Atomic Plasma and Quantum control

Elementary processes in plasma

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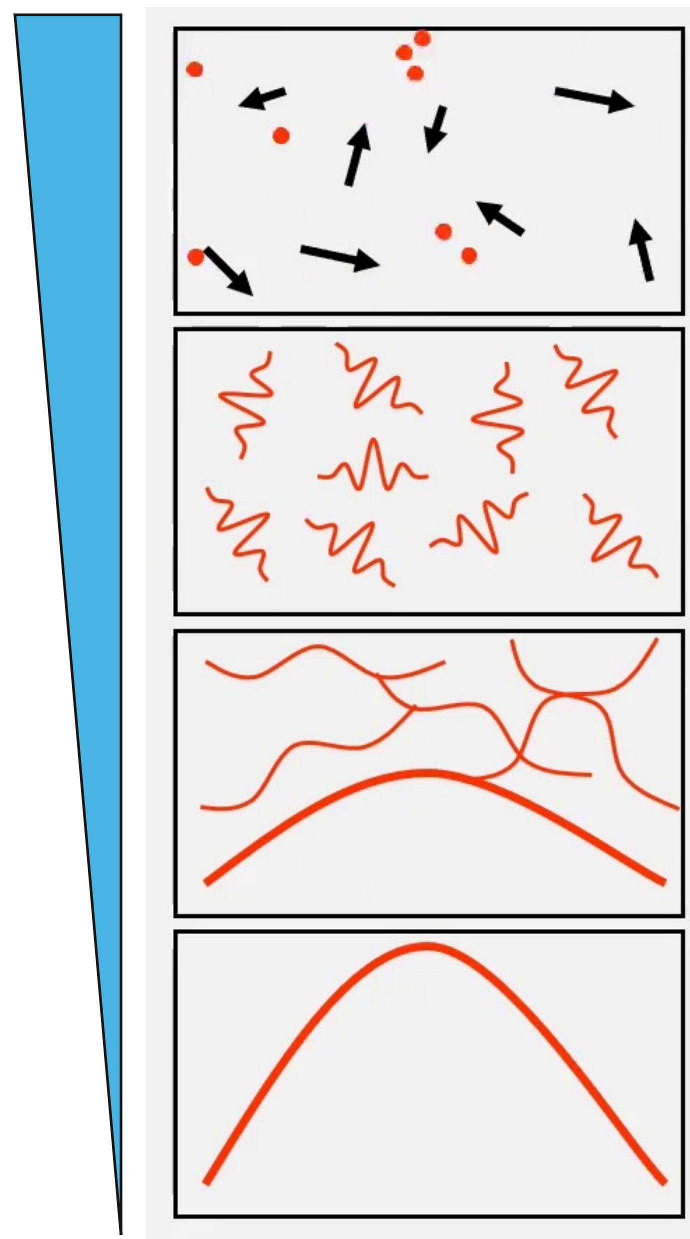
Plasma categorisation

- Classical vs Quantum
- Coupled Strongly or Weakly

Classical vs Quantum

- Thermal de Broglie wavelength
  - For an electron at 1 mK, λth = 2 µm
  - For a Ca+ ion λth = 9 nm
  - For Rb atom at T = 10-7 K, 600 nm, BEC
  - Quantum if λth > mean free path

$$\lambda_{\mathrm{th}} = \sqrt{\frac{2\pi\hbar^2}{m_e k_B T_e}},$$



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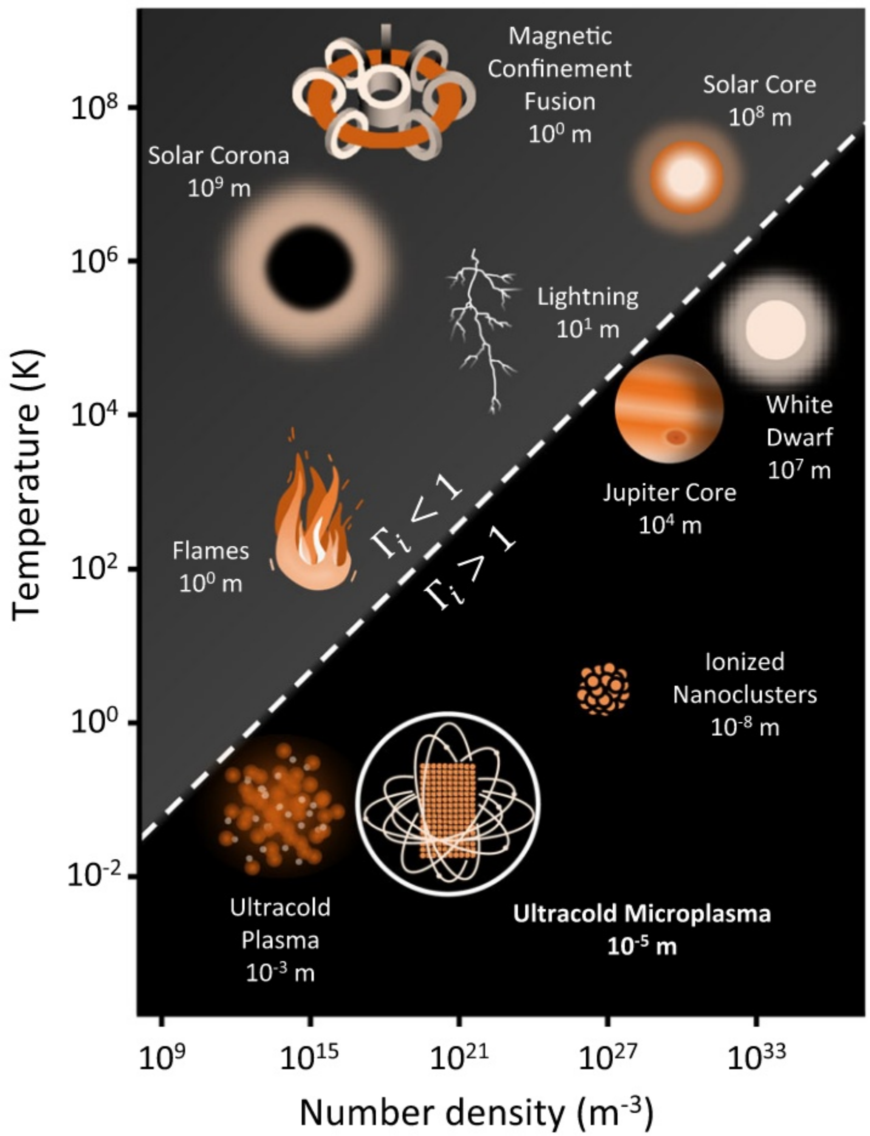
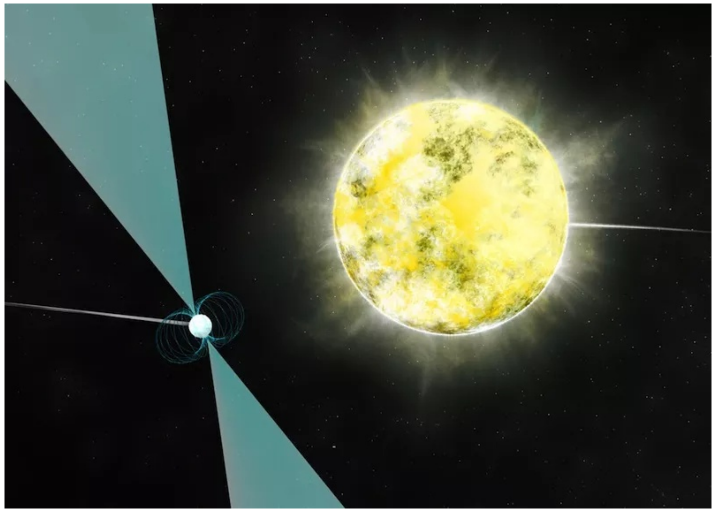
Coupling Strong vs Weak



