the conservation of the pseudospin norm. We show that this latter has key consequences on the dynamical behavior of the system. In the case of a sudden switching of two-body losses, we show that the superfluid order parameter decays much more quickly than the particle density at short times and eventually slows down, setting into a power-law decay at longer timescales driven by the depletion of the system. We then consider a quench of pairing interaction, leading to coherent oscillations in the unitary case, followed by the switching of the dissipation. We show that losses affect the dynamical BCS synchronization by introducing not only damping but also a renormalization of the frequency of coherent oscillations, which depends nonlinearly on the rate of the two-body losses.

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Introduction. The nonequilibrium dynamics of superfluids and superconductors has attracted fresh interest in recent years. Nonlinear optical spectroscopy and manipulation of collective modes in the superconducting phase have been demonstrated [1,2] together with reports of light-induced superconductivity in variety of materials [3–6], among the most striking demonstration of light control of quantum matter and Floquet engineering [7–9]. In atomic physics, the realization of fermionic superfluids [10–12] has led to the investigation of different dynamical phenomena, such the spectroscopy of driven superfluids [13]. These experimental developments have stimulated theoretical interest on the subject of dynamics in superfluids and superconductors [14–26]. In most cases, theoretical investigations of these phenomena have focused on the dynamics of closed isolated systems. Dissipation is, however, not only unavoidable in realistic experimental contexts, such as in the solid state, but can sometime be controlled with high degree of flexibility, as in certain ultracold atom experiments, and used as a tool to control the dynamical long-time behavior of the system. Dissipative quantum many-body systems represent a platform where novel dynamical phenomena and phase transitions can appear as result of the competition between unitary evolution and dissipative couplings [27–33].

A particularly interesting scenario is realized when dissipation has a genuine many-body character, since it involves correlated processes such as heating due to stimulated emission [34–36], spontaneous emission [37], or two-particle losses [38–43]. These types of dissipative inelastic scattering processes naturally arise, for example, in experiments with ultracold fermions made of alkali-warth atoms [44–46]. Their role for the dynamics has recently attracted large interest in the context of Dicke states [41,47,48] and quantum Zeno effect (QZE) [49] where the effective dissipation decreases as the loss rate is increased [50–59]. The effect of two-body losses on the dynamics of superfluids and superconductors is particularly intriguing, since dissipation here affects directly the degrees of freedom involved in the condensate and could, for example, couple nontrivially to its collective modes or induce nontrivial responses which are not expected for single-particle dissipative processes.

In this Letter, we study the dissipative dynamics of a fermionic superfluid, modeled as an attractive Hubbard model [60] in the presence of weak local two-body losses. Recent works in this context have focused on simplified descriptions of dissipation in terms of a non-Hermitian Bardeen-Cooper-Schrieffer (BCS) problem [61] or an effective unitary dynamics with complex pairing potential [62]. Here, using a variational approach for Lindblad dynamics, we show that a complete dissipative BCS theory includes an effective, density-dependent, single-particle loss term, which corresponds to decoupling the two-body losses in the particle-particle and particle-hole channels. We show that this term completely controls the long-time dynamics of the system, leading to a power-law decay of particle density and to a crossover in the superfluid order parameter from a short-time exponential decay to a long-time power law decay controlled by the depletion of the system.Furthermore, we show that a weak dissipation has a dramatic effect on the BCS synchronization dynamics [15] whose frequency of coherent oscillations is strongly renormalized. We understand this effect as arising from a weak breaking of Anderson pseudospin length and construct a dissipative soliton solution which qualitatively captures the observed frequency renormalization. Our results can be experimentally tested in experiments with ultracold fermionic superfluids [63,64], where two-body losses can be introduced through photoassociation [40,43] as well as cavity QED simulators of nonequilibrium superfluidity [65,66].

