A Single-Atom Heat Engine

Shivam Sinha

Content

- Introduction
- Heat Engine
- Microscopic and Nanoscopic Heat Engines
- Stirling Cycle
- Doppler cooling
- Paul trap
- Experimental implementation
- Future Perspectives and Potential Applications
- Conclusion

Introduction

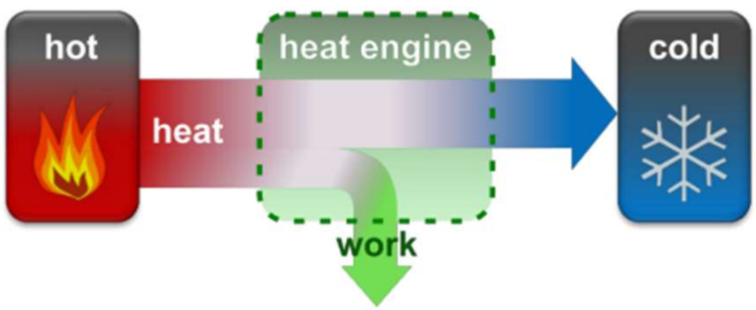
The team of experimental Physicists led by Johanesse Roßnagel at the University of Mainz in Germany built the smallest working Heat engine in 2015.

The engine has the same working principle as the well-known [combustion] car engine.

It follows the same four strokes: expanding then cooling, contracting, then heating.

Heat Engine

A heat engine is a cyclically working device that converts a difference in thermal energy between a hot reservoir and a cold reservoir to some degree into mechanical energy. Thereby, it converts non-directed thermal motion of atoms into directed and coherent motion or, in other words, heat into work.

