Ten quectonewton local force sensor with atom interferometry for probing atom-surface interactions

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SYRTE, Observatoire de Paris

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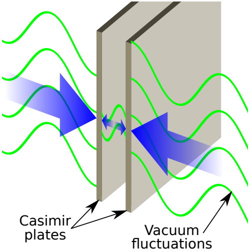
Probing atom-surface interactions : Casimir-Polder force

Casimir force



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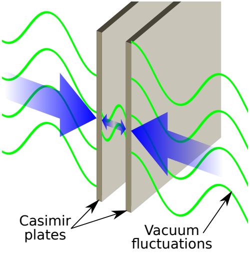
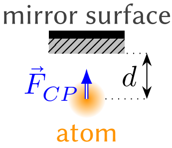
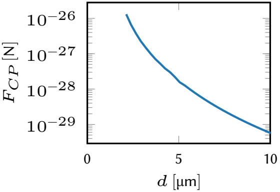


Casimir-Polder force

QED effect :



$$F_{CP} = \frac{3\hbar c \alpha_0}{32\pi^2 \epsilon_0 d^5}$$



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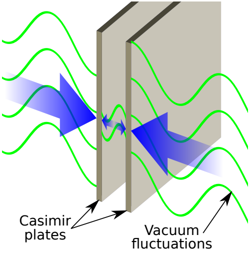

Casimir-Polder force

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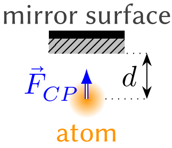

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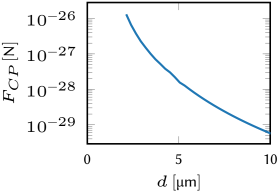
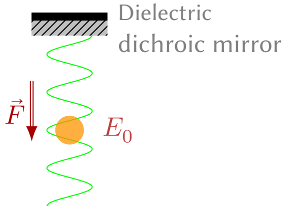


Objective : Metrological measurement of F_{CP} with controlled d

- Check QED predictions
- Observation of the thermal regime (for $d > 8\,\mu$m, $F_{CP} \propto d^{-4}$)
- Additional interaction in µm range ?

Atom interferometry with trapped atoms

Rb atoms trapped in
optical vertical lattice



$U \approx 4E_r$

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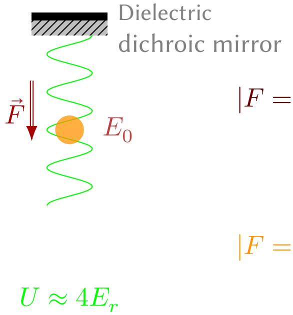
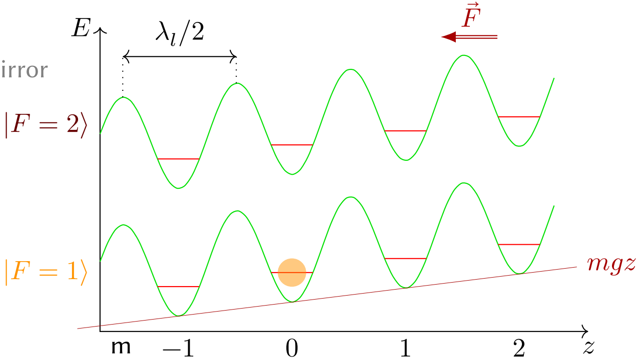


Wannier-Stark ladder



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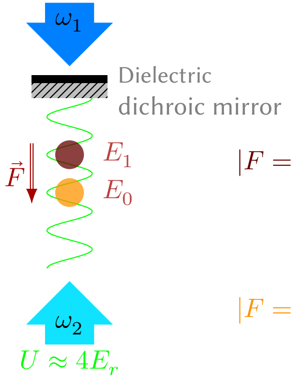

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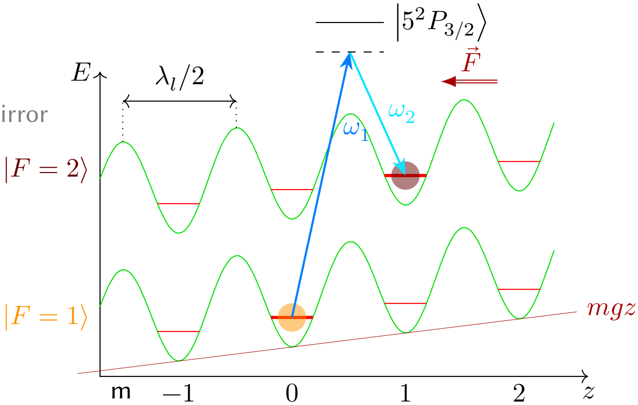