Coupling parameter

$$\Gamma = \frac{Z^2 e^2}{4\pi\epsilon_0 a_{\rm ws}} \frac{1}{k_{\rm B} T}, \qquad a_{\rm ws} = (3/4\pi n_i)^{1/3}$$



An artist's impression of the white dwarf star orbiting with the pulsar PSR J2222-0137. (Image credit: B. Saxton (NRAO/AUI/NSF))

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Kroker, T. et al. Ultrafast electron cooling in an expanding ultracold plasma. Nat Commun 12, 596 (2021).

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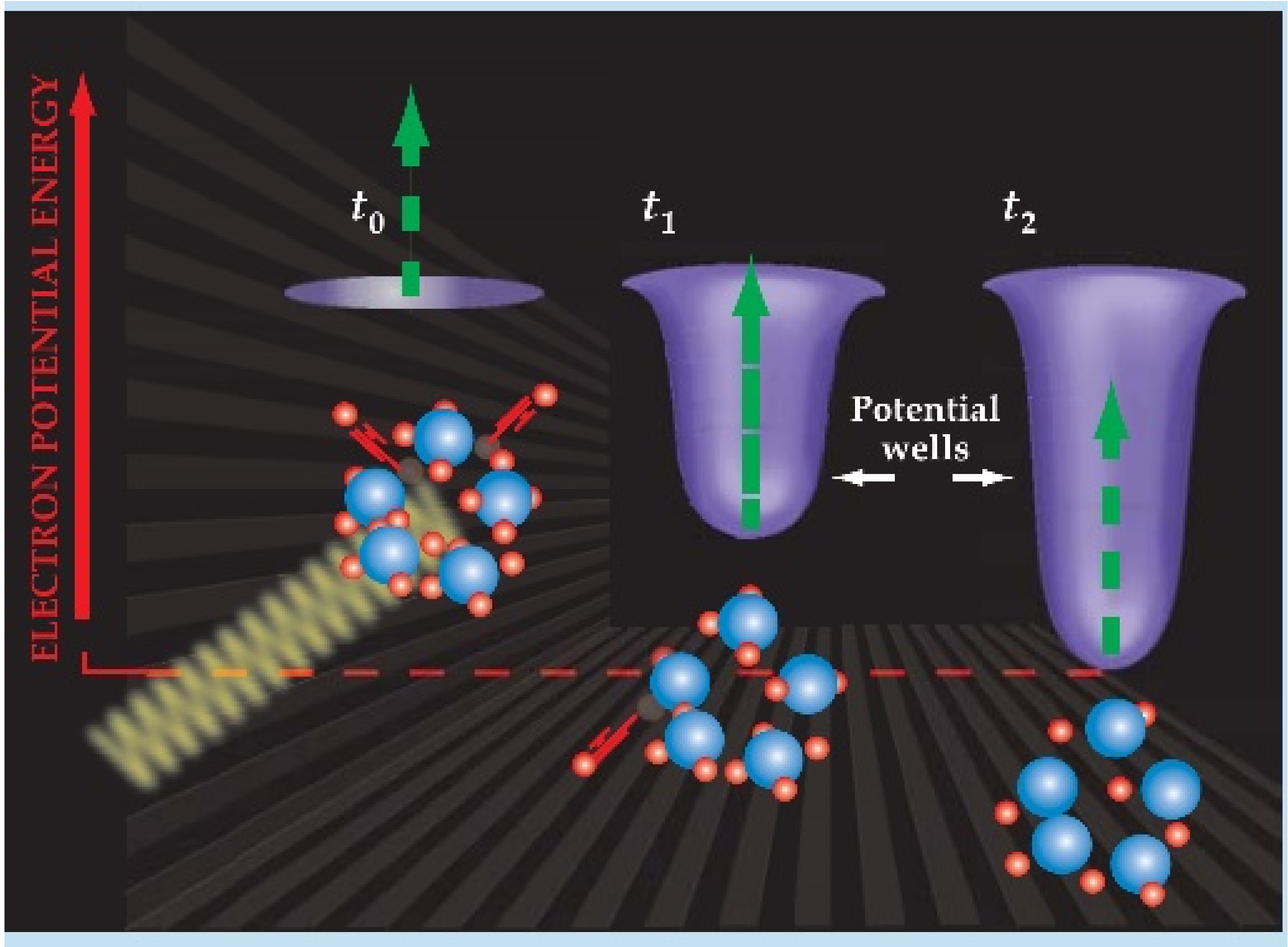
Generation