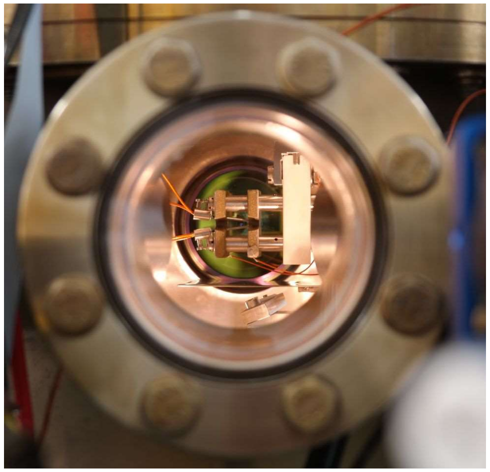


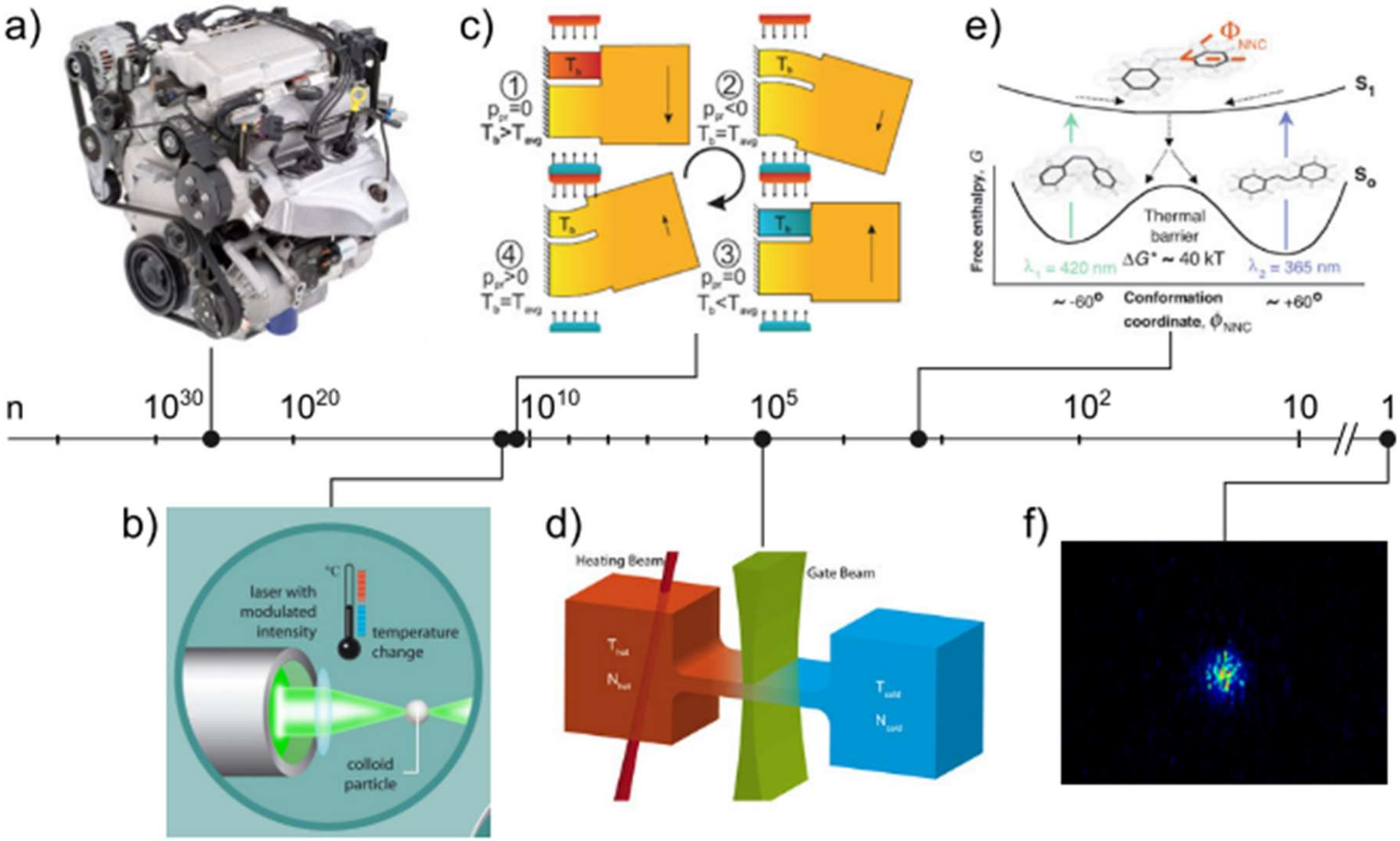
Efficiency = Work Output/Heat Input

$$\eta = \frac{w}{Q_{in}}$$

Microscopic and nanoscopic heat engines

- The miniaturization process has led to a growing interest in small-scale engines, while the technical achievements in increasing the precision of modern experiments have provided the necessary tools.
- Inspired by nature and by the biological motors in muscle cells, the creation of nanosized engines started with the synthesis of appropriate molecular structures.

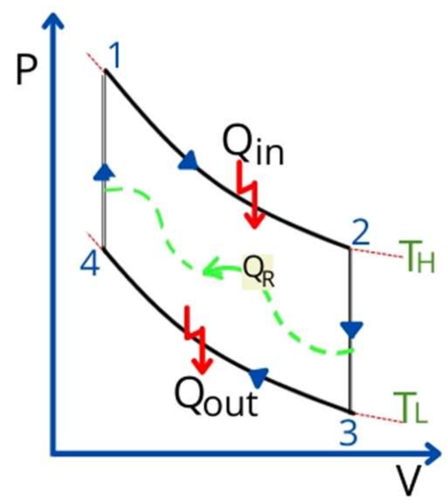


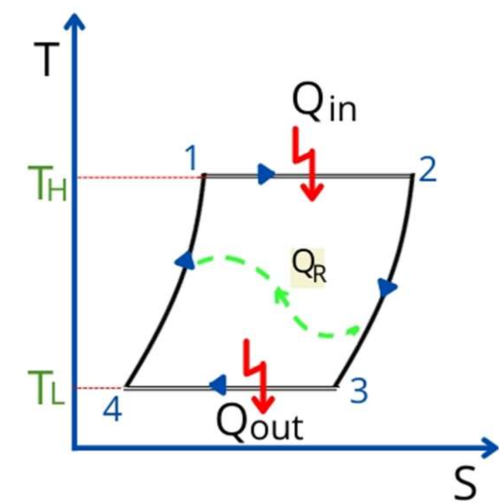

a)
c)
e)
n
10^{30}
10^{20}
10^{10}
10^5
10^2
10
1
b)
d)
f)
laser with modulated intensity
temperature change
colloid particle
Heating Beam
Gate Beam
Thermal barrier
$\Delta G^* \sim 40$ kT
$\lambda_1 = 420$ nm
$\lambda_2 = 365$ nm
Free enthalpy, G
Conformation coordinate, ϕ_{NNC}
~ -60°
~ +60°
S_1
S_0
Φ_{NNC}

Stirling Cycle

- The Stirling cycle is a thermodynamic cycle that consists of two isothermal processes and two isochoric processes. It is patented in 1816 by Robert Sterling.

- It is slightly different than the [Carnot cycle](). The Stirling cycle replaces the isentropic processes in the Carnot cycle with the isochoric processes. This cycle has the same maximum efficiency as that of the ideal Carnot cycle.





