Matter-wave interferometery of a free-falling nanoparticle

James Bateman
(M. Rashid, D. Hempston, J. Vovrosh, & H. Ulbricht)

Matterwave Group
School of Physics & Astronomy
University of Southampton
Southampton, SO17 1BJ, UK

`jbateman@soton.ac.uk`

Frascati, 28–30 April 2014

Overview

UNIVERSITY OF Southampton

Interference of 10^6 amu particles with optically resolvable fringes

Near-field interferometry of a free-falling nanoparticle from a point-like source, Bateman, Nimmrichter, Hornberger, & Ulbricht, `arXiv:1312.0500`

Overview

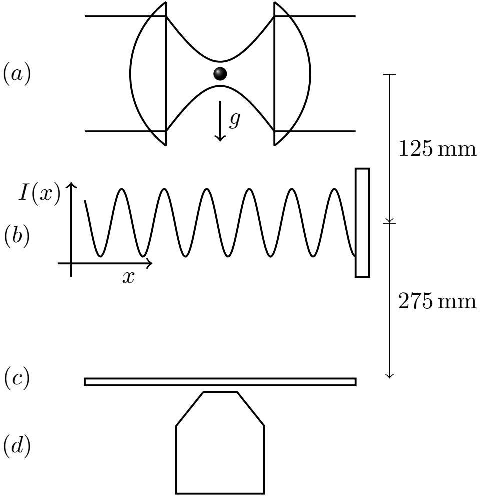
Interference of 10^6 amu particles with optically resolvable fringes

Near-field interferometry of a free-falling nanoparticle from a point-like source, Bateman, Nimmrichter, Hornberger, & Ulbricht, `arXiv:1312.0500`

"Macroscopicity of Mechanical Quantum Superposition States"
Nimmrichter, Hornberger, PRL **110**, 160403 (2013)

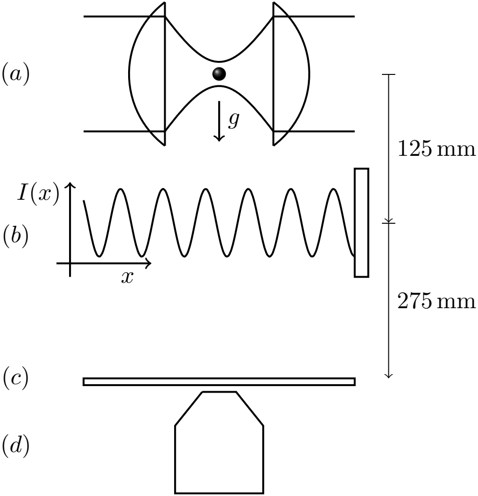
Schematic

(a) Nanoparticle in dipole trap
10^6 amu (10 nm sphere)
localised to < 30 nm



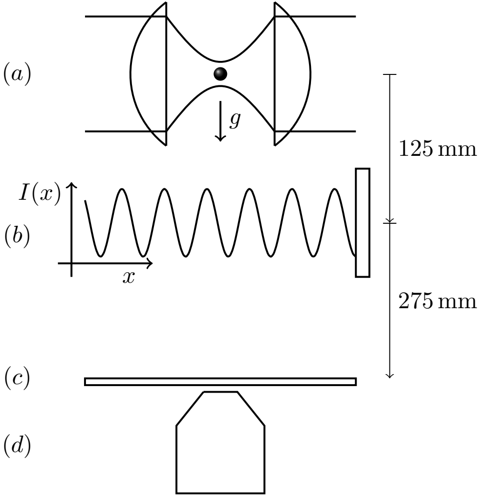
Schematic

- (a) Nanoparticle in dipole trap
  - 10^6 amu (10 nm sphere)
  - localised to < 30 nm
- (b) Phase grating
  - 177 nm period
  - ns, mJ, trippled Nd:YAG



