Breathing modes of a 1D Bose gas

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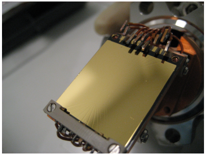
Outline

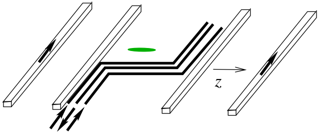
Outline

Realisation of very anisotropic traps on an atom chip

Magnetic confinement of $^{87}R_b$ by micro-wires

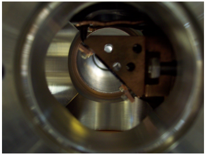
A 3-wire guide

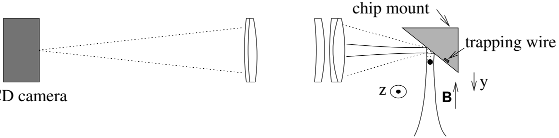




$$\begin{cases} \omega_\perp/2\pi = 2 - 40 \text{ kH} \\ \omega_z/2\pi = 5 - 10 \text{ Hz} \end{cases}$$

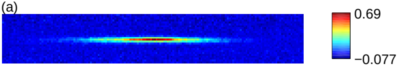
$$1\text{D} : T, \mu \ll \hbar\omega_\perp$$
$$g = 2\hbar\omega_\perp a$$





In-situ images

absolute calibration



$$T \simeq 400 - 15nK$$
$$\simeq 3.0 - 0.1\hbar\omega_\perp$$
$$N \simeq 5000 - 1000.$$

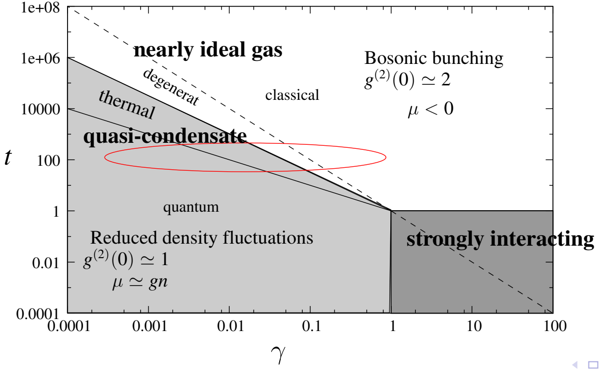
1D Bose gas with repulsive contact interaction

$$H = -\frac{\hbar^2}{2m}\int dz\psi^+ \frac{\partial^2}{\partial_z^2}\psi + \frac{g}{2}\int dz\psi^+\psi^+\psi\psi,$$

Exact solution : Lieb-Liniger Thermodynamic : Yang-Yang (60') n, T

Length scale : $l_g = \hbar^2/mg$, Energy scale $E_g = g^2 m/2\hbar^2$

Parameters : $t = T/E_g$, $\gamma = 1/nl_g = mg/\hbar^2 n$

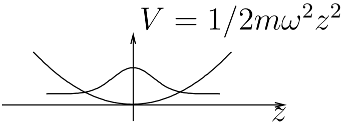


Smooth crossovers

Quasi-condensation : $t \simeq \gamma^{-3/2}$

Trapped 1D Bose gas

Local density approach :
$\mu(z) = \mu_0 - m\omega^2 z^2/2$

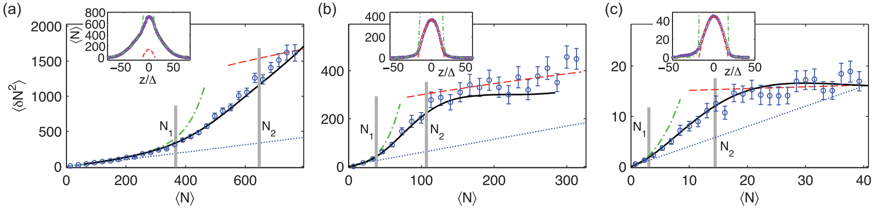


Local density and correlations properties :
that of a homogeneous gas with $\mu = \mu(z)$.
Validity : $l_c \ll \frac{1}{n}\frac{dn}{dz}$.