Process	Change in Internal energy	Heat Interaction	Work Interaction
Process(c) 1-2	0	RT1 ln(V2/V1)	RT1 ln(V2/V1)
Process(d) 2-3	Cv(T1-T2)	Cv(T1-T2)	0
Process(a) 3-4	0	RT2 ln(V4/V3)	RT2 ln(V4/V3)
Process(b) 4-1	Cv(T1-T2)	Cv(T1-T2)	0

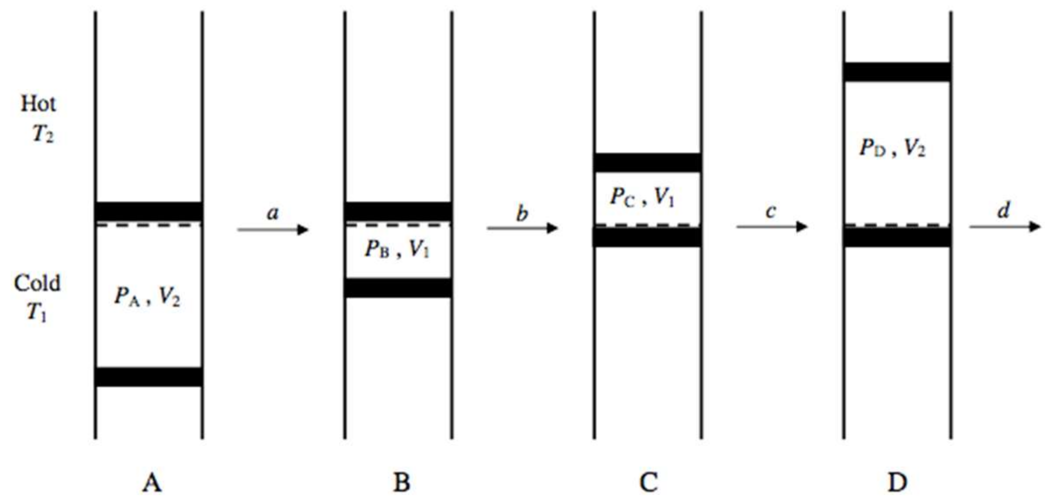


FIGURE XI.4

$V_2 = V_3$ & $V_4 = V_1$

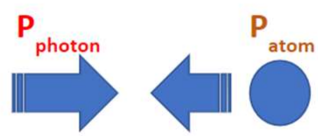
$$\eta = \frac{R\,(T_2 - T_1)\ln(V_2/V_1)}{C_V\,(T_2 - T_1) + RT_2\ln(V_2/V_1)}.$$

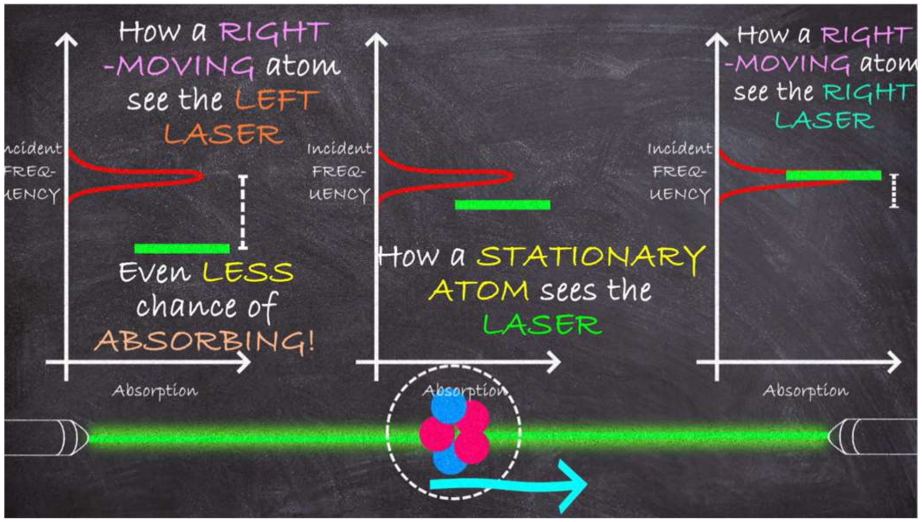
The above equation is similar to the equation of Carnot cycle efficiency

$$\eta = 1 - \mathrm{T_1/T_2}$$

Doppler cooling

What is coolness and laser cooling?





What is the Doppler effect?