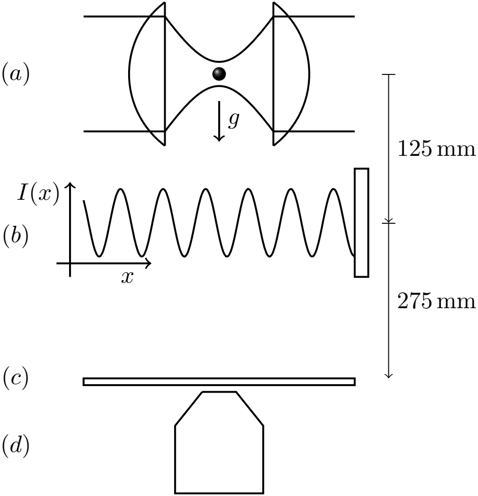
Schematic

- (a) Nanoparticle in dipole trap
  - 10^6 amu (10 nm sphere)
  - localised to $<$ 30 nm
- (b) Phase grating
  - 177 nm period
  - ns, mJ, trippled Nd:YAG
- (c) Glass slide
  - Fixed fall time $\approx$ 300 ms
  - Near-field (Fresnel)
  - Scaled Talbot effect



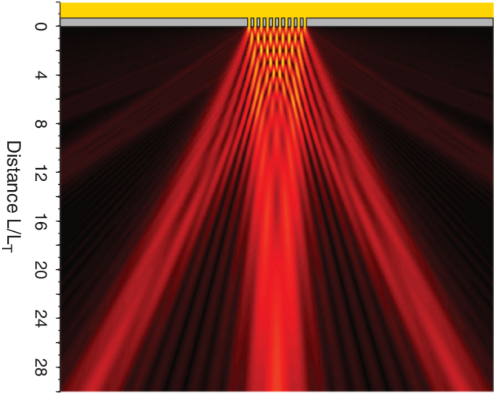
Schematic

- (a) Nanoparticle in dipole trap
  - 10^6 amu (10 nm sphere)
  - localised to < 30 nm
- (b) Phase grating
  - 177 nm period
  - ns, mJ, trippled Nd:YAG
- (c) Glass slide
  - Fixed fall time ≈ 300 ms
  - Near-field (Fresnel)
  - Scaled Talbot effect
- (d) Optical detection
  - High NA with fitting to PSF



Talbot Effect

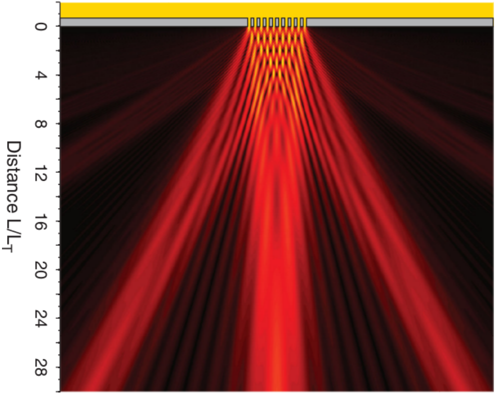
- Near-field (Fresnel)
- Periodic reconstruction
- Far-field
  → diffraction orders



Colloquium: Quantum interference of clusters and molecules
Hornberger, Gerlich, Haslinger, Nimmrichter, and Arndt,
`DOI: 10.1103/RevModPhys.84.157`

Talbot Effect

- Near-field (Fresnel)
- Periodic reconstruction
- Far-field
  → diffraction orders
- Plane-wave
  →same period as grating
- Point-source
  → geometrical scaling



Colloquium: Quantum interference of clusters and molecules
Hornberger, Gerlich, Haslinger, Nimmrichter, and Arndt,
`DOI: 10.1103/RevModPhys.84.157`

Phase-space description

for Wigner function introduction, see e.g. Case, Am. J. Phys. **76** 10 (2008)

Initial thermal state
of 200kHz harmonic trap

- $\sigma_x \sim 10\text{nm}$
- $\sigma_p/m \sim 10\text{mm/s}$
- Wigner $\rightleftharpoons$ Charateristic

$$w_0\left(x,p\right) = \frac{1}{2\pi\sigma_x\sigma_p}\exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{p^2}{2\sigma_p^2}\right)$$

$$w_0\left(x,p\right) \rightleftharpoons \chi_0\left(s,q\right) = \exp\left(-\frac{\sigma_x^2 q^2 + \sigma_p^2 s^2}{2\hbar^2}\right)$$

Phase-space description

for Wigner function introduction, see e.g. Case, Am. J. Phys. **76** 10 (2008)