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Behaviour I

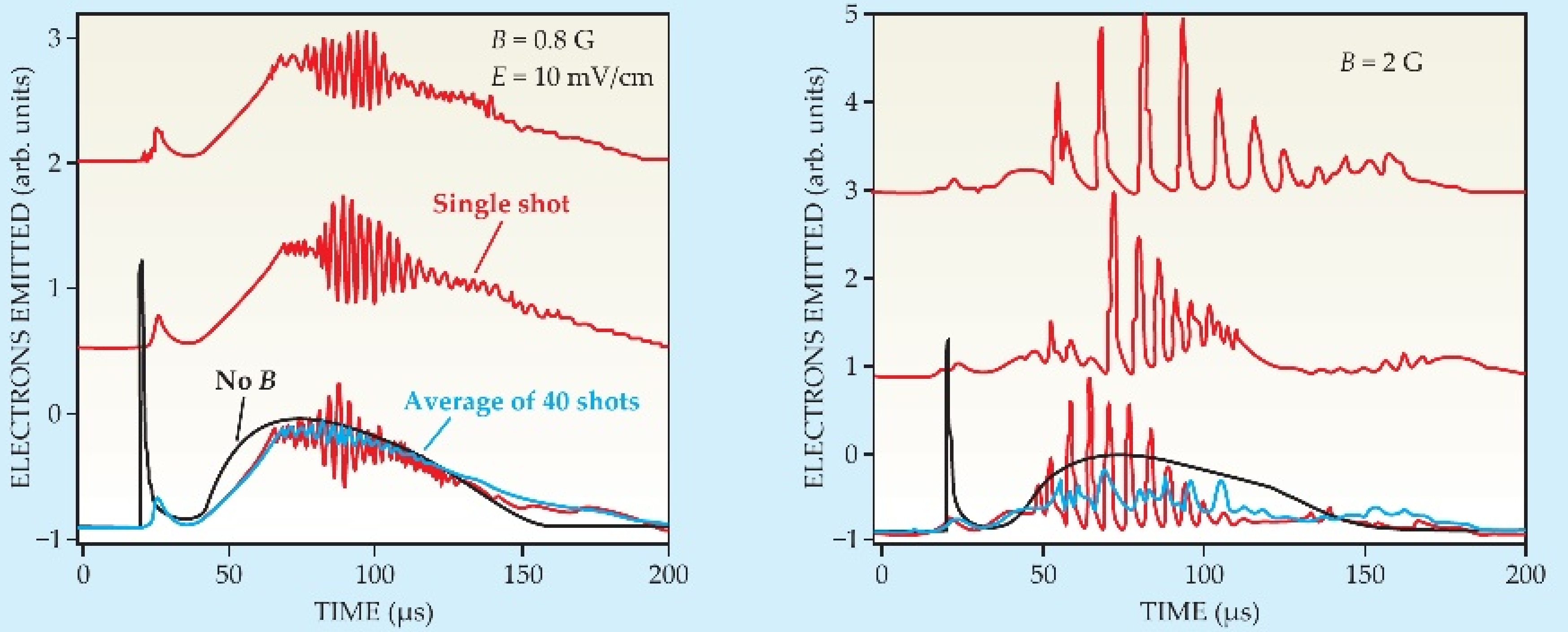

Figure 1. An ultracold plasma instability. When an ultracold plasma is subjected to crossed electric and magnetic fields, **E** and **B**, it emits electrons not continuously but in pulses, a signature of a plasma instability. Each red curve (offset for clarity) is the signal from a single plasma realization, and the blue curves are averages over 40 realizations. Black curves show the typical smooth signal in no magnetic field.

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Behaviour II

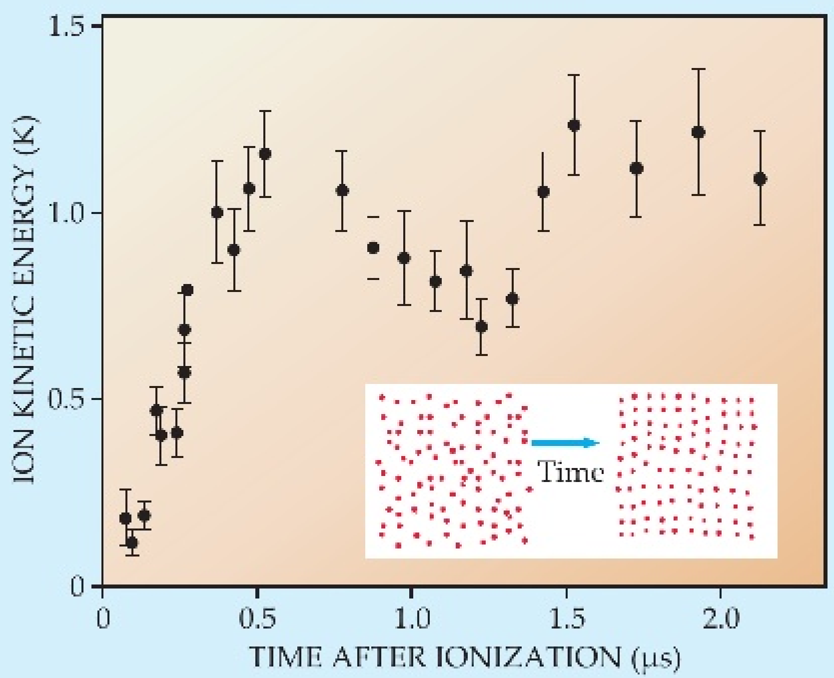

Figure 2. Equilibration dynamics in an ultracold plasma. In the first 0.5 μs after ionization, the plasma experiences rapid disorder-induced heating as the ions' excess potential energy is converted into kinetic energy. Thereafter, the kinetic energy exhibits damped oscillations about its equilibrium value as the cloud of ions settles into its potential-energy minimum and adopts a liquidlike short-range order, as shown in the inset.