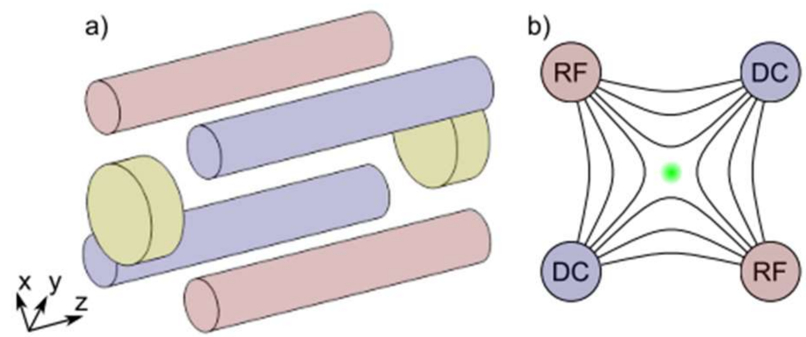
A change in the frequency(wavelength) of light due to relative motion between source and observer is called the Doppler effect.

$$\nu = \frac{\nu_0\sqrt{1-\frac{v^2}{c^2}}}{1-\frac{v\cos\theta}{c}}$$

$$\nu = \nu_0\left(1-\frac{v}{c}\right)$$

If moving away from the source, → Light is Red-shifted
If moving towards the source, → Light is blue-shifted

Linear Paul trap

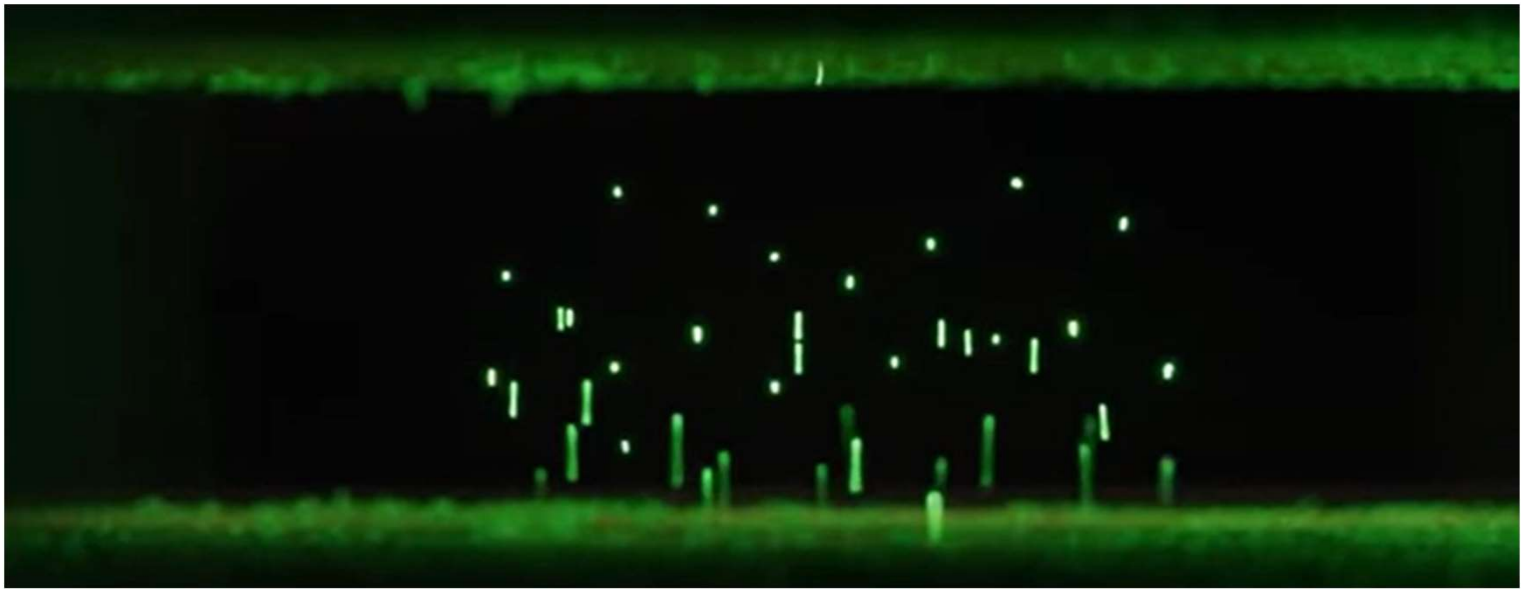


A constant voltage is applied to the endcaps and provides a static confinement in the z-direction

In order to satisfy, the Laplace equation, $\nabla^2\phi = 0$
for traping potential, a combination of both static and oscilating electric field is needed.

