cloud that initially has two well separated density peaks (Fig. 3). The reason can be captured by the following argument. The fluid cells $[x, x+\delta x]$ that are around either of the two peaks contain more quasi-particles, including quasi-particles of large rapidities, than the fluid cells near the center at $x = 0$. Under time-evolution, the quasi-particles from the left peak that have a large positive rapidity $+u$ soon meet the ones coming from the right peak that have a large negative rapidity $-u$, around $x = 0$. Then, the distribution of rapidities near $x = 0$ is double-peaked, with maxima at $v \simeq \pm u$, so it is clearly very far from a thermal equilibrium distribution, which would be single-peaked. This phenomenon is obvious for non-interacting particles, Eq. (2) reducing to the standard Liouville equation, and GHD calculations indicate that this is true also for interacting particles [17, 54].

Expansion from a double-well. To realize the above scenario, we prepare a cloud of $N = 6300 \pm 200$ atoms, with $\omega_\perp = 2\pi \times (8.1 \pm 0.03)$ kHz, at thermal equilibrium in a longitudinal double-well potential $V(x)$, such that the atomic density presents two well separated peaks, the peak density corresponding to $\gamma = (2.45 \pm 0.07) \times 10^{-2}$. Then at $t = 0$ we suddenly switch off the potential $V(x)$ and measure the in situ profiles at time $t = 10$, 25, 40, 55 ms (Fig. 3).

To compare with theoretical predictions, we need to know the initial temperature T of the cloud. However we cannot estimate T from fitting the initial density profile $n_0(x)$ with the Yang-Yang equation of state and LDA because we do not have a good knowledge of the initial potential $V(x)$ that we create on the chip. Instead, we proceed as follows. First we postulate an initial temperature T and construct the initial rapidity distribution $\rho_T(x, v)$ such that, for a given x, $\rho_T(x, v)$ is the thermal equilibrium rapidity distribution of Yang-Yang [40] at temperature T and density $n_0(x)$. We then evolve $\rho_T(x, v)$ using GHD and compute $n_T(x, t)$. While, by construction, $n_T(x, 0) = n_0(x)$, $n_T(x, t)$ may differ from the data at later times. We repeat this procedure for several initial temperatures and we select the value of T whose time evolution is in best agreement with the data [55]. We obtain $T \simeq 0.3\,\mu$K, corresponding to $\theta \simeq 2 \times 10^2$, see Fig. 2(b).

The comparison between the expansion data and GHD is shown in Fig. 3(i); the agreement is excellent. We also simulate the time-evolution of the cloud with CHD, for the exact same initial state. As we expected, expanding from a double-well potential reveals a clear difference between CHD and GHD, see Fig. 3(ii). Two large density waves emerge in CHD and large gradients develop, eventually leading to shocks [14], features which are not seen in GHD [54].

Quench from double-well to harmonic potential. Finally, we trap $N = 3500 \pm 140$ atoms, with $\omega_\perp = 2\pi \times (5.4 \pm 0.02)$ kHz, in a double-well potential, and we study the evolution of the cloud after suddenly switching off the double-well and replacing it by a harmonic potential of frequency $\omega_\parallel = 2\pi \times (6.5 \pm 0.03)$ Hz. We measure the in situ profiles at time $t = 0, 20, 40, \ldots, 180$ ms, see Fig. 4. The initial peak density corresponds to $\gamma = (2.13 \pm 0.07) \times 10^{-2}$. To estimate the temperature of the cloud, we proceed as in the previous case [55]; we find $T \simeq 0.15\,\mu$K, corresponding to $\theta \simeq 2.2 \times 10^2$ (Fig. 2(b)).

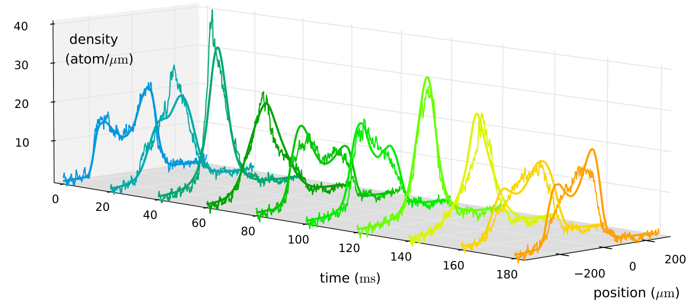

FIG. 4. Quench from double-well to harmonic potential, compared to the GHD prediction, with an atomic cloud that contains $N = 3500 \pm 140$ atoms initially. The main features of the experimental data are well reproduced by GHD. One experimental effect, not modeled in GHD, that appears to be particularly important, are the three-body losses: after 180 ms, the number of atoms drops by approximately 15%.

This quench protocol mimics the famous quantum Newton's Cradle experiment [56] —see also Refs. [57, 58] for recent realizations—, which is realized here in a weakly interacting gas. Exactly like in the previous paragraph, this is a situation where GHD predicts the appearance of non-thermal rapidity distributions [17, 59], and must therefore differ strongly from CHD. In fact, we have observed that CHD develops a shock at short times (around $t \simeq 30$ ms), so it is simply unable to give any prediction for the whole evolution time investigated experimentally [60].

Importantly, the motion is not periodic, contrary to what would be seen purely in the IBG or in the strongly interacting fermionized regime. Nevertheless, the motion of the cloud preserves an *approximate* periodicity, with a period close to, but slightly longer than, $2\pi/\omega_\parallel$ [59] (of course, if the cloud was symmetric under $x \to -x$, the period would be divided by two). At a quarter of the period —and three quarters of the period—, the density distribution shows a single thin peak located near $x = 0$. We find good agreement with the GHD predictions, with the initial temperature T as the only free parameter [55]. However, experimental effects not taken into account by the GHD equations (2) appear to be more important in this setup than in the previous ones of Figs. 1-3, where shorter times were probed. For instance, the number of atoms N is not constant in our experimental setup: it decreases with time and drops by approximately 15% after 180 ms, probably because of three-body losses which occur at large density. This might partially explain the difference between the experimental density profile and the GHD one. We also suspect the small residual roughness of the potential $V(x)$ of affecting the experimental profiles.