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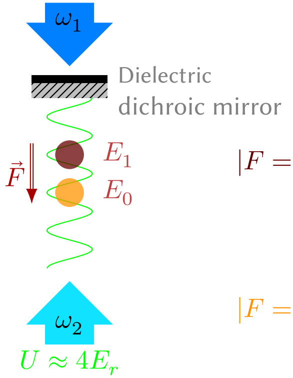

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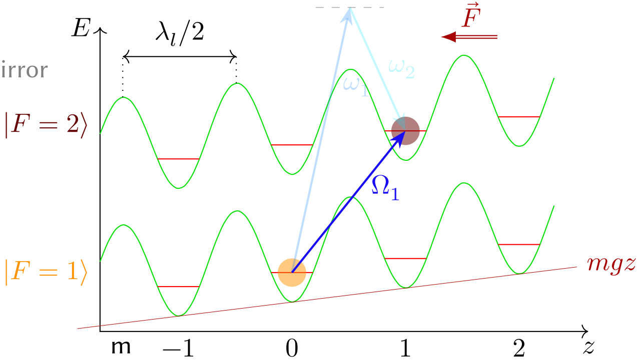

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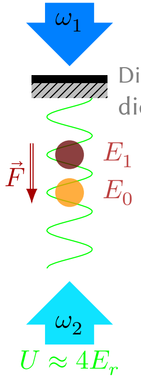

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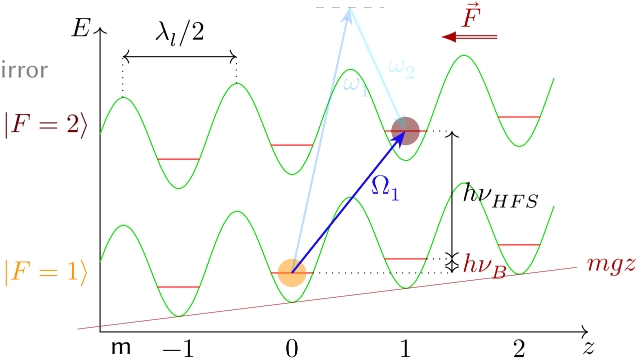

Bloch frequency $\nu_B = \frac{E_1 - E_0}{h} = \frac{F\lambda_l}{2h} \approx 568\,\text{Hz}$

$F = mg + \delta F \implies$ shift on ν_B

Atom interferometry with trapped atoms

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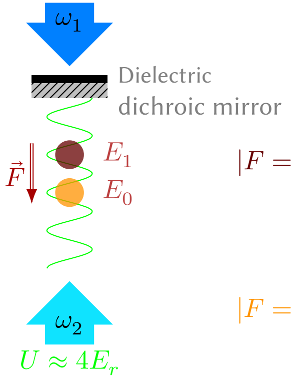

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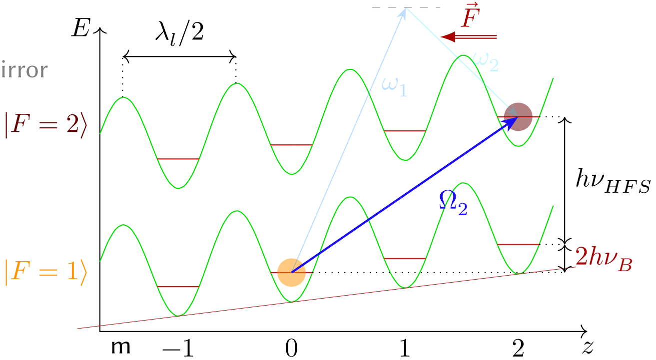

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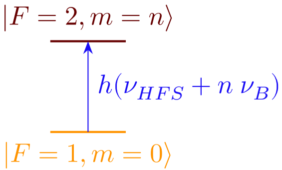
$F = mg + \delta F \implies$ shift on ν_B