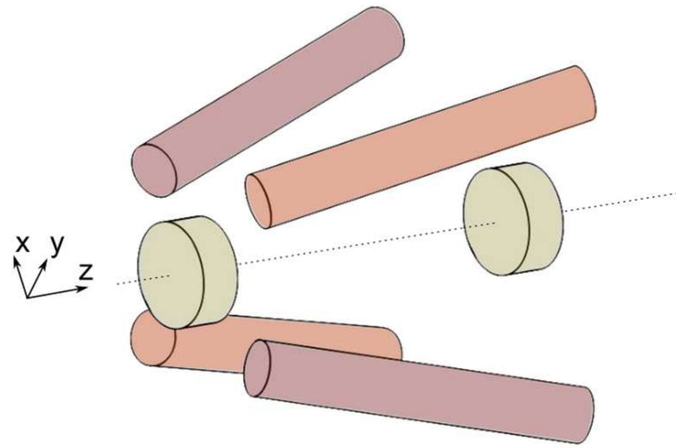
Oscillating potential, $V_{\mathrm{rf}}(t) \propto \frac{U_{\mathrm{rf}}}{r_0^2} \sin(\Omega_{\mathrm{rf}}\, t) \cdot (x^2 - y^2),$

$$\Phi_p = \frac{1}{2}\left(\alpha_x x^2 + \alpha_y y^2 + \alpha_z z^2\right), \qquad m\,\frac{d^2\vec{x}(t)}{dt^2} = -\vec{\nabla}\Phi_p,$$ Equation of motion



Linear ion trap

Funnel-shaped Paul trap



Modified Oscillating Potential of the form,

$$V_{\mathrm{rf}}(x,y,z,t) \propto \frac{U_{\mathrm{rf}} \sin(\Omega_{\mathrm{rf}}\, t)}{(r_0 + z\ \tan\theta)^2} \cdot (x^2 - y^2) + \frac{U_{\mathrm{dc}}}{z_0^2} \cdot z^2.$$

$$\Phi_p(x,y,z) = \frac{m}{2} \frac{(\omega_{0x}^2\, x^2 + \omega_{0y}^2\, y^2) r_0^4}{(r_0 + z\ \tan\ \theta)^4} + \frac{m}{2} \omega_{0z}^2\, z^2,$$

$$\omega_{x,y} = \frac{\omega_{0x,0y}}{(1 + z \tan\theta / r_0)^2}.$$

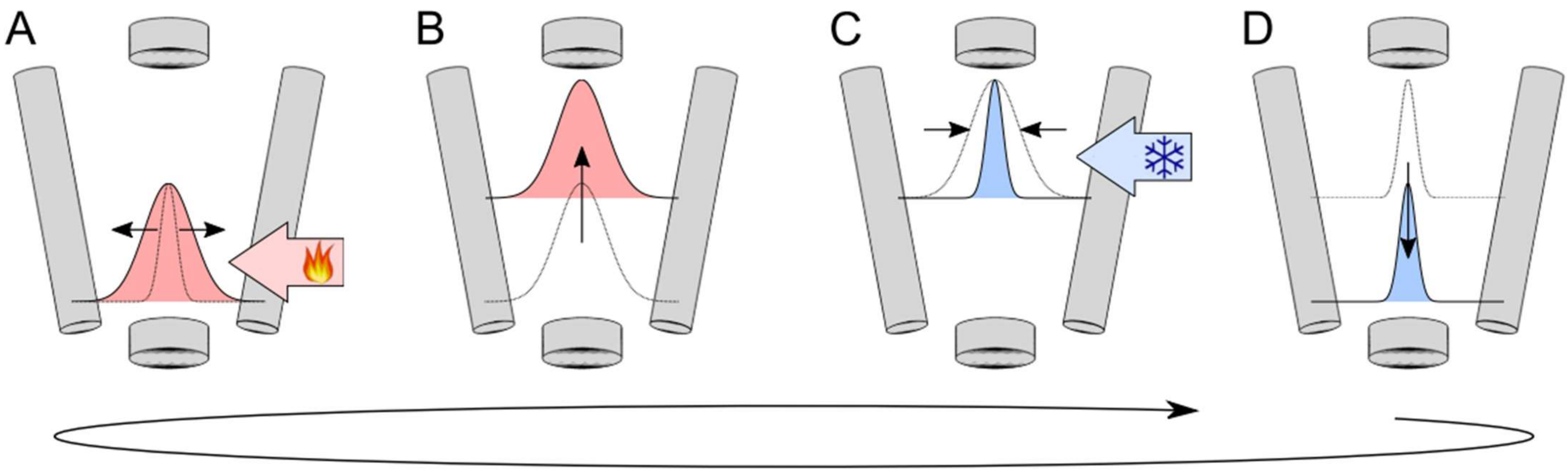
The solution gives a result in radial frequency, $\omega_r(z)$ that depends on axial position Z.