- $t \ll \gamma(z=0)^{-3/2}$: cloud deeply into quasi-condensate regime. $\mu \simeq gn \Rightarrow$ Thomas Fermi shape $\rho(z) = \rho_0(1-(z/Z_{TF})^2)$
- $t \ll \gamma(z=0)^{-3/2}$: cloud into ideal Bose gas regime
- General : $\rho(z)$ knonwed for a given T and ρ_0 (Yang-Yang)

Exploiting in-situ images

- Fitting with Yang-Yang the density profile $\Rightarrow T$
- Measuring density fluctuations $\Rightarrow T = \Delta \partial\rho/\partial\mu$



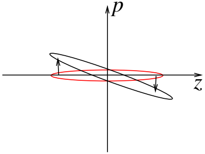
Beyond purely 1D physics :

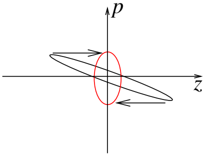
- In the quasi-condensate regime if $\mu \gtrsim \hbar\omega_\perp$. $\Rightarrow$ quasi-condensate equation of state $\mu = \hbar\omega_\perp\sqrt{1+4\rho a}$
- Thermally populated excited transverse states : treated as ideal Bose gases.

Momentum distribution measurement

Focussing techniques

- Short kick of a strong harmonic potential
$\Rightarrow \delta p = -Az$





- Free fligh until focuss

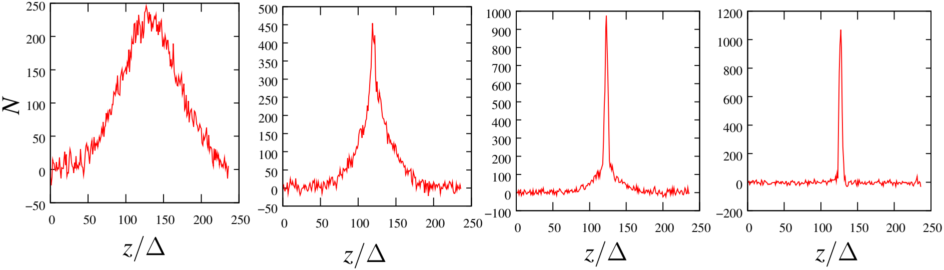
Final spatial distribution : initial momentum distribution, averaged over the initial position

Experiment well adapted :

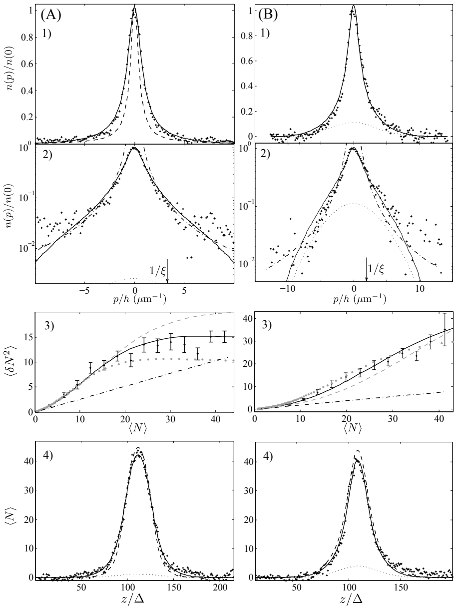
- longitudinal confinement undependent on transverse one
- Purely harmonic potential (up to order z^5)

Momentum distribution measurement

Images taken at focus ($t_v = 15$ms) for different initial temperatures (initial RF knife position)



Momentum distribution measurement



Momentum distribution compared with Quantum Monte Carlo

Healing length :

$\xi = \hbar/\sqrt{m\rho_0 g}$

Data A :

Quasi-condensate

$\Delta p \ll \hbar/\xi$

Data B :