Coupling possible between $|m=0\rangle$ and $|m>1\rangle$

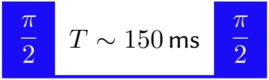
$\Omega_m = \Omega \langle m=0| \, e^{ik_{eff}\hat{z}} \, |m=n\rangle$

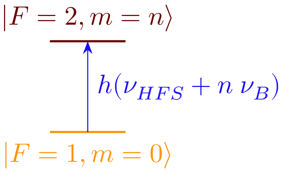
Bloch frequency measurement



Bloch frequency measurement

Ramsey interferometer :





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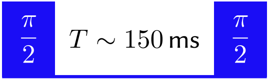

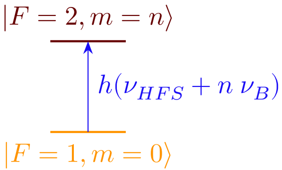

Fluorescence imaging : transition

probability $P_e = \dfrac{N_{|F=2\rangle}}{N_{|F=2\rangle} + N_{|F=1\rangle}}$

Bloch frequency measurement

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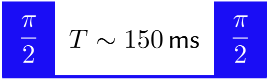

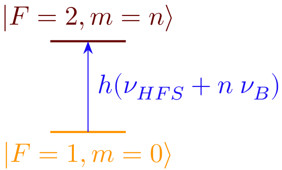

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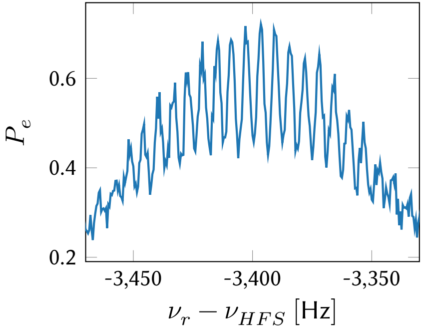
$$= \frac{C}{2}\cos(\varphi)$$

Interferometric phase :

$$\varphi = 2\pi(\nu_R - \nu_{HFS} - n\,\nu_B)T$$

$$F = \nu_B \frac{2h}{\lambda_l} = \nu_B \times 2.49 \times 10^{-27}\,\text{N/Hz}$$

Transition $n = -6$



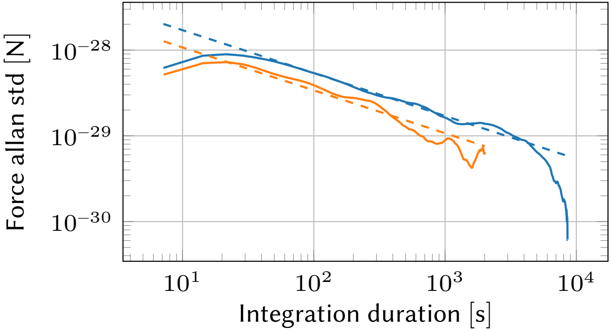
Force sensitivity

1 s sensitivity

$130\,\text{mHz} \implies 3.4 \times 10^{-28}\,\text{N}$

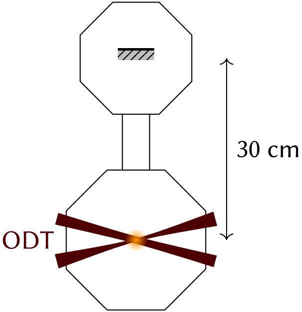
Long term sensitivity

$1.5\,\text{mHz} \implies 4\,\text{qN}\ (4 \times 10^{-30}\,\text{N})$



Sensitive to Casimir-Polder to distance up to $8\,\mu\text{m}$

Control of the distance to mirror : Bloch elevator



Evaporative cooling in dipolar trap : $150\,000$ atoms at $500\,\mathrm{nK}$, $\sigma_z \sim 10\,\mu\mathrm{m}$
Adiabatic compression $\implies \sigma_z \sim 4\,\mu\mathrm{m}$

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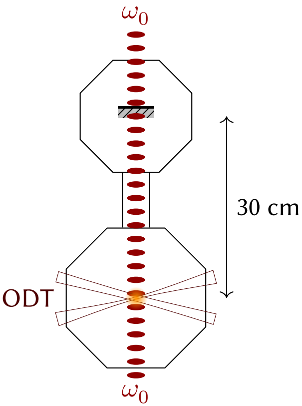

