the problem, and there is negligible tunnelling among the tubes. We can vary the weighted average number of atoms per tube, N_{tube}, and the axial oscillation period, τ. For a given array, τ is the same to within 6% for all 1,000–8,000 tubes. The 1D coupling strength is given by $\gamma = |2/a_{1\mathrm{D}} n_{1\mathrm{D}}|$, where $n_{1\mathrm{D}}$ is the 1D density, $|a_{1\mathrm{D}}| \approx a_{\mathrm{r}}^2/2a$ is the 1D scattering length, $a = 5.3$ nm is the three-dimensional (3D) scattering length, $a_{\mathrm{r}} = (\hbar/m\omega_{\mathrm{r}})^{1/2} = 41.5$ nm is the transverse oscillator width, and m is the Rb mass[18].

To study the 1D Bose gases, we turn off the crossed dipole trap and allow the atoms to expand in one dimension for 27 ms before taking an absorption image from the transverse direction. When we integrate the image transverse to the tubes, we get a 1D spatial distribution that corresponds to the momentum distribution after expansion, $f(p_{\mathrm{ex}})$. Although the individual 1D gases have Thomas–Fermi or Tonks–Girardeau $f(p_{\mathrm{ex}})$ profiles, we measure gaussian $f(p_{\mathrm{ex}})$ distributions, as expected when the $f(p_{\mathrm{ex}})$ for many 1D Bose gases with different N_{tube} are summed.

To create non-equilibrium momentum distributions, we pulse on a 3.2 THz detuned 1D lattice along the tubes, which acts as a phase grating for the atoms. Two pulses, with intensity 11 W cm^{-2} and pulse widths of 23 μs separated in time by 33 μs, can deplete the zero momentum state and transfer atoms to $\pm 2\hbar k$ peaks[19,20] where k is the wavevector of the 1D lattice light. We wait after the grating pulses for a variable time, t, before measuring $f(p_{\mathrm{ex}})$. Figure 2 shows a time series of absorption images spanning a full oscillation in the crossed dipole trap, when the weighted average of the initial peak γ in each tube, γ_{o}, is 1.0. The two momentum groups collide with each other in the centre of the crossed dipole trap twice each full cycle, for instance at $t = 0$ and $\tau/2$, as illustrated in Fig. 1b. The total collision energy is $8(\hbar k)^2/2m = 0.45\hbar\omega_{\mathrm{r}}$, less than one-quarter the energy needed for transverse vibrational excitation[21], so the colliding gases remain 1D.

The first and last images in Fig. 2 differ because the oscillating atoms dephase. Illustrated conceptually in Fig. 1b, there is dephasing due to the gaussian crossed dipole trap anharmonicity, which gives an ~8% spread of τ across the full-width at half-maximum of each of the colliding clouds. The top curves in Fig. 3a–c show the time-averaged $f(p_{\mathrm{ex}})$ over the first cycle for different γ_{o}. Differences in shape among them reflect the initial energy per particle, which increases with $n_{1\mathrm{D}}$, and hence γ_{o}^{-1}. Within 10τ to 15τ, $f(p_{\mathrm{ex}})$ stops changing noticeably during an oscillation period. The central observations in this letter are of the evolution of $f(p_{\mathrm{ex}})$ that are dephased, like the lower curves of Fig. 3a–c. Comparing only dephased distributions avoids the complication of how the momentum distribution in the trap evolves into $f(p_{\mathrm{ex}})$ during expansion, which may slightly depend on the initial spatial distributions. As atoms have clearly dephased within each tube, dephasing among tubes is irrelevant.