Degenerate nearly ideal Bose gas

$\Delta p > \hbar/\xi$

Outline

Hydrodynamic breathing mode

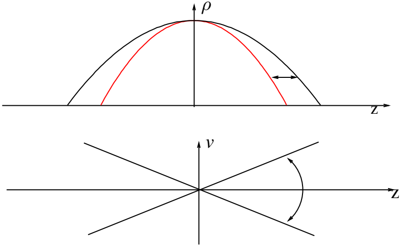
Long wave length perturbation : hydrodynamic equations

$$\begin{cases} \partial_t \rho + \partial z(\rho v) = 0 \\ m\rho\partial_t v + \rho\partial_z(V + mv^2/2) + \partial_z p = 0 \end{cases}$$

Quasi-condensate equation of state : $p = -\partial E/\partial V = gn^2/2$

$V = 0$, small perturbations : phonons $\omega = ck$, $c = \sqrt{\rho g}$

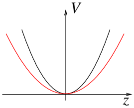
V harmonic and $\rho(t=0)$ inverted parabola : self similar solution

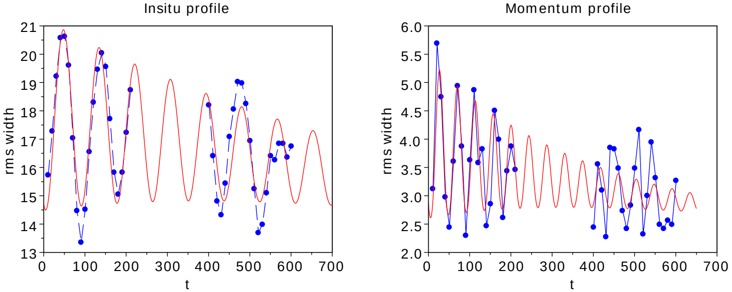


$$\rho(t,z) = \rho(t=0, z/\eta)/\eta$$

Experimental observation

Quench of the longitudinal confinement





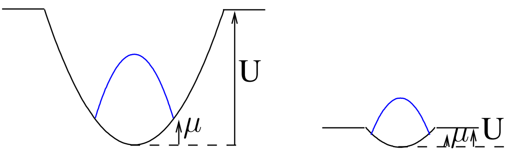
Insitu profile : $\omega_B = 0.94\sqrt{3}\omega_D$ Momentum profile : $\omega_{Bp} = 2\omega_B$

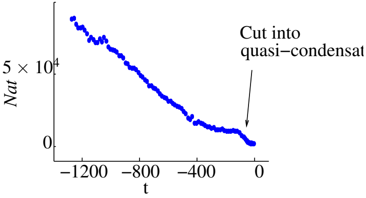
Very large amplitude in momentum space : $P \simeq (\hbar/\xi)\Delta\sigma/\sigma$

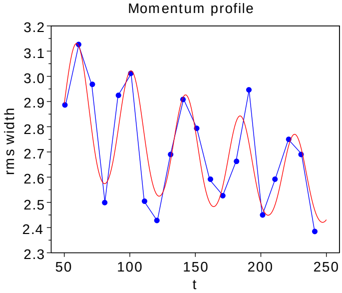
First observation in momentum space.