Model. We consider a system of spinful fermions hopping on a lattice, in the presence of a local pairing interaction as described by the attractive Hubbard model whose Hamiltonian reads

$$H = \sum_{\langle ij\rangle\sigma} t_{ij} c^{\dagger}_{i\sigma} c_{j\sigma} - |U| \sum_i n_{i\uparrow} n_{i\downarrow}, \tag{1}$$

where $-|U|$ is the attraction and the t_{ij} the nearest neighbor hopping. The hopping gives rise to a single-particle band of width W. For simplicity, we consider a band characterized by a flat density of states. Different choices do not affect in any qualitative way our results as long as the density of states is nonsingular. This model has been studied in thermal equilibrium [67] in the context of the BCS to BEC superfluidity crossover [68–71], while its unitary dynamics has received attention recently and revealed a variety of dynamical phase transitions [72–78]. Here we focus on an open quantum system setting in which the evolution of the system density matrix $\rho(t)$ is described by a Lindblad master equation [79], ($\hbar = 1$),

$$\partial_t \rho = -i[H, \rho] + \sum_i \left(L_i \rho L_i^{\dagger} - \frac{1}{2}\{L_i^{\dagger} L_i, \rho\}\right), \tag{2}$$

with local, on-site, jump operators describing Markovian dissipation. Here we consider dissipative processes in which pairs of fermions on the same site and with opposite spins escape from the system to the environment, leading to a jump operator of the form $L_i = \sqrt{\Gamma} c_{i\downarrow} c_{i\uparrow}$. The resulting dissipative dynamics does not conserve the total number of particles. In the absence of any driving term to counterbalance the loss of particles into the environment, the system evolves at long times toward the zero density limit. We note that two-body losses conserve instead the total spin, which would prevent the system from reaching complete depletion [48], unless the system is initially prepared in a total singlet state as in our case here. While the stationary state properties of the model are therefore trivial, its depletion dynamics can still reveal intriguing features and give rise to different dynamical regimes, as we are going to discuss.

Method. To study the dynamics of the system, we use a time-dependent variational approach. While for a unitary system the Dirac's variational principle is a standard and much used result, both for Gaussian and for correlated wave functions, its generalization to the open system case poses some challenges. Recent work [80] has proposed a variational principle for the stationary state, which is not of direct use here, where the long-time limit is the vacuum. To focus on dynamics, we proceed along a different line, directly inspired by work on unitary quantum dynamics. We note that stating that a density matrix ρ evolves according to Eq. (2) is equivalent to saying that the functional $S[\rho_0, \rho_{\rm aux}] = \int dt \mathrm{Tr}\,[\rho_{\rm aux}(i\partial_t\rho_0 - \mathcal{L}[\rho_0])]$ is stationary with respect to any given density matrix $\rho_{\rm aux}$. Using this condition on a Gaussian density matrix ρ_0 for which Wick's theorem applies, including normal and anomalous contractions, allows us to obtain the following variational dynamics [81]:

$$\partial_t \rho_0 = -i[\tilde{H}_{\rm BCS}, \rho_0] + \Gamma \frac{n}{2} \sum_\sigma \mathcal{L}^{\rm 1p-loss}_\sigma[\rho_0], \tag{3}$$

which takes the form of an effective Lindblad master equation. Here the unitary part comes from the usual BCS mean-field Hamiltonian plus an imaginary pairing field $i\Gamma$

$$\tilde{H}_{\rm BCS} = H_{\rm BCS} + i\Gamma \sum_i (\Delta c_{i\downarrow} c_{i\uparrow} - \Delta^* c^{\dagger}_{i\uparrow} c^{\dagger}_{i\downarrow}), \tag{4}$$

where Δ is the superfluid order parameter

$$\Delta(t) = \frac{1}{V} \sum_{\mathbf{k}} \mathrm{Tr}(\rho_0 c^{\dagger}_{\mathbf{k}\uparrow} c^{\dagger}_{-\mathbf{k}\downarrow}),$$

while the dissipative part $\mathcal{L}^{\rm 1p-loss}_\sigma[\rho_0]$ in Eq. (3) contains effective single-particle losses of strength $\Gamma_{\rm eff} = n(t)\Gamma$, with $n(t) = \frac{1}{V}\sum_{i\sigma} \mathrm{Tr}\rho_0 n_{i\sigma}$ being the time-dependent particle density. The variational dynamics associated to the above effective Lindbladian reads

$$\dot{\sigma}^x_{\mathbf{k}} = -2\varepsilon_{\mathbf{k}} \sigma^y_{\mathbf{k}} + 2\mathrm{Im}(\Phi)\sigma^z_{\mathbf{k}} - \Gamma n \sigma^x_{\mathbf{k}}, \tag{5}$$