Initial thermal state
of 200kHz harmonic trap

- $\sigma_x \sim 10\text{nm}$
- $\sigma_p / m \sim 10\text{mm}/\text{s}$
- Wigner $\rightleftharpoons$ Charateristic
- Fall for $t_1 = 160\text{ms}$
- Shearing $\rightarrow$ *locally* well-defined momentum

$$w_0(x, p) = \frac{1}{2\pi\sigma_x\sigma_p} \exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{p^2}{2\sigma_p^2}\right)$$

$$w_0(x, p) \rightleftharpoons \chi_0(s, q) = \exp\left(-\frac{\sigma_x^2 q^2 + \sigma_p^2 s^2}{2\hbar^2}\right)$$

Phase-space description

for Wigner function introduction, see e.g. Case, Am. J. Phys. **76** 10 (2008)

Initial thermal state
of 200kHz harmonic trap

- $\sigma_x \sim$ 10nm
- $\sigma_p/m \sim$ 10mm/s
- Wigner $\rightleftharpoons$ Charateristic
- Fall for $t_1 = 160$ms
- Shearing → *locally* well-defined momentum

$$w_0(x,p) = \frac{1}{2\pi\sigma_x\sigma_p}\exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{p^2}{2\sigma_p^2}\right)$$

$$w_0(x,p) \rightleftharpoons \chi_0(s,q) = \exp\left(-\frac{\sigma_x^2 q^2 + \sigma_p^2 s^2}{2\hbar^2}\right)$$

$$\chi_1(s,q) \approx \frac{\sqrt{2\pi}\hbar}{\sigma_p}\exp\left(-\frac{\sigma_x^2 q^2}{2\hbar^2}\right)\delta\left(s - \frac{qt_1}{m}\right)$$

Phase-space description

for Wigner function introduction, see e.g. Case, Am. J. Phys. **76** 10 (2008)

Initial thermal state
of 200kHz harmonic trap

- $\sigma_x \sim 10\text{nm}$
- $\sigma_p/m \sim 10\text{mm/s}$
- Wigner $\rightleftharpoons$ Charateristic
- Fall for $t_1 = 160\text{ms}$
- Shearing → *locally* well-defined momentum
- Grating interaction

$$w_0\left(x,p\right) = \frac{1}{2\pi\sigma_x\sigma_p}\exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{p^2}{2\sigma_p^2}\right)$$

$$w_0\left(x,p\right) \rightleftharpoons \chi_0\left(s,q\right) = \exp\left(-\frac{\sigma_x^2 q^2 + \sigma_p^2 s^2}{2\hbar^2}\right)$$

$$\chi_1\left(s,q\right) \approx \frac{\sqrt{2\pi}\hbar}{\sigma_p}\exp\left(-\frac{\sigma_x^2 q^2}{2\hbar^2}\right)\delta\left(s - \frac{q t_1}{m}\right)$$

Phase-space description

for Wigner function introduction, see e.g. Case, Am. J. Phys. **76** 10 (2008)

Initial thermal state
of 200kHz harmonic trap

- $\sigma_x \sim 10\text{nm}$
- $\sigma_p/m \sim 10\text{mm/s}$
- Wigner $\rightleftharpoons$ Charateristic
- Fall for $t_1 = 160\text{ms}$
- Shearing → *locally* well-defined momentum
- Grating interaction

$$w_0(x,p) = \frac{1}{2\pi\sigma_x\sigma_p}\exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{p^2}{2\sigma_p^2}\right)$$

$$w_0(x,p) \rightleftharpoons \chi_0(s,q) = \exp\left(-\frac{\sigma_x^2 q^2 + \sigma_p^2 s^2}{2\hbar^2}\right)$$

$$\chi_1(s,q) \approx \frac{\sqrt{2\pi}\hbar}{\sigma_p}\exp\left(-\frac{\sigma_x^2 q^2}{2\hbar^2}\right)\delta\left(s - \frac{q t_1}{m}\right)$$

$$\chi_1(s,q) \to \sum_n B_n(s/d)\,\chi_1(s, q + nh/d)$$

where $B_n(\xi) = J_n(\phi_0 \sin\pi\xi)$ or $J_n(\phi_0\pi\xi)$

Phase-space description

for Wigner function introduction, see e.g. Case, Am. J. Phys. **76** 10 (2008)