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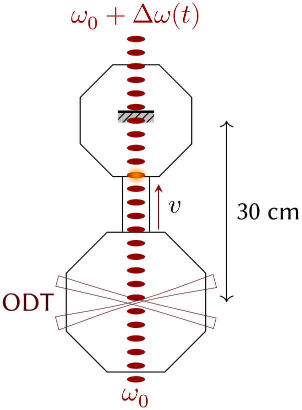
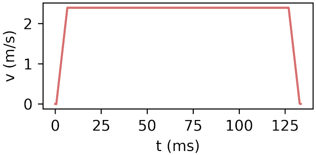
Transport the atoms close to the mirror

Control of the distance to mirror : Bloch elevator





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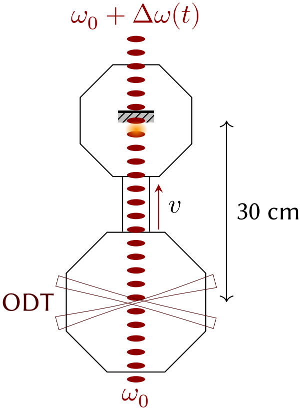
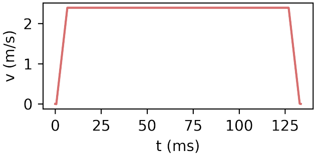
Transport the atoms close to the mirror

Using a moving lattice $v(t) = \dfrac{\Delta\omega(t)}{2k}$

$z = \int v(t)\,\mathrm{d}t \implies$ **Precise control on the transport distance**





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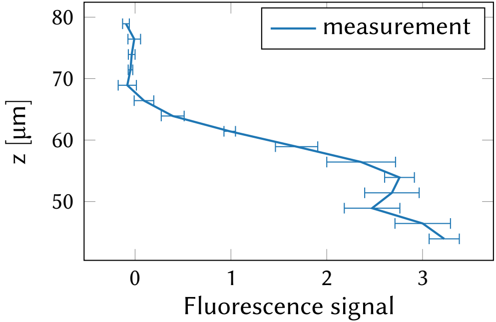
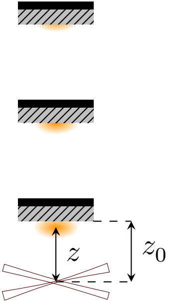
10 000 atoms at the end of the transport, with heavy spontaneous emission (heating, unpolarization)

Measure of the distance to mirror

Use mirror surface as position reference





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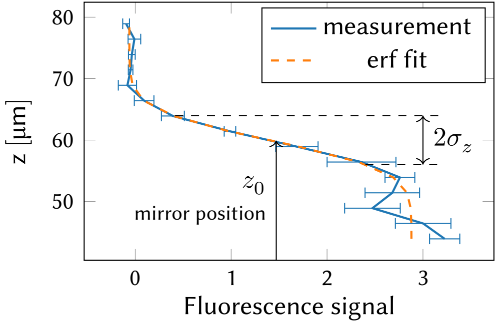

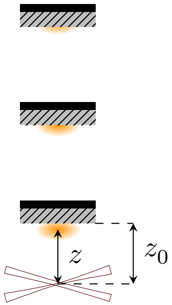

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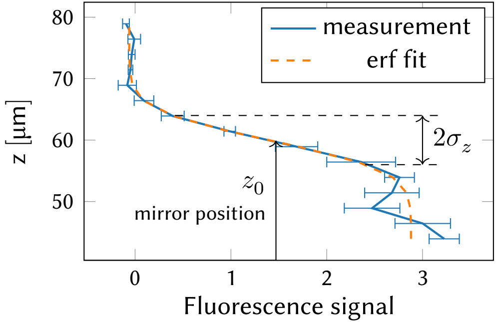

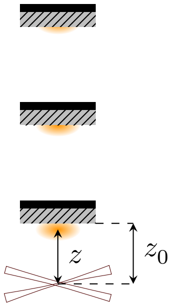

Position fluctuations $< 1\,\mu m$

$\sigma_z = 3.9\,\mu m$

$\simeq 50$ wells

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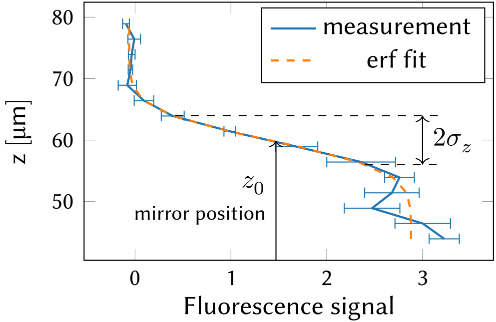