Breathing mode excited by strong evaporation

Cutting into the Thomas-Fermi profile by RF knife



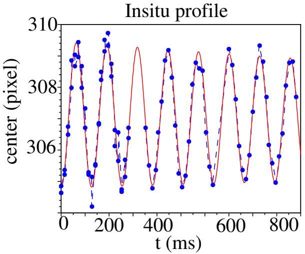


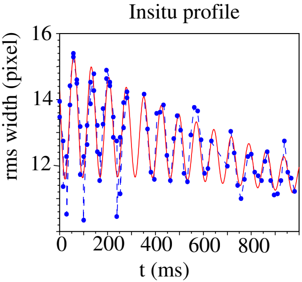


$$\omega_{Bp} = 0.98 \times 2\sqrt{3}\omega$$

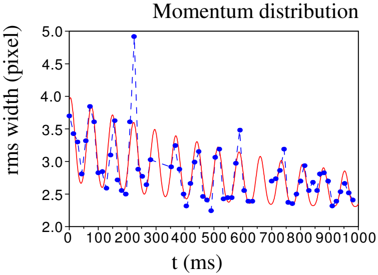
Outline

Ab-normal breathing mode resulting from evaporation



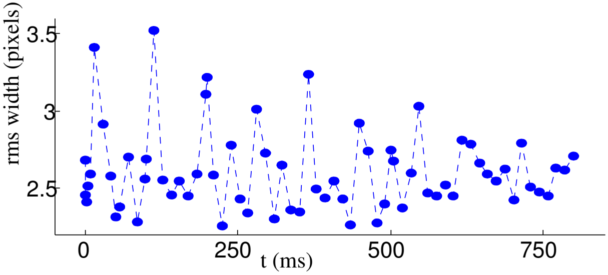


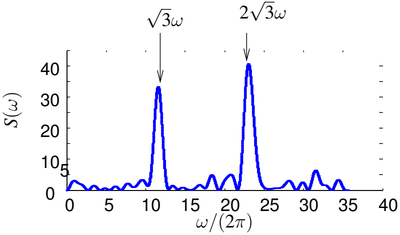
$$\omega_B = 1.01 \times \sqrt{3}\omega_D$$



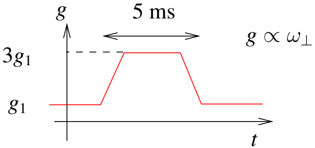
$$\omega_{Bp} = 1.00 \times \sqrt{3}\omega_D$$

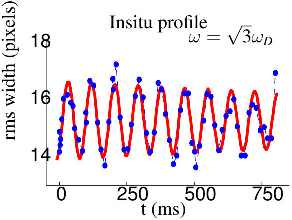
Co-existence of both modes

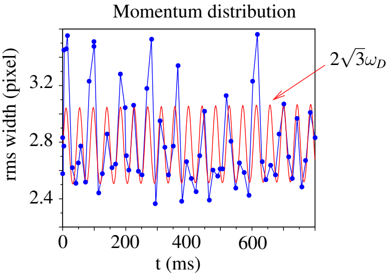


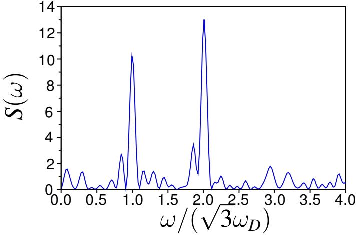


Effect of a quench of g









Both frequency visible.

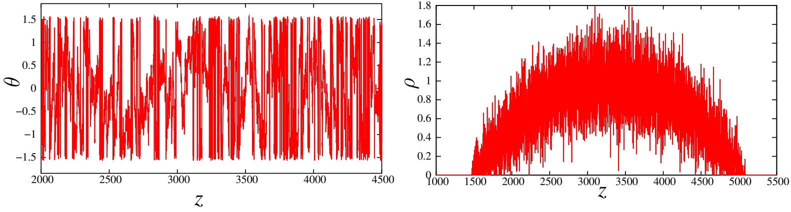
Physical origin ?

Adiabatic temperature change to the compression of the gas ?
Not the good order of mangnitude

Gross-Pitaevski calculations.
Initial thermal state : use Local density approximation