Debye shielding

$$\lambda_D = \sqrt{\varepsilon_0 k_b T / n e^2},$$

Strong coupling

$$n \lambda_D{}^3 < 1$$

Disorder-induced heating

Contrast to cooling of coffee mug

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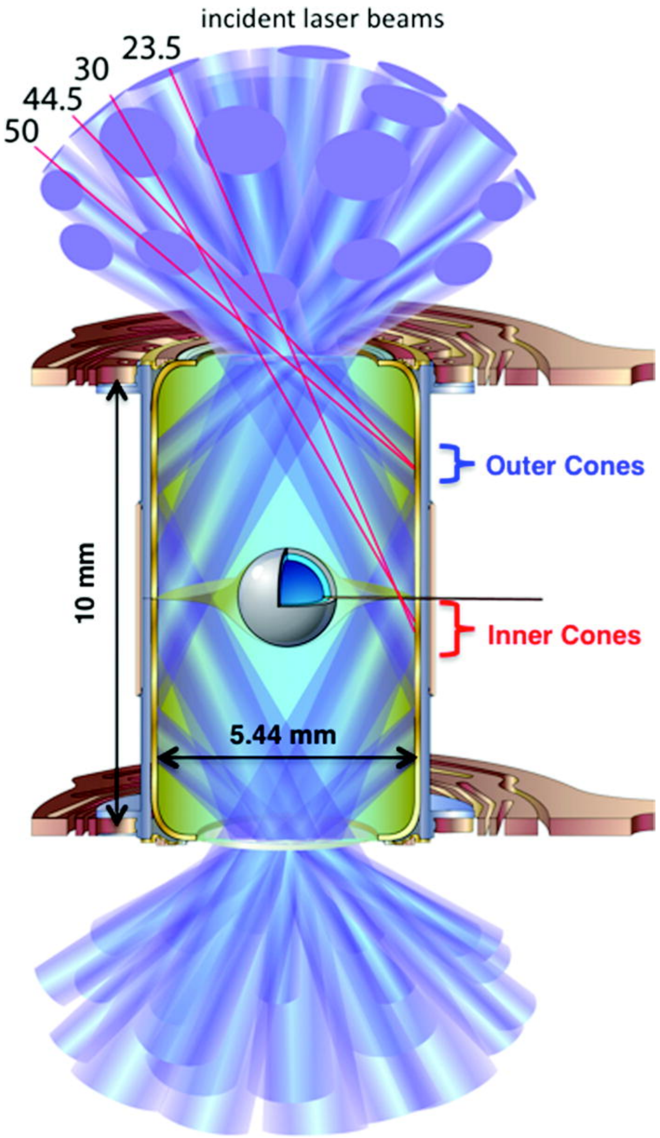
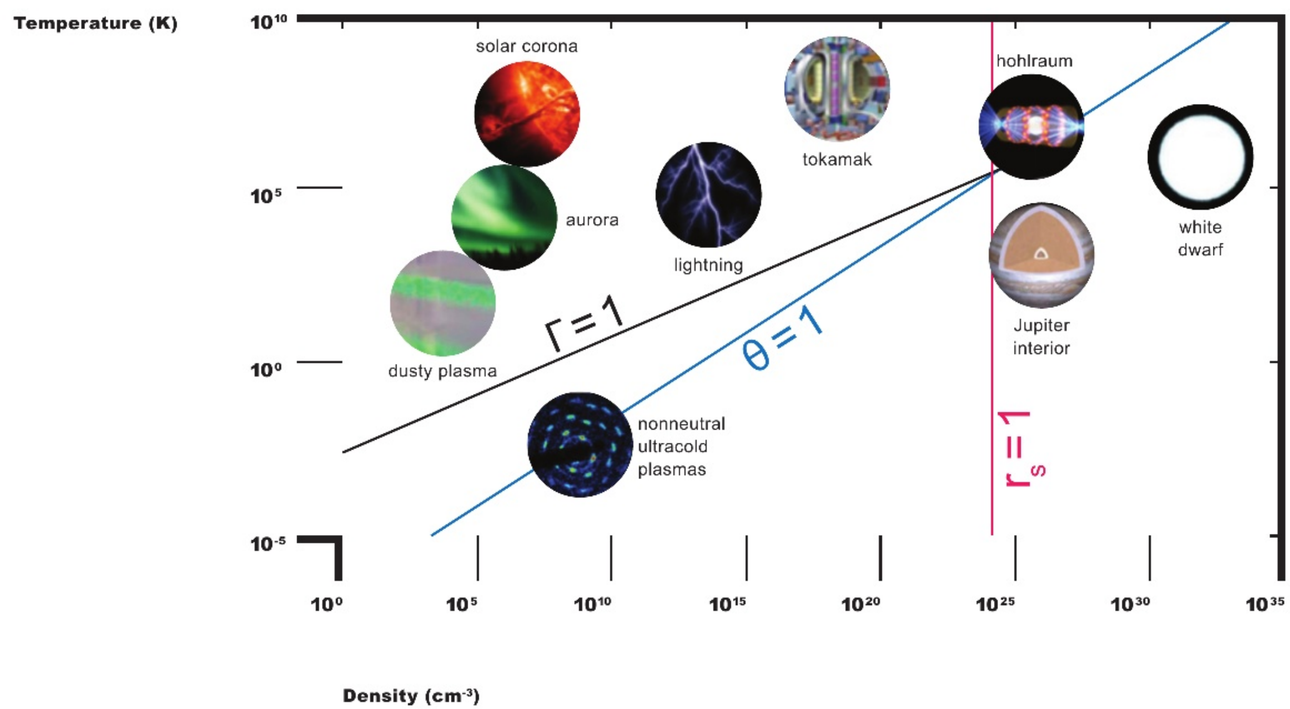
Relevance



Crossovers



Report of the Panel on Frontiers of Plasma Science, Plasma: at the frontier of scientific discovery, US Department of Energy, 2016

Degeneracy parameter θ = (de Broglie wvl.)^2/aws^2

Brueckner parameter $r_s = \frac{a_{ws}}{a_B}$

D. E. Hinkel, M. D. Rosen, E. A. Williams, A. B. Langdon, C. H. Still, D. A. Callahan, J. D. Moody, P. A. Michel, R. P. J. Town, R. A. London, S. H. Langer; Stimulated Raman scatter analyses of experiments conducted at the National Ignition Facility . Phys. Plasmas 1 May 2011; 18 (5): 056312. https://doi.org/10.1063/1.3577836