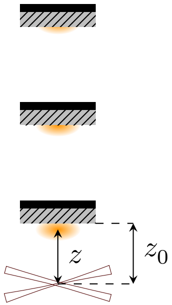

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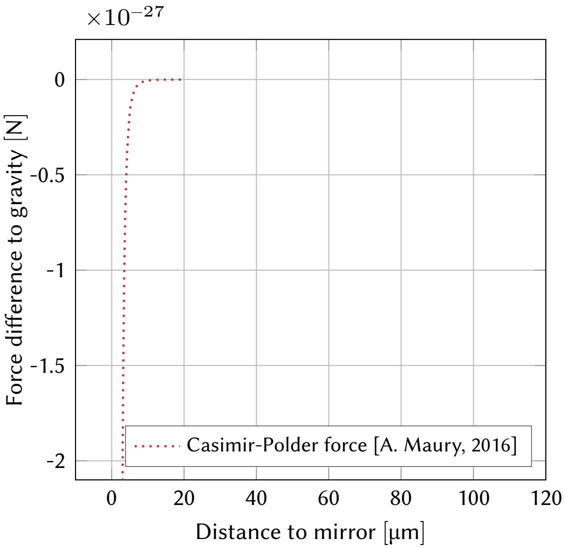
Quectonewton force sensor with micrometer spatial sensitivity

Force measurements



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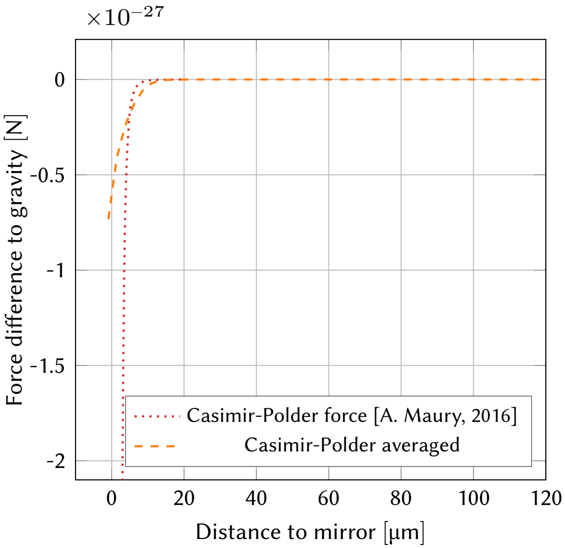

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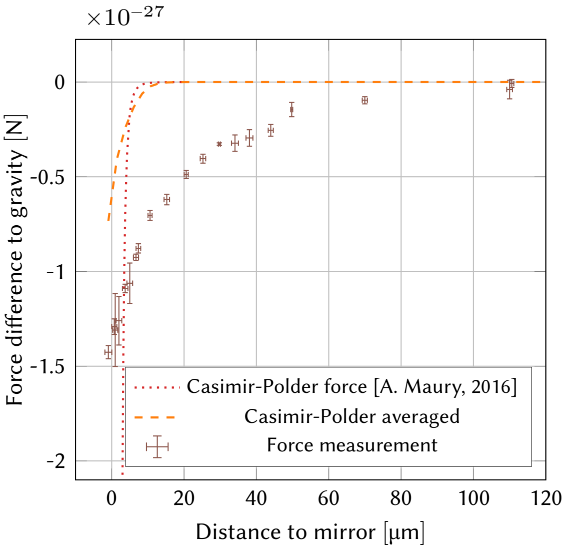


Differential force measurement, relative to 400 µm away from the mirror surface

Measured force : same order of magnitude than expected Casimir-Polder force

Additional force, on longer range

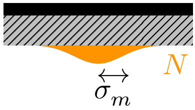
Parasitic force from adsorbed atoms

[Cornell, 2004] : « Alkali-metal adsorbate polarization on conducting and insulating surfaces probed with Bose-Einstein condensates »