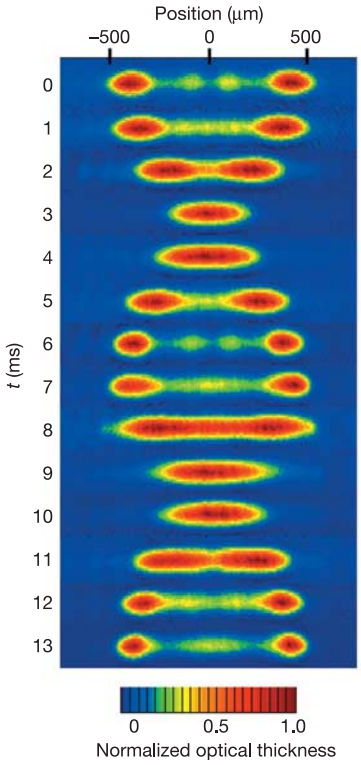

Figure 2 | Absorption images in the first oscillation cycle for initial average peak coupling strength $\gamma_{\mathrm{o}} = 1$. Atoms are always confined to one dimension, in this case in 3,000 parallel tubes, with a weighted average of 110 atoms per tube. After grating pulses put each atom in a superposition of $\pm 2\hbar k$ momentum, they are allowed to evolve for a variable time t in the anharmonic 1D trap (crossed dipole trap), before being released and photographed 27 ms later. The false colour in each image is rescaled to show detail. These pictures are used to determine $f(p_{\mathrm{ex}})$. The first image shows that some atoms remain near $p_{\mathrm{ex}} = 0$ at $t = 0$. How many remain there depends on $n_{1\mathrm{D}}$, implying that these remnant atoms do not result from an imperfect pulse sequence, but rather from interactions during the grating pulses or evolution of the momentum distribution during expansion. The relative narrowness of the peaks in the last image compared to the first is indicative of the reduction in spatial density that results from dephasing (Fig. 1b). The transverse spatial width of each of the 14 image frames is 70 μm. Horizontal in the figure corresponds to vertical in the experiment, a minor distinction because a magnetic field gradient cancels gravity for the atoms.

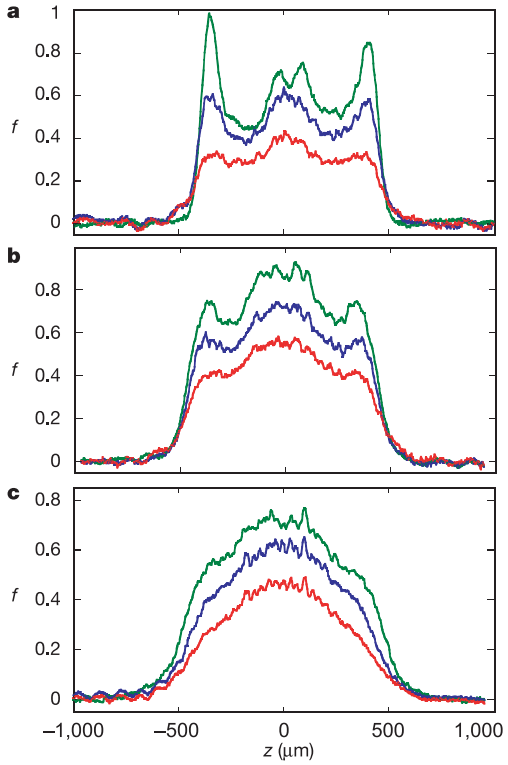

Figure 3 | The expanded momentum distribution, $f(p_{\mathrm{ex}})$, for three values of γ_{o}. The curves are obtained by transversely integrating absorption images like those in Fig. 2. The spatial position, z, is approximately proportional to the expanded momentum, p_{ex}. The vertical scale is arbitrary, but consistent among the curves. **a**, $\gamma_{\mathrm{o}} = 4$; **b**, $\gamma_{\mathrm{o}} = 1$; and **c**, $\gamma_{\mathrm{o}} = 0.62$. The highest (green) curve in each set is the average of $f(p_{\mathrm{ex}})$ from the first cycle, that is, from the images like those in Fig. 2. The lower curves in each set are $f(p_{\mathrm{ex}})$ taken at single times, t, after the atoms have dephased: **a**, $\tau = 34$ ms, $t = 15\tau$ (blue) and 30τ (red); **b**, $\tau = 13$ ms, $t = 15\tau$ (blue) and 40τ (red); and **c**, $\tau = 13$ ms, $t = 15\tau$ (blue) and 40τ (red). The changes in the distribution with time are attributable to known loss and heating. (See Supplementary Information for a discussion of the fine spatial structure in these curves.)