$$\dot{\sigma}^y_{\mathbf{k}} = 2\varepsilon_{\mathbf{k}} \sigma^x_{\mathbf{k}} - 2\mathrm{Re}(\Phi)\sigma^z_{\mathbf{k}} - \Gamma n \sigma^y_{\mathbf{k}}, \tag{6}$$

$$\dot{\sigma}^z_{\mathbf{k}} = 2\mathrm{Re}(\Phi)\sigma^y_{\mathbf{k}} - 2\mathrm{Im}(\Phi)\sigma^x_{\mathbf{k}} - \Gamma n\big(\sigma^z_{\mathbf{k}} + 1\big), \tag{7}$$

where we have introduced the Anderson's pseudospin $\sigma^\alpha_{\mathbf{k}} = \mathrm{Tr}(\rho_0 \Psi^{\dagger}_{\mathbf{k}} \sigma^\alpha \Psi_{-\mathbf{k}})$ with $\sigma^{\alpha=x,y,z}$ given by the Pauli matrices, where $\varepsilon_{\mathbf{k}}$ is the bare energy dispersion of the lattice and $\Phi(t) = (-|U| + i\Gamma)\Delta(t)$ is the self-consistent pairing field. This dynamics describes the competition between precession of Anderson's pseudospin around an effective magnetic field, as in the unitary case, and loss-induced decoherence toward the steady state $\sigma^x_{\mathbf{k}} = \sigma^y_{\mathbf{k}} = 0$ and $\sigma^z_{\mathbf{k}} = -1$, corresponding to vanishing order parameter and density. We note that the length of the pseudospin $\mathcal{S} = \sum_{\alpha\mathbf{k}} (\sigma^\alpha_{\mathbf{k}})^2$ is *not* conserved due to the presence of the single-particle loss term proportional to the density. Furthermore, the purity of the variational state $P = \mathrm{Tr}(\rho_0^2)$ is also not conserved, as expected for a dissipative Lindblad dynamics. The dynamical equations above differ therefore from those that can be obtained by Hubbard-Stratonovich decoupling [62], which essentially take the form of a unitary dynamics with a complex pairing term $U + i\Gamma$. This difference arises due to the presence of the effective single-particle loss term in Eq. (3) that couples the Keldysh contours. We will discuss below the consequences of this term for the physics of the problem. We note that instead the equations above coincide with those that can be obtained through a direct mean-field decoupling of Hamiltonian and dissipator, including both contributions coming from particle-particle and particle-hole channels.

Results: Dissipation quench. We begin our discussion from the dynamics after a sudden switching of the two-body losses Γ, starting from the ground state of the attractive Hubbard model with $|U|/W = 1.0$.

In Fig. 1, we plot the time evolution of the order parameter $\Delta(t)$ and particle density $n(t)$ for different values of the dissipation measured with respect to the interaction $\Gamma/|U|$. We see in the right panels that the density remains constant at short times while above a timescale which depends weakly on the loss rate it displays a power-law decay toward zero, corresponding to the vacuum state, with an exponent $\sim t^{-1}$ which is independent of Γ. On the other hand, the dynamics of the superfluid order parameter $\Delta(t)$ is richer and shows a crossover