1. Atoms adsorbed on the mirror : electric dipole $\vec{\mu}$
2. Energy shift on the neutral atoms $U_E = -\frac{\alpha_{DC}}{2}|\vec{E}|^2$
3. Force $\vec{F} = \frac{\alpha_{DC}}{2} \overrightarrow{\text{grad}} \, |\vec{E}|^2$

$$F_s(z) = \alpha_{DC} E_s(z) \frac{\partial E_s}{\partial z}$$

N atoms adsorbed on the surface, over a radius σ_m:



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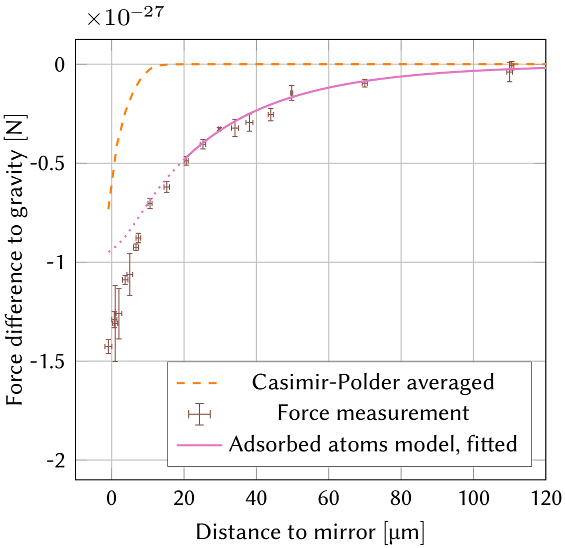

Dipolar electric field fit parameters :
$N_\mu = 2 \times 10^{10}$ atoms,
$\sigma_m = 88\,\mu\text{m} \sim 2\sigma_x$

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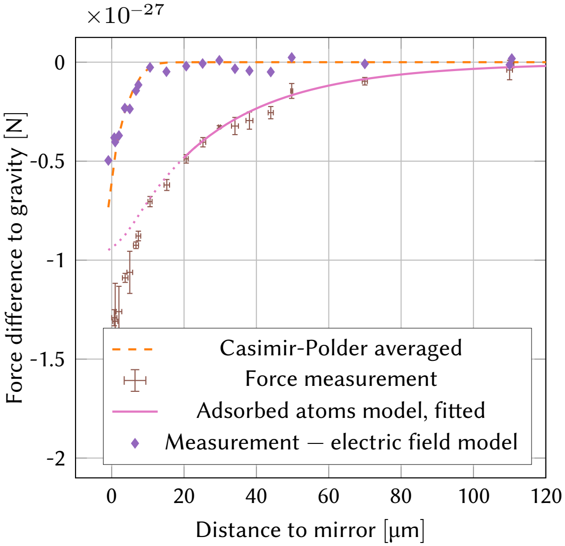

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Suppression of parasitic eletrostatic force : UV shinning

Attempt of desorption of atoms : UV shinning on the mirror

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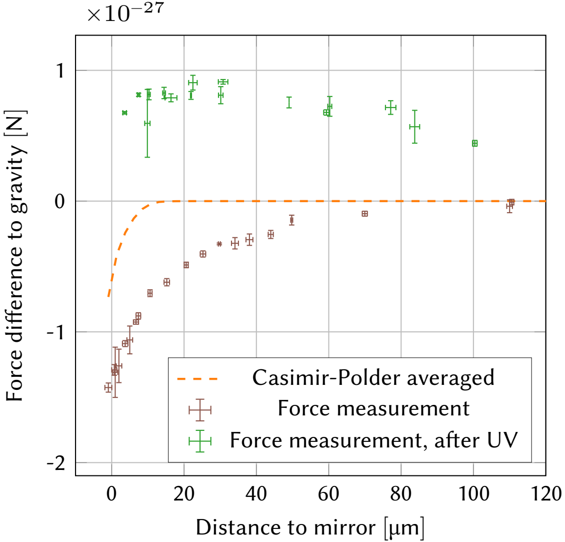
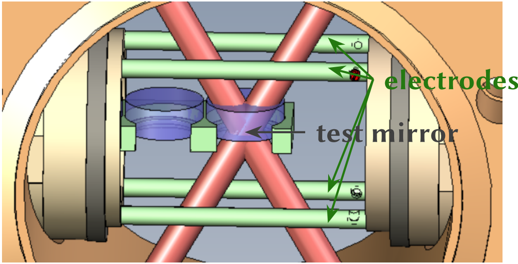