Working cycle of the single-atom heat engine

Spatial distribution of the thermal state of the form,

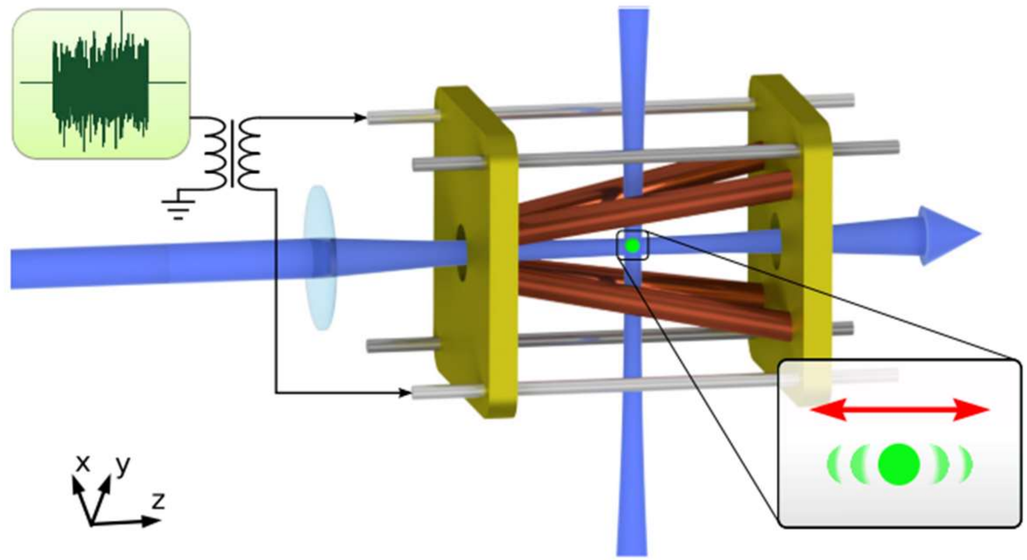
$$\xi_{\mathrm{r}}(r,\phi,T) = \frac{1}{2\pi\sigma_{\mathrm{r}}^2}\exp\left[\frac{-(r-r_0)^2}{2\sigma_{\mathrm{r}}^2}\right],$$

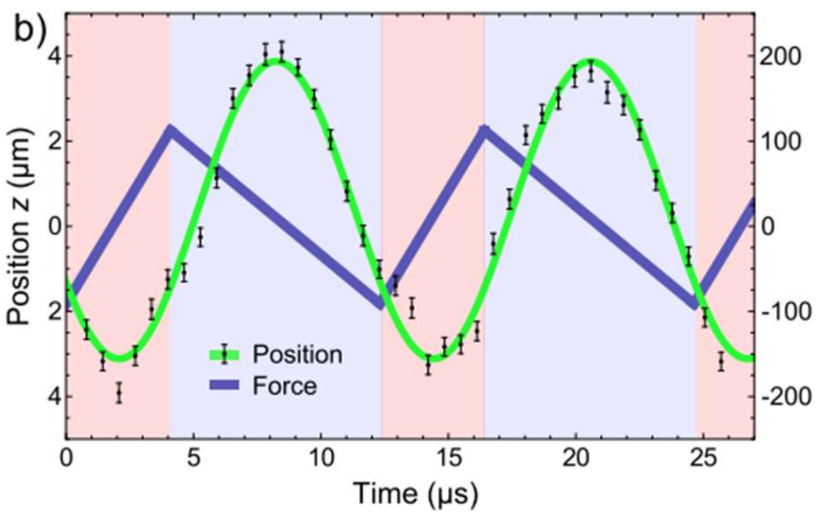
$$\sigma_{\mathrm{r}}(T) = \sqrt{\frac{k_B T}{m\omega_r^2}}.$$



Experimental implementation of single-atom heat engine

The setup of the heat-engine experiment is composed of a single trapped ion(green).