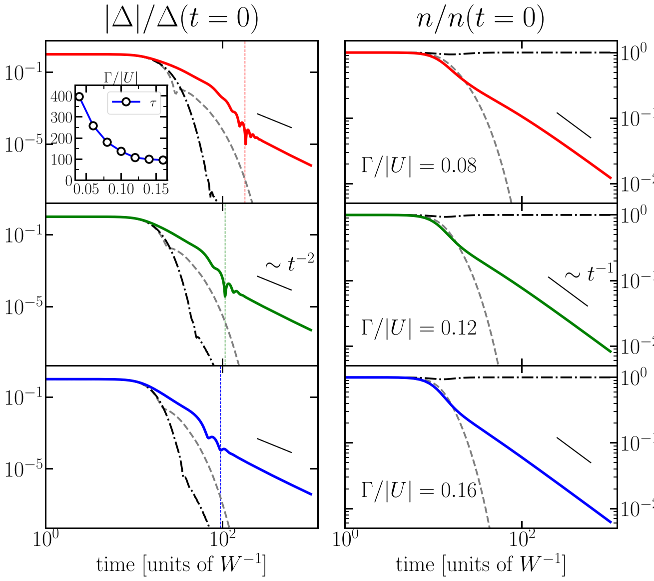

FIG. 1. (Left panels) Dynamics of the order parameter after a sudden quench of two-body losses, for three values $\Gamma/|U| = 0.08$, $\Gamma/|U| = 0.12$, and $\Gamma/|U| = 0.16$ from top to bottom and $|U|/W = 1.0$. (Right panels) Dynamics of the particle density for the same parameters used in the left panels. The full lines mark the $\sim t^{-1}$ behavior for the density, and $\sim t^{-2}$ for the order parameter. Dot-dashed lines represent same quantities in the presence of an additional single-particle pump that keeps the density constant. Dashed lines represent the dissipative dynamics considering single-particle losses in place of the two-body ones. The inset shows the timescale of the crossover from the exponential to power law behavior of the order parameter amplitude (vertical lines in left panels).

from an exponential decay at short times followed by a slower power law decay on longer timescales. Importantly, we see that the decay of the order parameter is faster than the density and compatible with a power law decay $|\Delta| \sim 1/t^2$, whose origin we will discuss below. We argue that the crossover in the dynamics of the order parameter, occurring on a timescale τ which decreases with Γ (see inset in Fig. 1), is a key dynamical signature of a dissipative superfluid with two-body losses, and it is controlled by the slow depletion of the system. For comparison, we show in Fig. 1 the behavior obtained when only single-particle losses (dashed lines) are present, or in the presence of an additional single-particle pump to keep the density constant in time (dot-dashed lines) [81]. In both cases, the long-time behavior of the order parameter changes into an exponential decay. The same happens for the density in the single-particle loss case.

To gain further insights, we derive [81] the dynamical equation for the single-particle density $n = \frac{1}{V}\sum_{\mathbf{k}} \sigma^z_{\mathbf{k}} + 1$ from Eqs. (5)–(7),

$$\frac{dn}{dt} = -2\Gamma|\Delta|^2 - \Gamma n^2. \tag{8}$$

The first term in Eq. (8) describes the depletion due to losses of Cooper pairs [62], while the second one accounts for the contribution of noncondensed pairs. This term, which arises due to the effective single-particle losses included in our variational approach [see Eq. (3)], is always present even when the system is in the normal phase and it becomes dominant

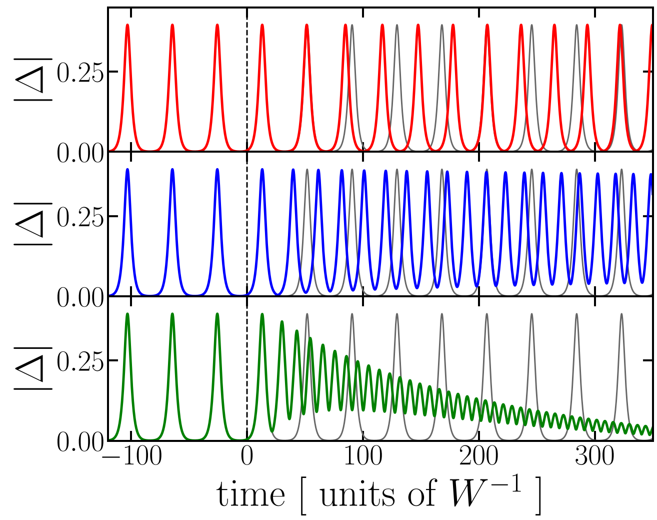

FIG. 2. Dynamics after a sudden quench of the interaction $|U_i|/W = 0.125 \rightarrow |U_f|/W = 1.0$. For $-200 < \text{time}\, W < 0$, the dynamics is unitary. For positive times, we switch on a finite dissipation, $\Gamma/|U_f| = 10^{-7}$, 10^{-4}, and 0.005, from top to bottom. In all the panels, the light gray lines represent the corresponding unitary dynamics.