Initial thermal state of 200kHz harmonic trap

- $\sigma_x \sim 10\text{nm}$
- $\sigma_p/m \sim 10\text{mm/s}$
- Wigner $\rightleftharpoons$ Charateristic
- Fall for $t_1 = 160\text{ms}$
- Shearing → *locally* well-defined momentum
- Grating interaction
- Fall for $t_2 = 120\text{ms}$
- Spatial distribution $\int w(x,p)dp = \mathcal{F}\left[\chi(0,q)\right](x)$

$$w_0(x,p) = \frac{1}{2\pi\sigma_x\sigma_p}\exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{p^2}{2\sigma_p^2}\right)$$

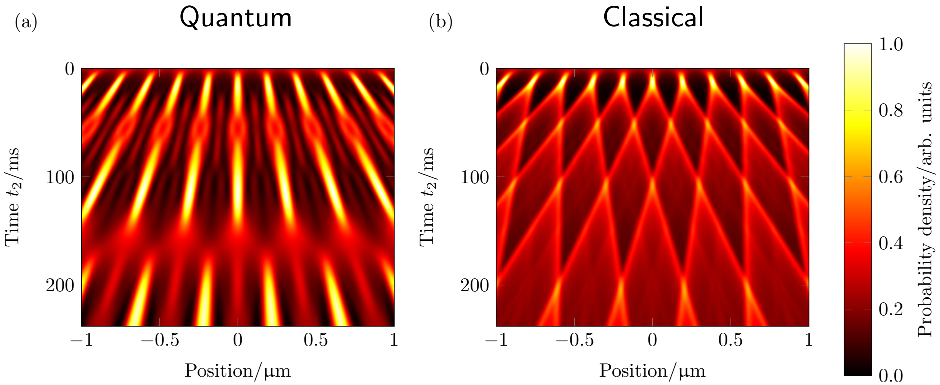
$$w_0(x,p) \rightleftharpoons \chi_0(s,q) = \exp\left(-\frac{\sigma_x^2 q^2 + \sigma_p^2 s^2}{2\hbar^2}\right)$$

$$\chi_1(s,q) \approx \frac{\sqrt{2\pi}\hbar}{\sigma_p}\exp\left(-\frac{\sigma_x^2 q^2}{2\hbar^2}\right)\delta\left(s - \frac{qt_1}{m}\right)$$

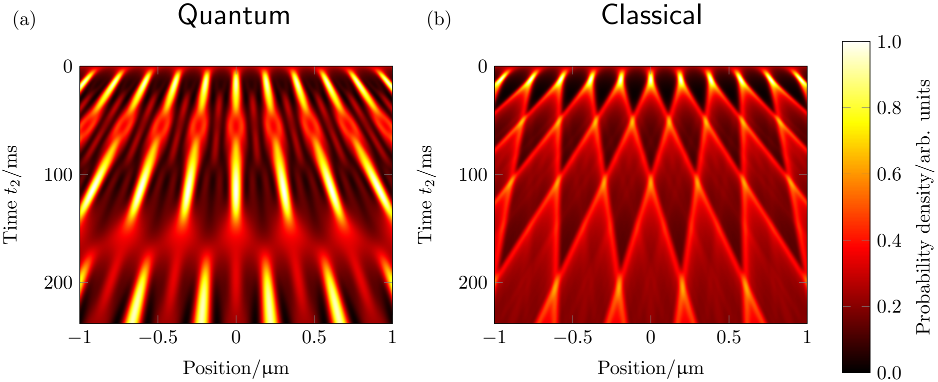
$$\chi_1(s,q) \to \sum_n B_n(s/d)\,\chi_1(s, q + nh/d)$$

where $B_n(\xi) = J_n(\phi_0 \sin\pi\xi)$ or $J_n(\phi_0\pi\xi)$

Phase-space description: Spatial distributions



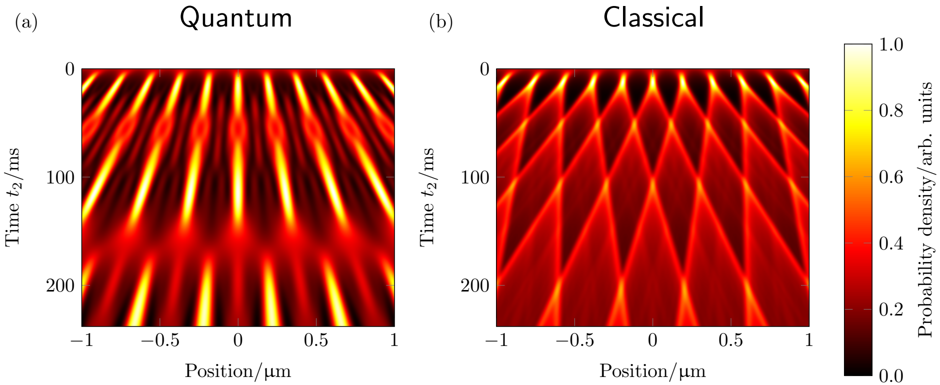
Phase-space description: Spatial distributions