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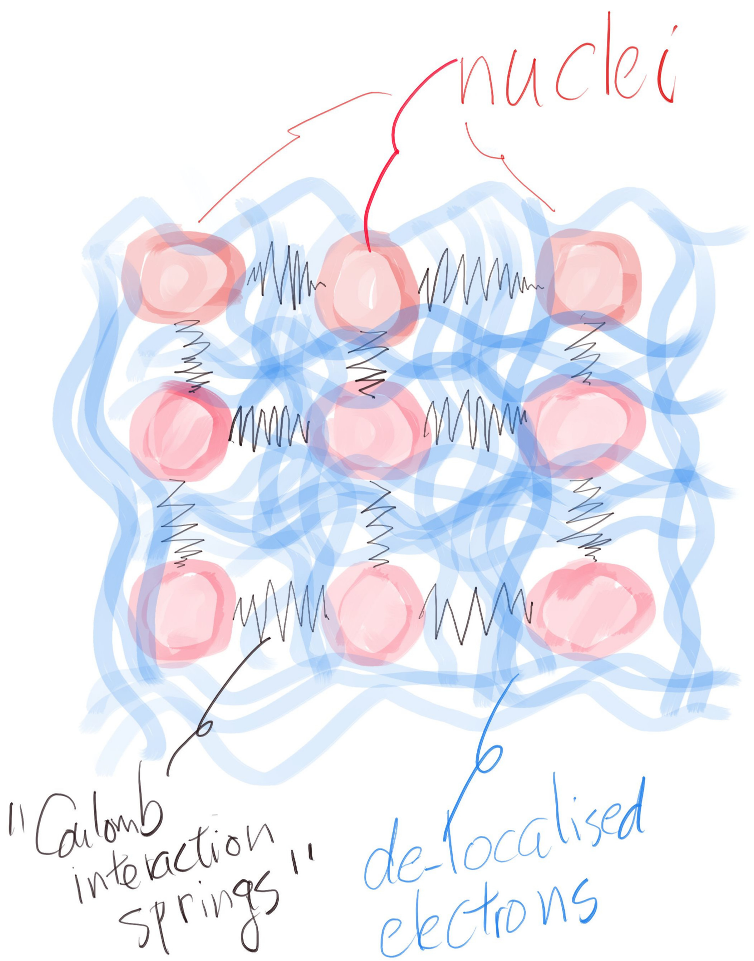
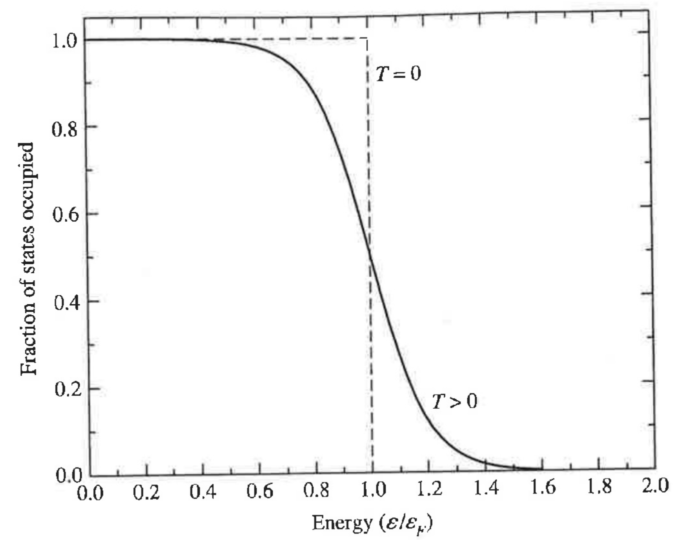
White Dwarf Star Core

Electron delocalisation

$$\lambda_{th} = \sqrt{\frac{2\pi\hbar^2}{m_e k_B T_e}}$$



e: neutralising background



thermal energy < Fermi energy

$$\frac{3}{2}kT < \frac{\hbar^2}{2m_e}\left[3\pi^2\left(\frac{Z}{A}\right)\frac{\rho}{m_H}\right]^{2/3},$$

or

$$\frac{T}{\rho^{2/3}} < \frac{\hbar^2}{3m_e k}\left[\frac{3\pi^2}{m_H}\left(\frac{Z}{A}\right)\right]^{2/3} = 1261\ \mathrm{K\ m^2\ kg^{-2/3}}$$

$$V_{ij}(r) = \frac{e^2 Z_i Z_j}{r_{ij}} e^{-r_{ij}/\lambda} \qquad (1)$$

with inter-particle separation r_{ij} and Thomas–Fermi screening length $\lambda^{-1} = 2k_F\sqrt{\alpha/\pi}$ (electron Fermi momentum $k_F = (3\pi^2\langle Z\rangle n)^{1/3}$, ion

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White Dwarf Stars

clocks of the universe, cooling rate influenced by composition

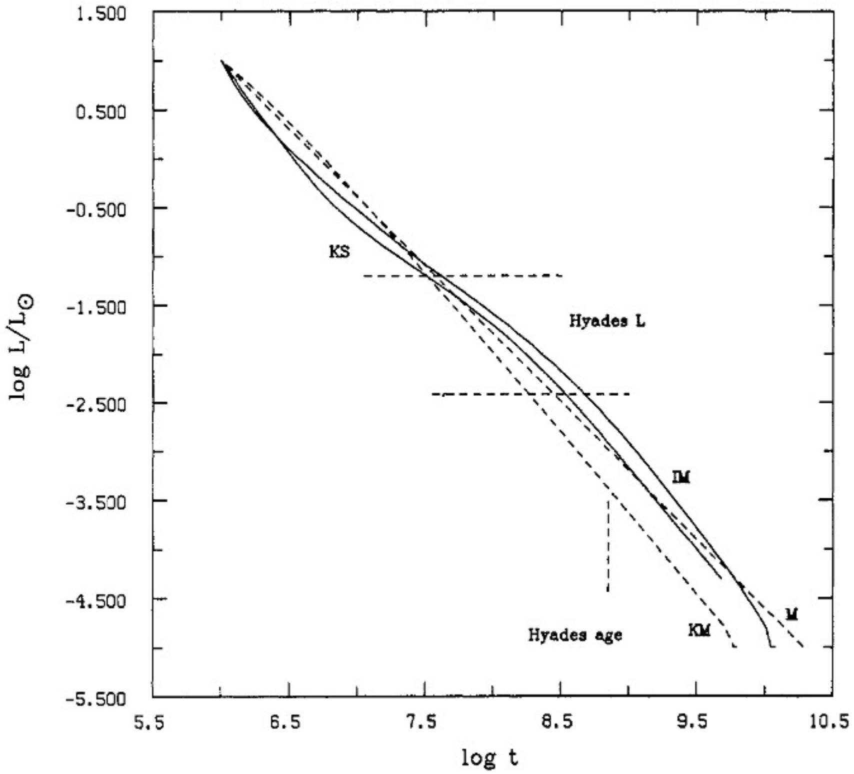

Figure 5. Cooling of white dwarfs with 0.6 $M_\odot$. Continuous lines: IM, Iben and MacDonald (1985); KS Koester and Schönberner (1986). Broken lines: simple models based on Mestel (1952) (M) and equation (4.20) with numbers *a* and *b* from Koester (1976). See text for further explanations.