at long times, correctly ensures that the steady state is the vacuum independent of the initial state. In fact, this second term is responsible for the power-law decay of the density, as one can readily understand by disregarding the order parameter, which gives $\dot{n} \sim -n^2$, implying $n \sim 1/t$. We can now understand the long-time behavior of the superfluid order parameter described in Fig. 1. Due to two-body losses, each of the $\sigma^{x/y}_{\mathbf{k}}$ components of Anderson pseudospin experience an effective single-particle dissipation $\Gamma_{\text{eff}} = n(t)\Gamma$ decreasing as $1/t$ at long times, leading to a $\sim 1/t$ power-law decay for each $\mathbf{k}$ mode. In addition, due to the pseudospin precession, each mode acquires a time dependent phase which depends on the momentum $\mathbf{k}$ and leads to an additional dephasing of the order parameter. At long times, when $|\Delta| \ll 1$, we have $\sigma^{x,y}_{\mathbf{k}} \sim e^{i2\varepsilon_{\mathbf{k}}t}/t$ and the sum $\sum_{\mathbf{k}} e^{i2\varepsilon_{\mathbf{k}}t}$ gives an additional $\sim 1/t$ decay, thus explaining the overall $1/t^2$. The crossover from exponential to power-law decay in the order parameter is controlled by the timescale at which the particle density enters the power-law decay regime. On the other hand, if the particle density is kept constant (by means of an additional pump) or in the presence only of single-particle losses, the decay rate for the pseudospins is constant in time, giving rise to an order parameter which decays exponentially [81].

Results: Double quench. We now consider the dynamics after a double quench, where first at some negative time the pairing interaction is suddenly changed $U_i \rightarrow U_f$ and then the two-body losses are suddenly switched on at time $t = 0$. This dynamical protocol allows us to discuss the effect of correlated dissipation on the dynamical synchronization transition [14–17] that is known to occur in the isolated case.

In Fig. 2, we plot the dynamics of the order parameter $\Delta(t)$ after a quench of the pairing attraction from $|U_i|/W = 0.125$ to $|U_f|/W = 1.0$, corresponding to the synchronized BCS regime in the isolated system, and for increasing values of two-body losses. We compare this dynamics to the purely

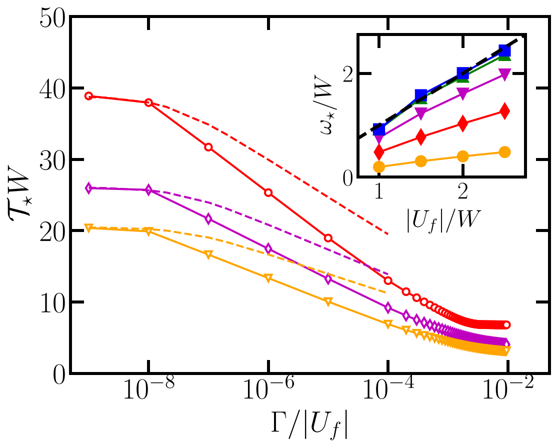

FIG. 3. Period of coherent oscillations as a function of the dissipation and different values of the final interaction $|U_f|/W = 1.00$ (circles), 1.50 (diamonds), and 2.00 (down triangles). Dashed lines indicate the analytic estimate using the dissipative soliton solution. (Inset) Frequency of oscillations $\omega_\star = 2\pi/\mathcal{T}_\star$ plotted as a function of $|U_f|$, and different values of the $\Gamma/|U_f| = 10^{-7}$ (circles), 10^{-4} (diamonds), 10^{-3} (down triangles), 5×10^{-3} (up triangles), and 10^{-2} (squares). Dashed line indicates the $\omega_\star = |U_f|$ line.