Decoherence via multiplicative factor

$$R_n = \exp\left\{-\Gamma\left(t_1 + t_2\right)\left[1 - f\left(\frac{nht_2}{mD}\right)\right]\right\}$$

Phase-space description: Spatial distributions



Decoherence via multiplicative factor

$$R_n = \exp\left\{-\Gamma\left(t_1+t_2\right)\left[1-f\left(\frac{nht_2}{mD}\right)\right]\right\}$$

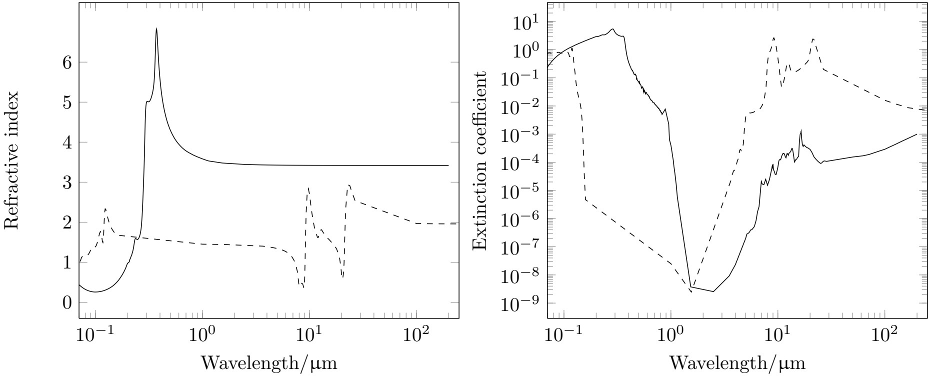
Decoherence mechanisms:

Gas collisions: $< 10^{-10}$mbar

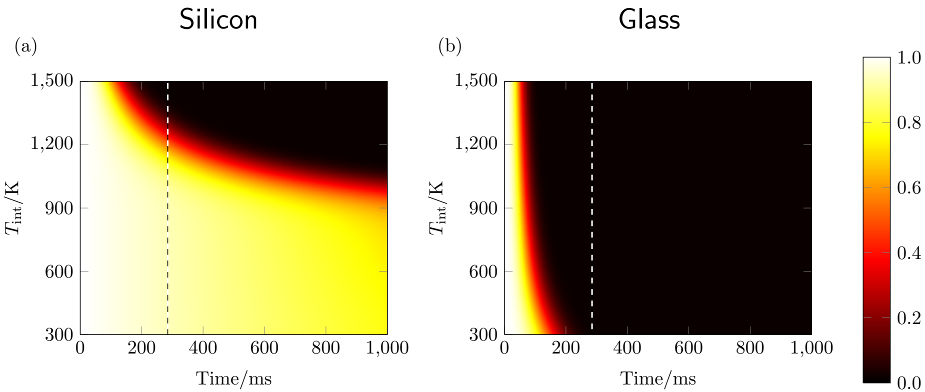
Blackbody radiation: ...

Decoherence via Blackbody radiation

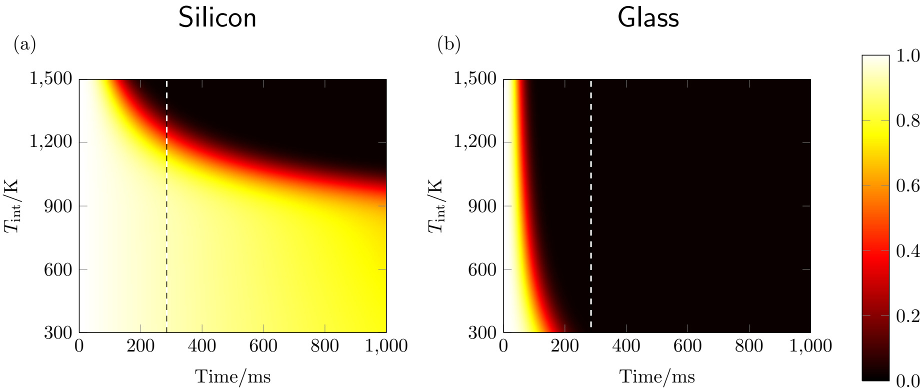
- Typical blackbody wavelength: $\gtrsim 10\mu\text{m}$
- Glass (dashed) absorbs; silicon (solid) is highly transparent