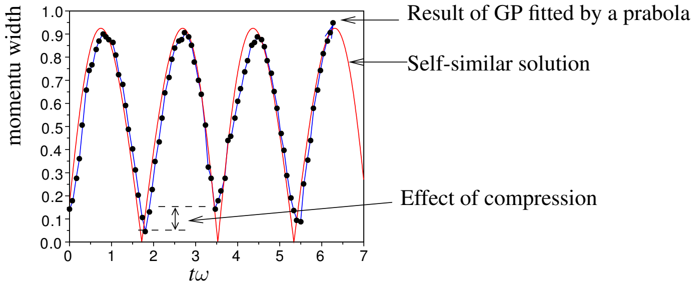
$$\langle(\theta(z)-\theta(z'))^2\rangle = mT/(\hbar^2\rho)|z-z'| \Rightarrow \text{Random walk}$$

$$\langle\delta\rho(z)\delta\rho(z')\rangle = mT/(\hbar^2)\sqrt{mg/(\hbar^2\rho)}e^{-2|z-z'|/\xi} \Rightarrow \text{Ornstein-Uhlenbeck}$$



Gross-Pitaevski calculations

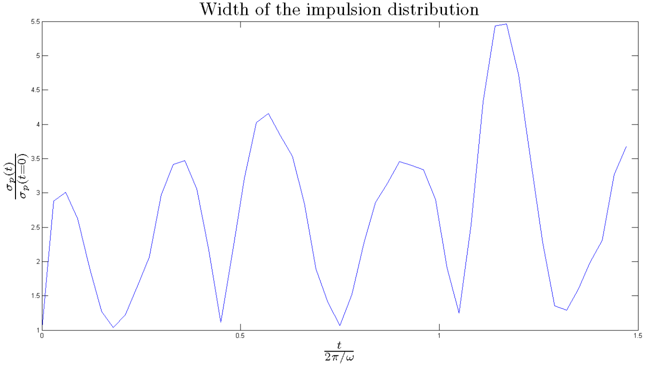
Time evolution according to Gross-Pitaevski after a quench of ω_z



Do not account for experimental observation

Gross-Pitaevski calculations : quench of g

Time evolution according to Gross-Pitaevski after the quench of g. Experimental parameters used

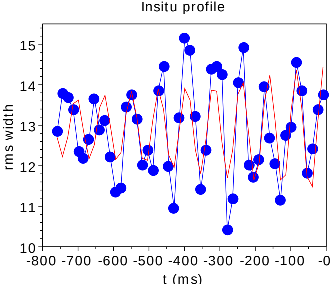


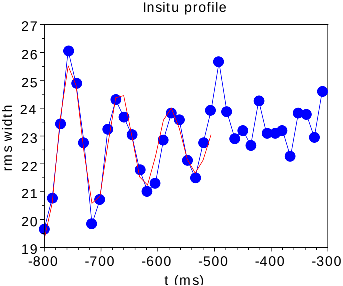
Do not account for experimental observation

Outline

Breathing mode frequency

- Quasi-condensation cross-over : $\omega : \sqrt{3}\omega \to 2\omega$
- Dimensionnal crossover (within quasi-bec) : $\omega : \sqrt{3}\omega \to \sqrt{5/2}\omega$



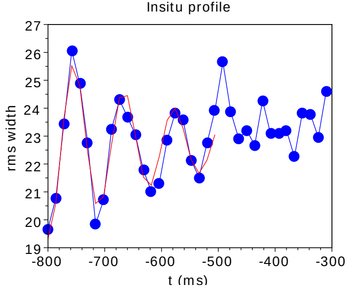


$\omega_B = 1.89\omega_D$
T from profile : 80 nK,
T from fluctuations : 20 nK

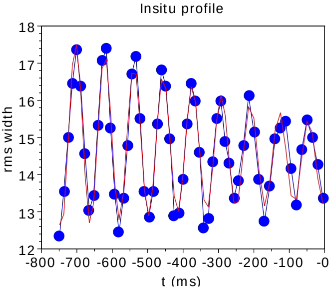
$T \simeq 180nK = 1.9\hbar\omega_\perp$
$\mu/(\hbar\omega_\perp) \simeq 0.1$

Lifetime of the breathing mode

- 3D case : lifetime limited by phonons/phonons coupling at non zero temperature.
- 1D case ?