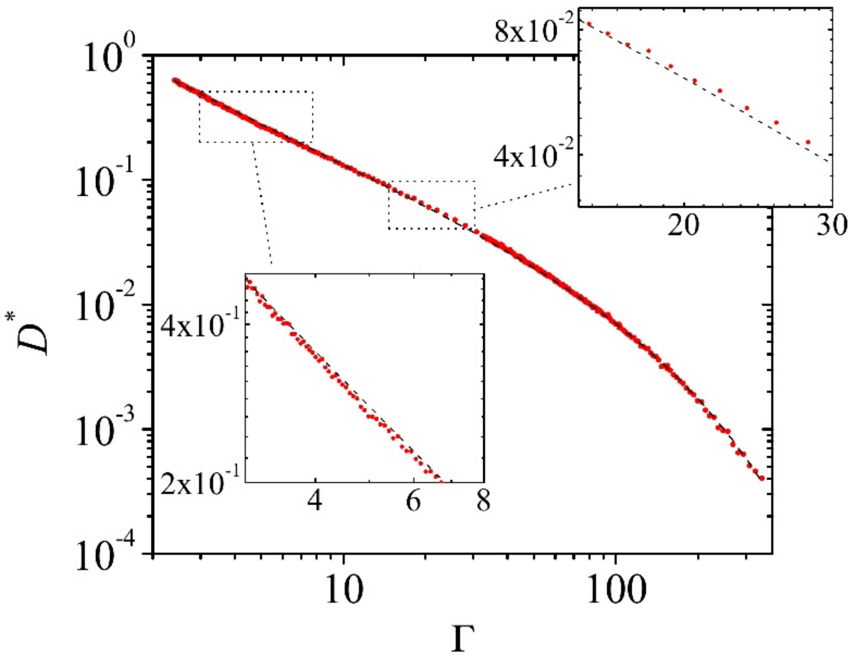

Figure 1. D^* for ^{16}O from MD (red) with fit from equation (4) (dashes) using best-fitting parameters $C = 0.7323$ and $B = 0.006937$. The fit is good to about 5 per cent for all Γ, but it is clear that it systematically overpredicts for $\Gamma \lesssim 10$ (bottom inset) and underpredicts for $10 \lesssim \Gamma \lesssim 100$ (top inset). Normalized residuals for all runs are shown in Fig. 2.

L ... luminosity
Rep. Prog. Phys. 53 (1990) 837-915.

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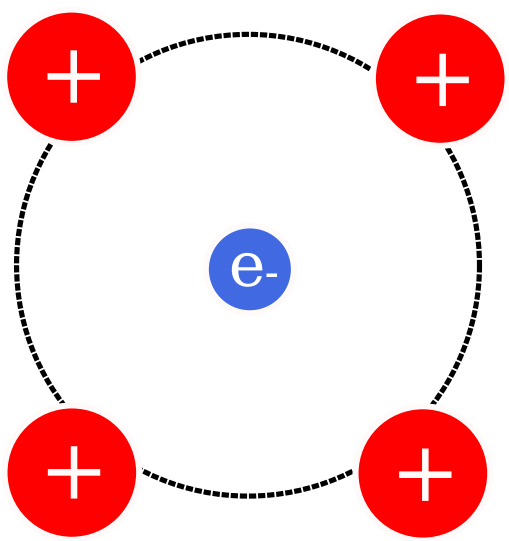
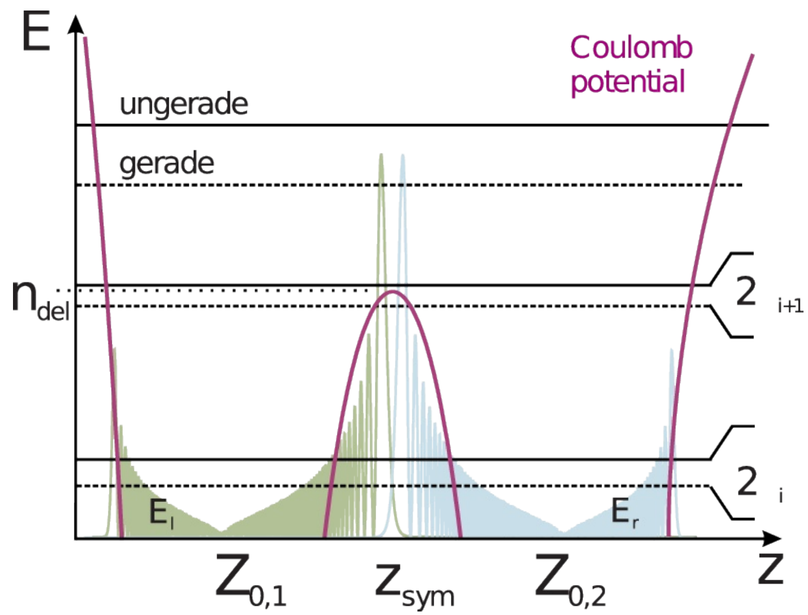
Benefits of light mass, low temperatures

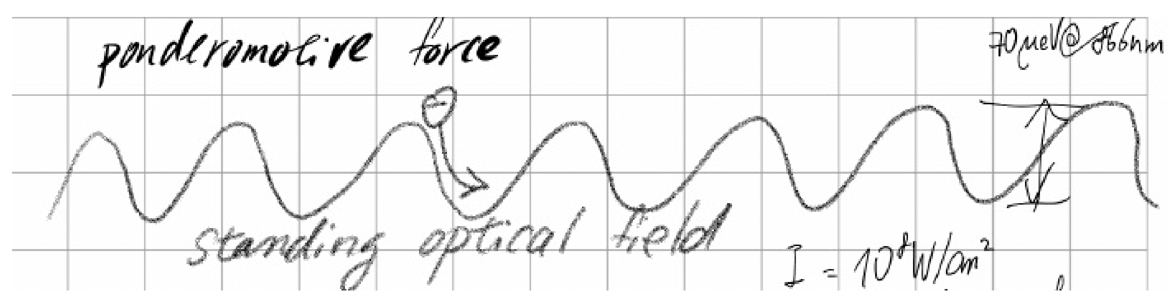


If $\lambda_{th} \approx a$, diffraction



Schroedinger cat state

Lesanovsky, I., Müller, M. & Zoller, P. Trap-assisted creation of giant molecules and Rydberg-mediated coherent charge transfer in a Penning trap. Phys. Rev. A 79, 010701 (2009).