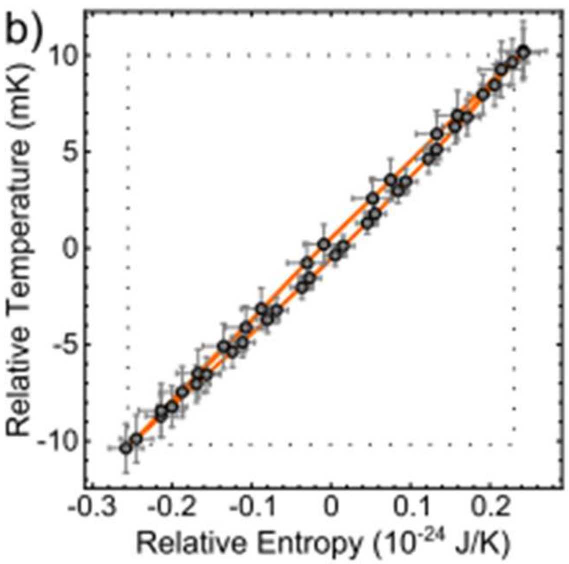


The position of the ion is imaged on an ICCD camera as a function of time, revealing its trajectory.
The position of the ion (black) is determined from the average of more than 200,000 camera images at each time step.

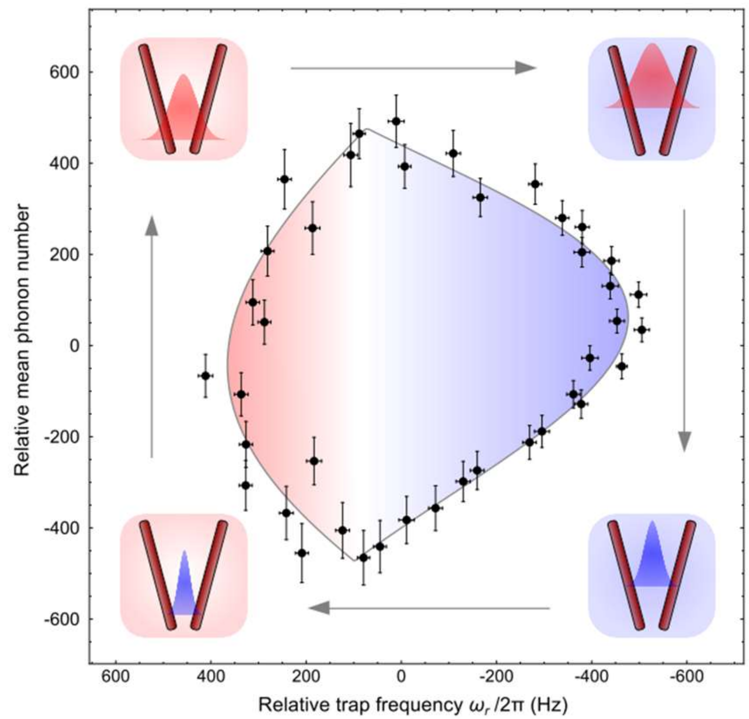
Thermodynamic cycle

- The change in trap frequency is deduced directly from the Z position of the ion.

- The relative phonon number $\langle n \rangle$ is determined from separate measurements.



$$\{\omega_r, \bar{n}_r\} \quad \rightarrow \quad \{S, T\}$$



$$n = \frac{k_B T}{\hbar \omega}$$

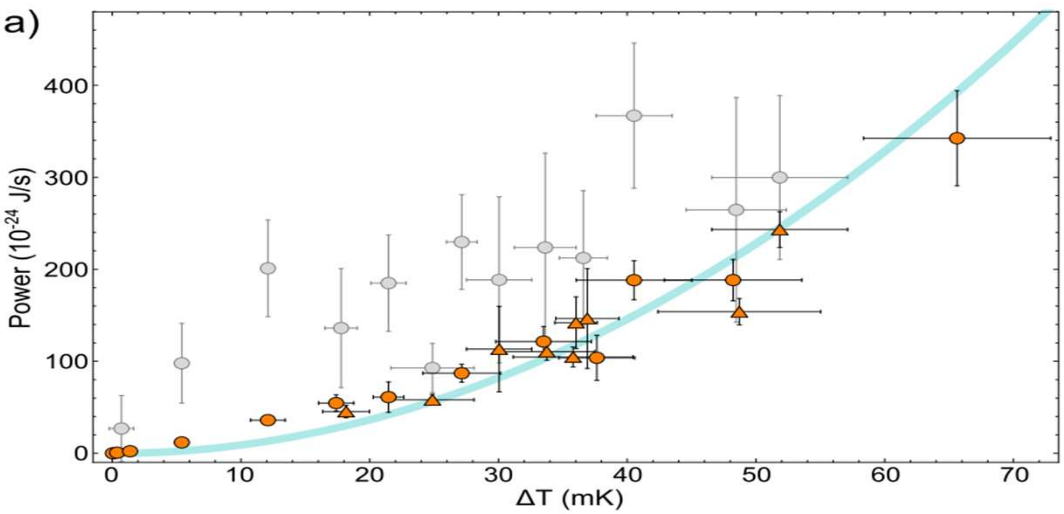
$$S = k_B \left[1 + \ln\left(\frac{k_B T}{\hbar \omega_r} \right) \right]$$