$T \simeq 180nK = 1.9\hbar\omega_\perp$

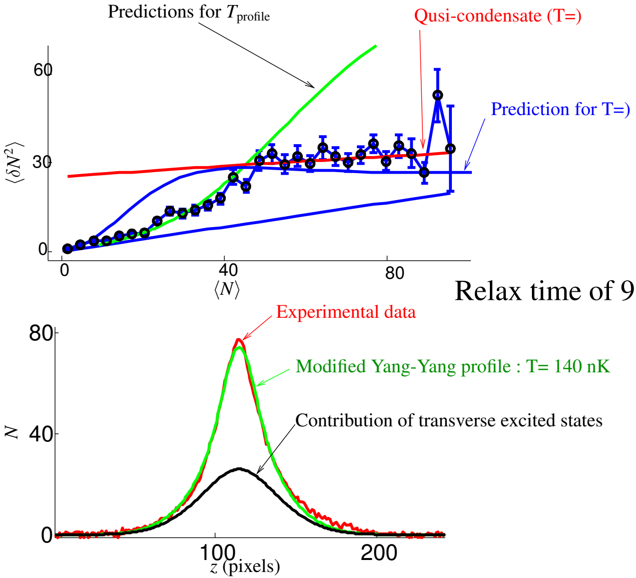


$T \simeq 30$ nK

$\tau = 850$ ms

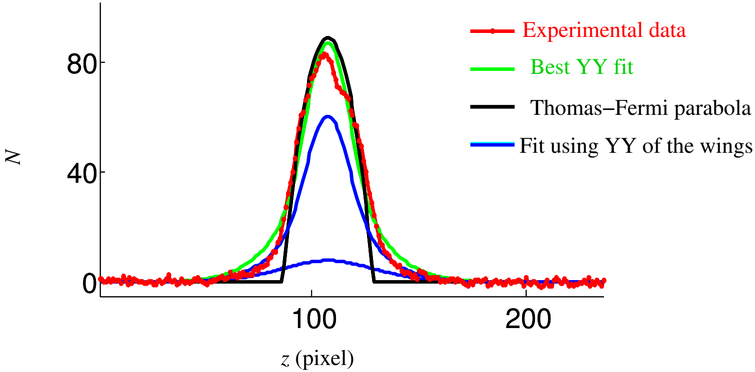
Outline

Long-lived out-of-equilibrium stationnary states

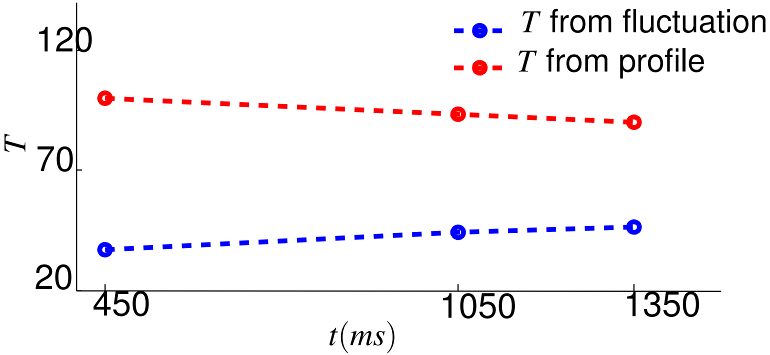


Relax time of 950 ms !

Long lived states with strange profile



Satbility of the non-equilibrium state



Outline

Conclusion and prospetcs

Conclusion

- First observation of the breathing mode in momentum space
- A strange behavior of the momentum distribution associated with breathing mode at finite temperature
- Very long lived out of thermal equilibrium states

Prospects

- Investigating the breathing mode frequency and lifetime across the quasi-condensation.
- Investigate the breathing mode frequency and lifetime across the dimensional crossover
- Relation of the long lived out of thermal equilibrium states with intergrability ? Change the 1D-ness (difficult) or add a lattice.
- Investigating effect of quenches of g.
- Going towards strongly interacting gases