Interaction with optical field

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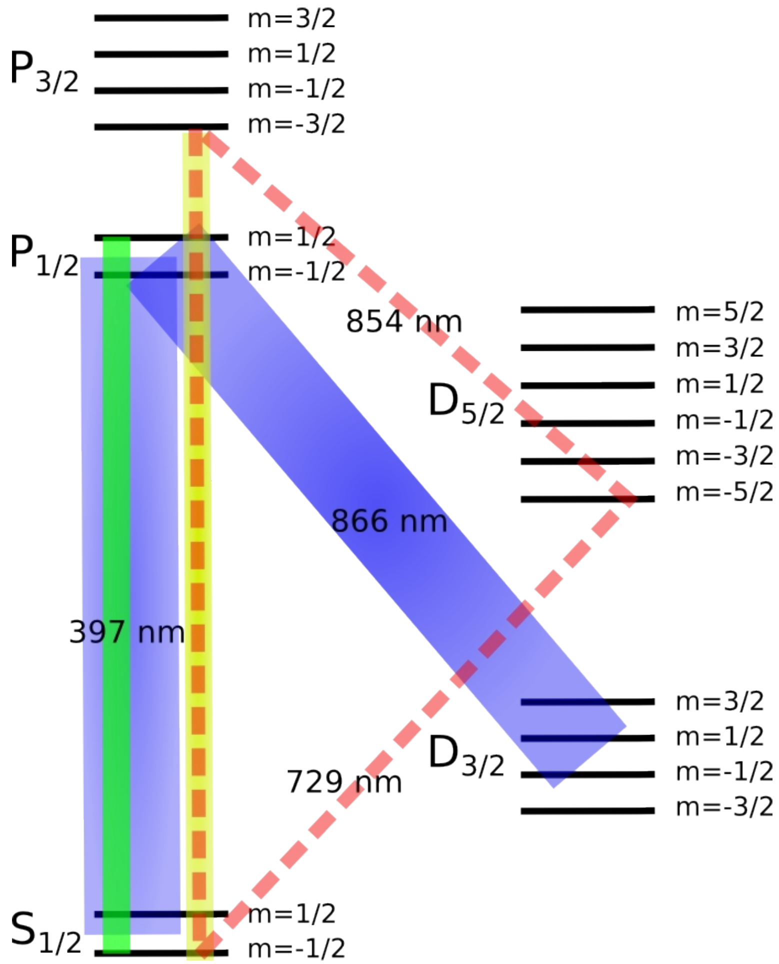
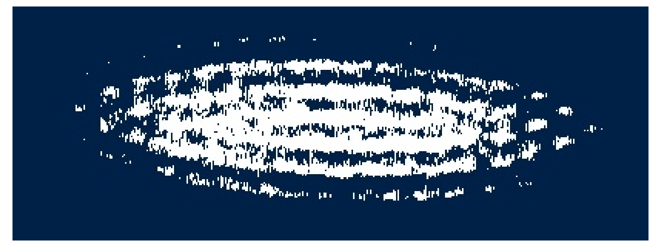
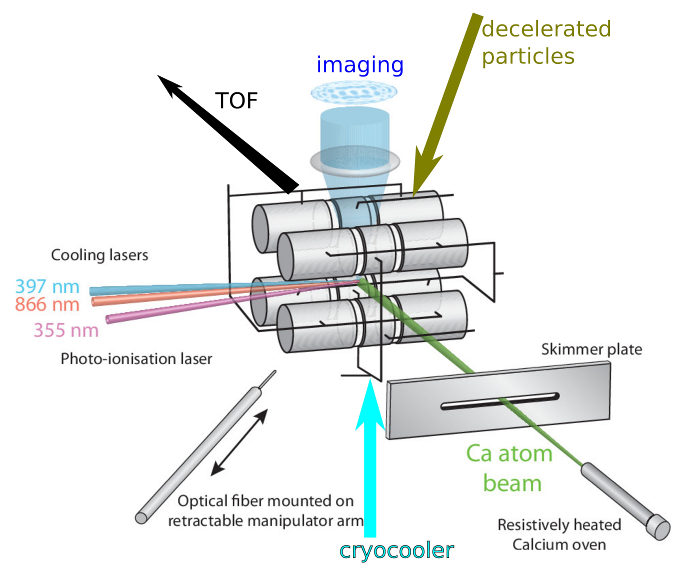
Production of ion Coulomb crystal