Decoherence via Blackbody radiation



Decoherence via Blackbody radiation



Choose trap wavelength 1550nm:

→ fiber laser technology

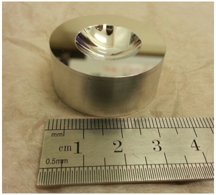
→ some issues: free space/high power/imaging

Dipole Trapping at 1550nm

Refracting optics: aspherics/objectives

- Designed for visible ($\lambda \lesssim 1\ \mu\mathrm{m}$)
- Significant aberrations at 1.5μm

Dipole Trapping at 1550nm

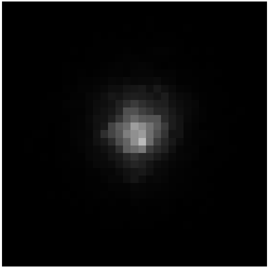


Refracting optics: aspherics/objectives

- Designed for visible ($\lambda \lesssim 1$ µm)
- Significant aberrations at 1.5µm

Reflecting optics: parabolic mirror

- Inherently achromatic
- Single-point diamond turning
- 15nm roughness ($\lambda/100$)
- $<$ 1µm form accuracy
- NA $= 0.995$
- Working distance $=$ 900µm



Position detection

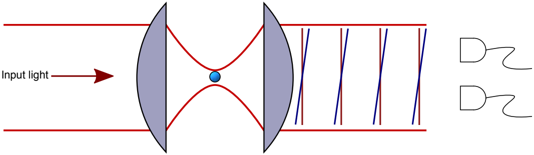
- Sense position and apply feedback [1,2]
- Centre-of-mass cooling to $\sim$ 10mK for $\sim$ 100nm particle [2]

[1] Li, Kheifets, Raizen, Nat. Phys. **7** 527 (2011)
[2] Gieseler, Deutsch, Quidant, Novotny, PRL **109** 103602 (2012)

Position detection

- Sense position and apply feedback [1,2]
- Centre-of-mass cooling to $\sim$ 10mK for $\sim$ 100nm particle [2]

Transmission imaging



- $\partial_x \phi \sim 1/f$
- $\partial_z \phi \sim 1/z_R$
- $E_{\mathrm{Ref}} \gg E_{\mathrm{Sca}}$

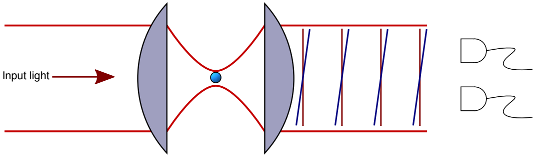
[1] Li, Kheifets, Raizen, Nat. Phys. **7** 527 (2011)
[2] Gieseler, Deutsch, Quidant, Novotny, PRL **109** 103602 (2012)

Position detection

- Sense position and apply feedback [1,2]
- Centre-of-mass cooling to $\sim$ 10mK for $\sim$ 100nm particle [2]

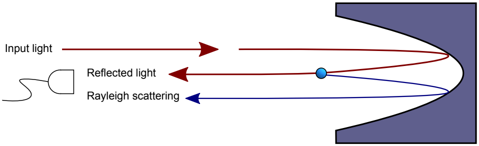
Transmission imaging

- $\partial_x \phi \sim 1/f$
- $\partial_z \phi \sim 1/z_R$
- $E_{\mathrm{Ref}} \gg E_{\mathrm{Sca}}$



Reflection imaging

- $\partial_x \phi \sim 1/f$
- $\partial_z \phi = 1/\frac{1}{2}\lambda$
- $E_{\mathrm{Ref}} \sim E_{\mathrm{Sca}}$