unitary case (gray lines in the background of each panel) where we recognize the characteristic coherent oscillations of the order parameter, with a period controlled by the ratio between initial and final gap [15]. We see that the switching of the dissipation at $t = 0$ drastically changes the time evolution, inducing not only a damping of coherent oscillations but also a substantial renormalization of their frequency, which increases with Γ. Remarkably we note from the upper panel of Fig. 2 that even a tiny dissipation, corresponding to $\Gamma/|U_f| = 10^{-7}$, has a sizable effect on the oscillation frequency. To highlight this point, we extract the dominant frequency $\omega_\star$ of the coherent oscillations of the order parameter, obtained by Fourier transforming the real-time signal over a time window $\Delta T = 1000W^{-1}$, and plot the associated period $\mathcal{T}_\star = 2\pi/\omega_\star$ in Fig. 3 as a function of $\Gamma/|U_f|$. We see that $\mathcal{T}_\star$ depends strongly on the losses, with a nonlinear behavior that we fit with a logarithmic dependence $\mathcal{T}_\star \sim -\ln(e^{-\mathcal{T}_\star^0} + c\frac{\Gamma}{|U_f|})$ where $\mathcal{T}_\star^0$ is the oscillation period in the isolated case and c a numerical prefactor. As the dissipation is increased, even though remaining a small fraction of the interaction $|U_f|$, we see that the frequency $\omega_\star$ tends to saturate to a value $\omega_\star = |U_f|$; see Fig. 3 (inset).

The fact that the dissipation changes so dramatically the frequency of oscillations of the order parameter is the second important result of this work. We can understand this effect by constructing a dissipative soliton solution for the BCS problem, assuming that the Anderson pseudospin norm conservation is weakly broken [81]. For small dissipation $\Gamma/|U_f| \to 0$, we consider an effectively unitary dynamics with a renormalized pseudospin length which we determine self-consistently. We obtain a dissipative soliton train solution [15] with period $\mathcal{T}_\star(\Gamma) = 2K(1 - \alpha(\Gamma)^2)/|U_f|\Delta_+(\Gamma)$, where $\alpha(\Gamma) = \Delta_-(\Gamma)/\Delta_+(\Gamma)$ and K is the complete elliptic integral of the first kind. The period depends on dissipation through the soliton amplitudes $\Delta_\pm(\Gamma)$ obtained by the solution of the self-consistent equations [81]. Remarkably, the dissipative soliton captures qualitatively well the logarithmic dependence of the oscillation period on the dissipation; see Fig. 3 dashed lines. Quantitatively, the dissipative solitons underestimate the frequency renormalization. This can be expected as the above argument is strictly valid only for times $t \sim \mathcal{T}_\star$, whereas the numerical frequencies are extracted by averaging over a large number of periods $\Delta T \gg \mathcal{T}_\star$. At large times, $\Gamma t \gg 1$ the dissipative solitons are washed away by the decay of the nonequilibrium superconducting pairs which occurs through excitations of energy $\sim |U_f| \gg 2\pi/\mathcal{T}_\star$ and determine a faster oscillatory dynamics. For $\Gamma/|U_f| \gtrsim 10^{-2}$, the decay dynamics quickly takes over the dissipative solitons, thus leading to the observed saturation to $\omega_\star = |U_f|$.

Conclusions. In this work, we have studied the dissipative dynamics of a fermionic superfluid with two-body losses. We have used a time-dependent variational method for open quantum systems, from which the resulting dynamics takes the form a BCS problem with complex pairing interactions and effective single-particle losses that were disregarded in previous works [61,62]. We show that the latter plays a key role for the dynamics of the system. It underlies both the power-law decay of particle density and order parameter after a dissipation quench as well as the strong renormalization of the period of coherent oscillations after a quench of dissipation and pairing interaction. We have qualitatively captured this latter effect in terms of a dissipative soliton solution.

Our results highlight the nontrivial nature of many-body dissipative processes in giving rise to power-law dynamical regimes and, in particular, to novel regimes of superfluidity. Future directions opened by this work include the study of Zeno-like superfluid dynamics in the strongly dissipative regime as well as the application of the variational dynamics to strongly correlated dissipative many-body systems, such as the dissipative Fermi-Hubbard model [43]. Finally, it would be interesting to investigate how the signatures of this dissipative dynamics can be observed in experiments with dissipative gases and cavity QED simulators.

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[81] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevA.107.L051301 for (i) the derivation of the bcs dissipative dynamics by using a time-dependent variational principle for the density matrix, (ii) the discussion of the long-time dynamics after a quench of dissipation, and (iii) the frequency renormalization after a double quench through a soliton solution.