Force became **repulsive** and on longer range

$\Longrightarrow$ additional charges

Measurement of parasitic electrostatic fields

Apply controlled external electric field



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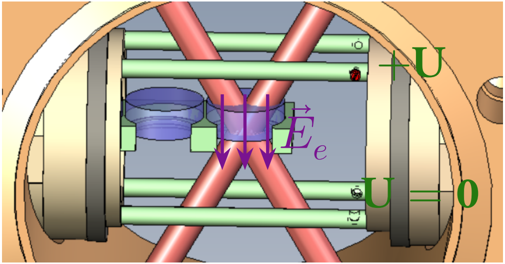
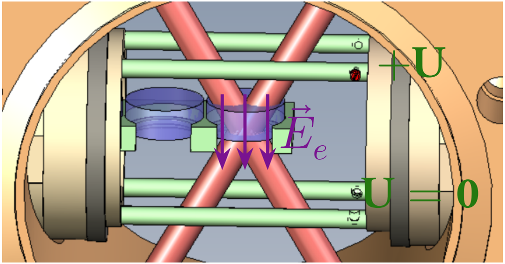


Measurement of parasitic electrostatic fields

Apply controlled external electric field

$$F_s(z) = \alpha_{DC} \frac{\partial E_s}{\partial z} E_s(z)$$



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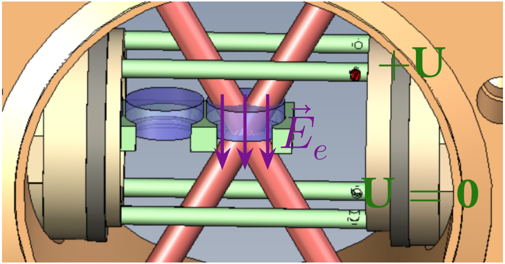

$$F_s(z) = \alpha_{DC} \frac{\partial E_s}{\partial z} E_s(z)$$

Electric gradient $\frac{\partial E_s}{\partial z}$

Uniform external electric field $E_e \implies$ force shift

$$F(E_e) = \alpha_{DC}(E_e + E_s) \frac{\partial E_s}{\partial z}$$

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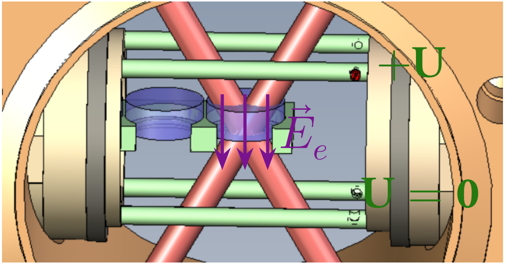

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Electric field $E_s(z)$ [Lodewyck, 2012]

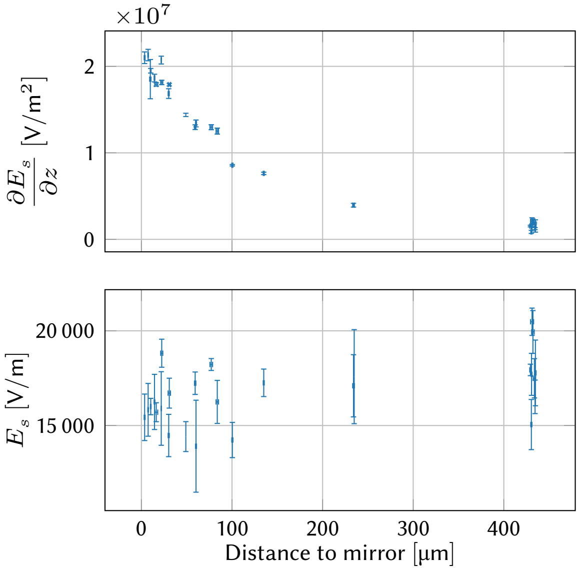
$$\Delta\omega_{HFS} = k_s |\vec{E}|^2$$