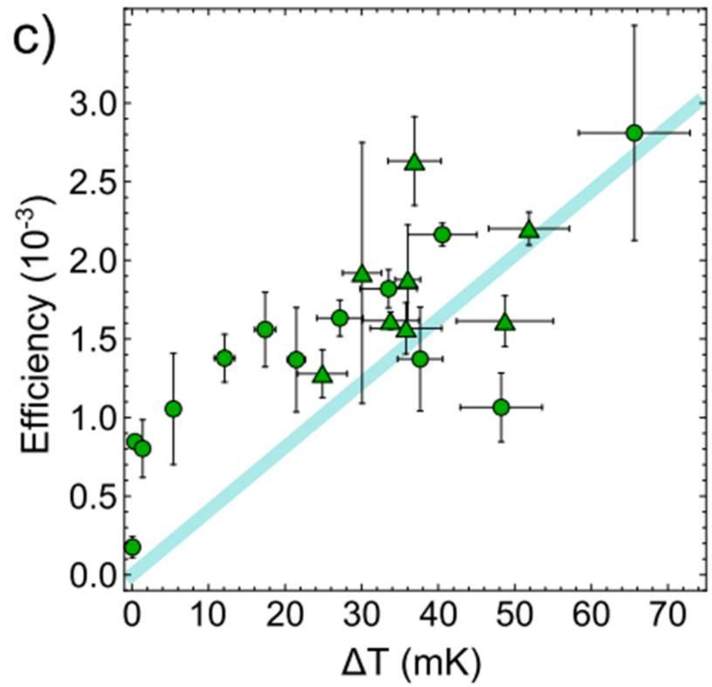
Power and efficiency

P = 342 x 10-24j

$$\eta = -W_c / Q_H \qquad Q_H = \int_H T dS \longrightarrow \eta_c = 0.28\,\%,$$

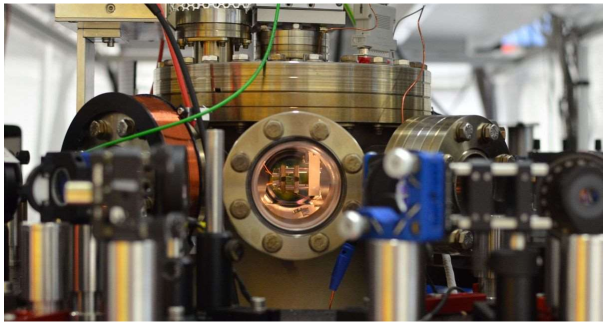
The corresponding efficiency at maximum power given by Curzon-Ahlborn formula $\eta_{CA} = 1 - \sqrt{T_1/T_2} = 1.9\%$





Future Perspectives and potential application

- Single-atom heat pump
- Application in nanotechnology and microelectronics.
- Fundamental research
- Nano-sized robots
- Toward a Quantum heat engine



Conclusion

A successful experimental realization of a Single-atom heat engine, although the efficiency and power is significantly less, the experiment was never meant to be a functioning part of the future machine but to reveal new insight into the fundamental science of heat engine.

> What are the possibilities of the small but movable machine? They may or may not be useful, but they surely would be fun to make.

Richard Feynman, 1959

References

- Johannes Roßnagel, Samuel Thomas Dawkins, 1510.03681, (2015).
- Johannes Roßnagel, A Single-Atom Heat Engine, Chapter- 1,2,4,7,8
- Samuel T. Dawkins, thermodynamics in the quantum regime, Chapter 36
- O. Abah, J. Roßnagel, G. Jacob, S. Deffner, F. Schmidt-Kaler, K. Singer and E. Lutz, Phys. Rev. Lett. 109, 203006 (2012).
- Electrodynamic Ion Traps - The LinearTrap, YouTube video
- Cooling with Light! Zeeman, Laser, Chirp, and Doppler Cooling Explained
- Pat Burchat, Physics 41N, Mechanics: Laser Cooling of Atoms (2007)

Thank you

Shivam Sinha