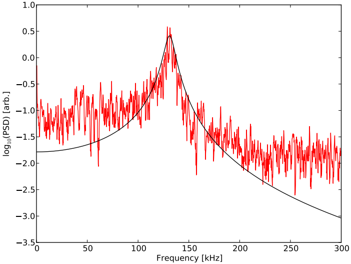


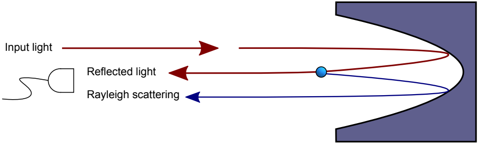
[1] Li, Kheifets, Raizen, Nat. Phys. **7** 527 (2011)
[2] Gieseler, Deutsch, Quidant, Novotny, PRL **109** 103602 (2012)

Position detection → feedback cooling

Done:

- Trap signal ✓
- Intensity modulation ✓





[1] Li, Kheifets, Raizen, Nat. Phys. **7** 527 (2011)
[2] Gieseler, Deutsch, Quidant, Novotny, PRL **109** 103602 (2012)

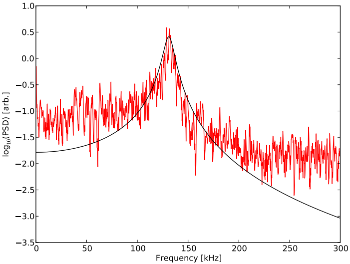
Position detection → feedback cooling

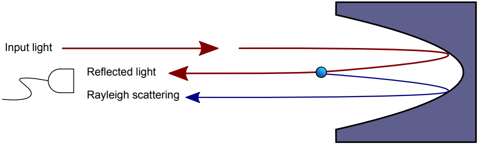
Done:

- Trap signal ✓
- Intensity modulation ✓

To do:

- Close loop with FPGA
- Repeat for transverse
- Pump down & cool





[1] Li, Kheifets, Raizen, Nat. Phys. **7** 527 (2011)
[2] Gieseler, Deutsch, Quidant, Novotny, PRL **109** 103602 (2012)

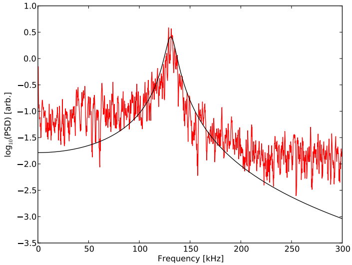
Position detection → feedback cooling

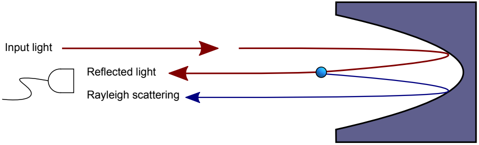
Done:

- Trap signal ✓
- Intensity modulation ✓

To do:

- Close loop with FPGA (✓)
- Repeat for transverse
- Pump down & cool





[1] Li, Kheifets, Raizen, Nat. Phys. **7** 527 (2011)
[2] Gieseler, Deutsch, Quidant, Novotny, PRL **109** 103602 (2012)

Particle source

Requirements:

- Pure Silicon
- Produce in UHV

Particle source

Requirements:

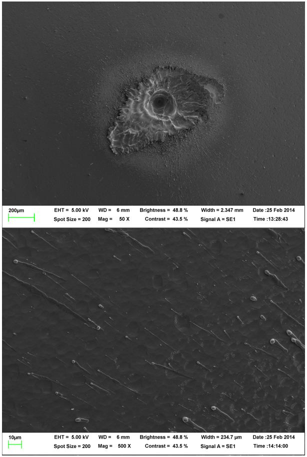
- Pure Silicon
- Produce in UHV

Approach (see also [1]):

- Nd:YAG ablation (ns; mJ; 532nm)
- Sub-200nm particles
  (limited by SEM resolution)

To do:

- Size selection
- Capture in UHV…



[1] Asenbaum, Kuhn, Nimmrichter, Sezer, Arndt, Nat. Comm. **4** 2743 (2013)

Summary & outlook

So far

- Theory including decoherence
- Use silicon, **not** glass
- 1550nm $\implies$ reflective optics
- Position sensing via back-scattering
- Crude particle source

To do

- Feedback cooling (✓)
- Capture Si in UHV
- . . . then grating and imaging