$$\Delta\omega_{HFS}(E_e) = k_s (E_e + E_s)^2$$

Clock measurement : MW Ramsey interferometer

$\Delta\omega_{HFS} = 10\,\text{mHz} \iff E_e = 600\,\text{V}$

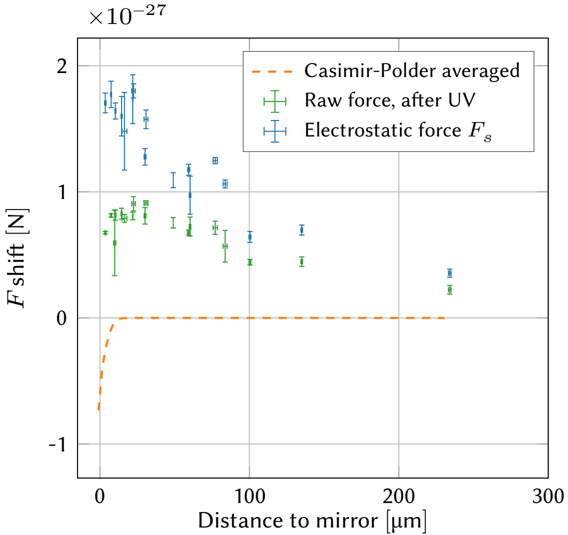
Measurements of electric fields



Relative sensitivity on $\frac{\partial E_s}{\partial z}$: 3 %

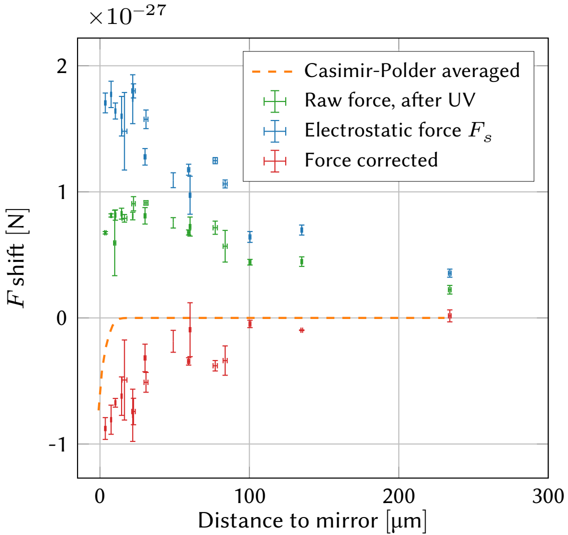
Relative sensitivity on E_s : 7 %

Force and parasitic force



$$F_s(z) = \alpha_{DC} E_s(z) \frac{\partial E_s}{\partial z}$$

Force and parasitic force



$$F_s(z) = \alpha_{DC} E_s(z) \frac{\partial E_s}{\partial z}$$

No recovering of only Casimir-Polder force

- electric fields in other directions ?
- non linearities in applied electric field ?

Conclusion

- Local force sensor, with a µm spatial resolution, up to a few qN
- We measure Casimir-Polder force, masked by others surface-atom interactions of same magnitude
- Able to characterise electric field near the surface

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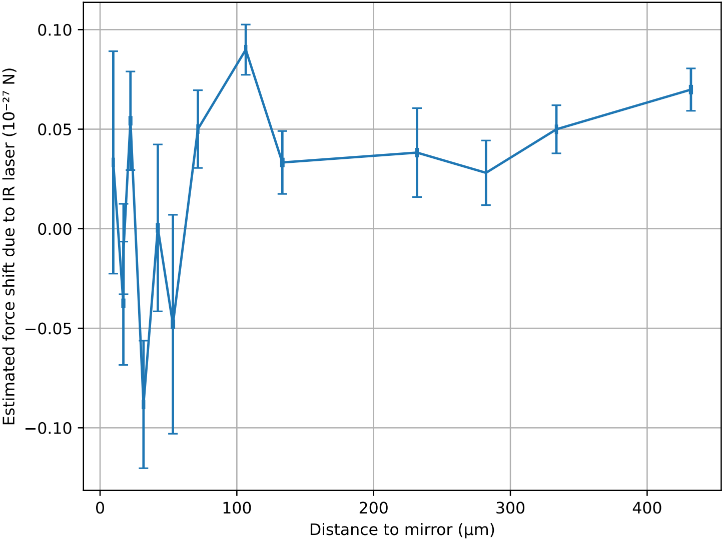
Perspectives:

- Better sensitivity : more atoms, smaller cloud, better coherence time
- Pursue better electric field characterization
- Measurement selective in position

- Measure temperature effect
- New surface test (metamaterials)

Thank you for your attention !

Force shift from IR beam



Force inhomogeneities