Doppler cooling limit: 0.5 mK
for calcium S-P transition



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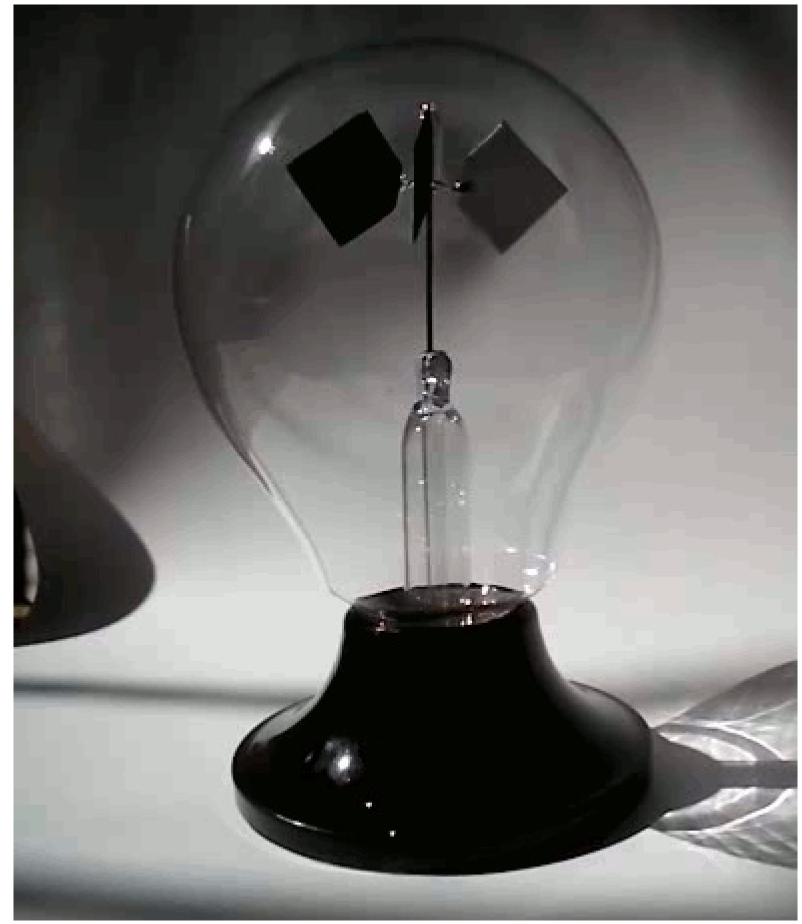
Interaction with radiation - macroscopic

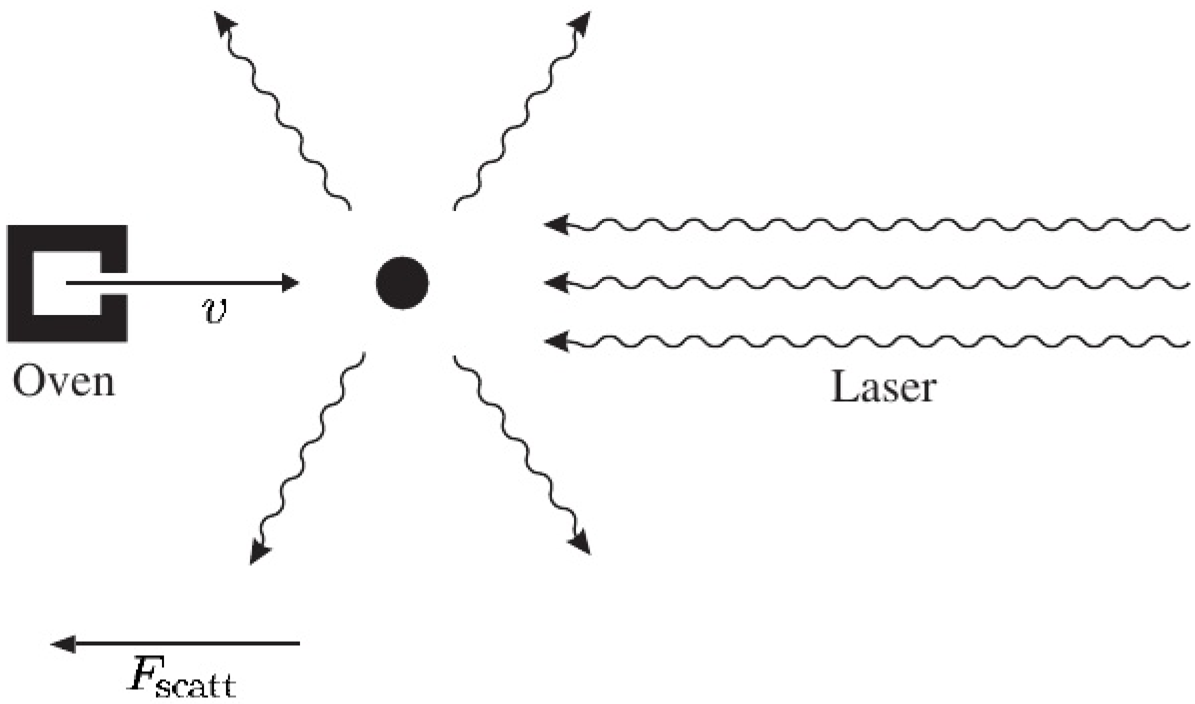
Radiation pressure



Crookes radiometer (!!!!)

Laser cooling by scattering force

Action on atoms



How large is the scattering force on atoms?

Force = (photon momentum) x (scattering rate)

$$F = \hbar k \times R_{scatt}$$

$$k = \frac{2\pi}{\lambda}$$

deceleration = Force / mass

$$a_{max} = \frac{F_{max}}{m} = \frac{\hbar k}{m} \times R_{scatt} = v_{rec} \times \frac{1}{2\tau}$$

Recoil velocity of Rb atom = 6 mm /s

Many photons

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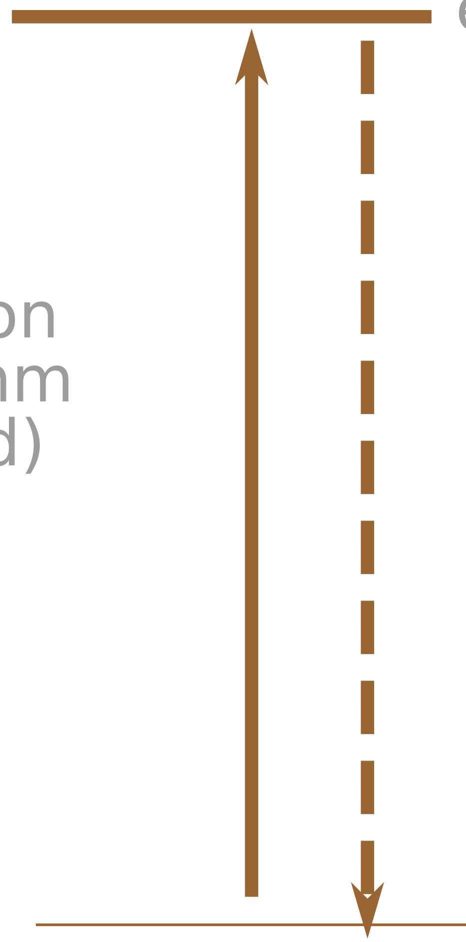
Two-level atom



$\tau = 28\,\mathrm{ns}$ for $^{87}\mathrm{Rb}$

How fast can we scatter?

$a_{max} = 10^5 \mathrm{m/s}^2 = 10^4 g$

Stopping distance

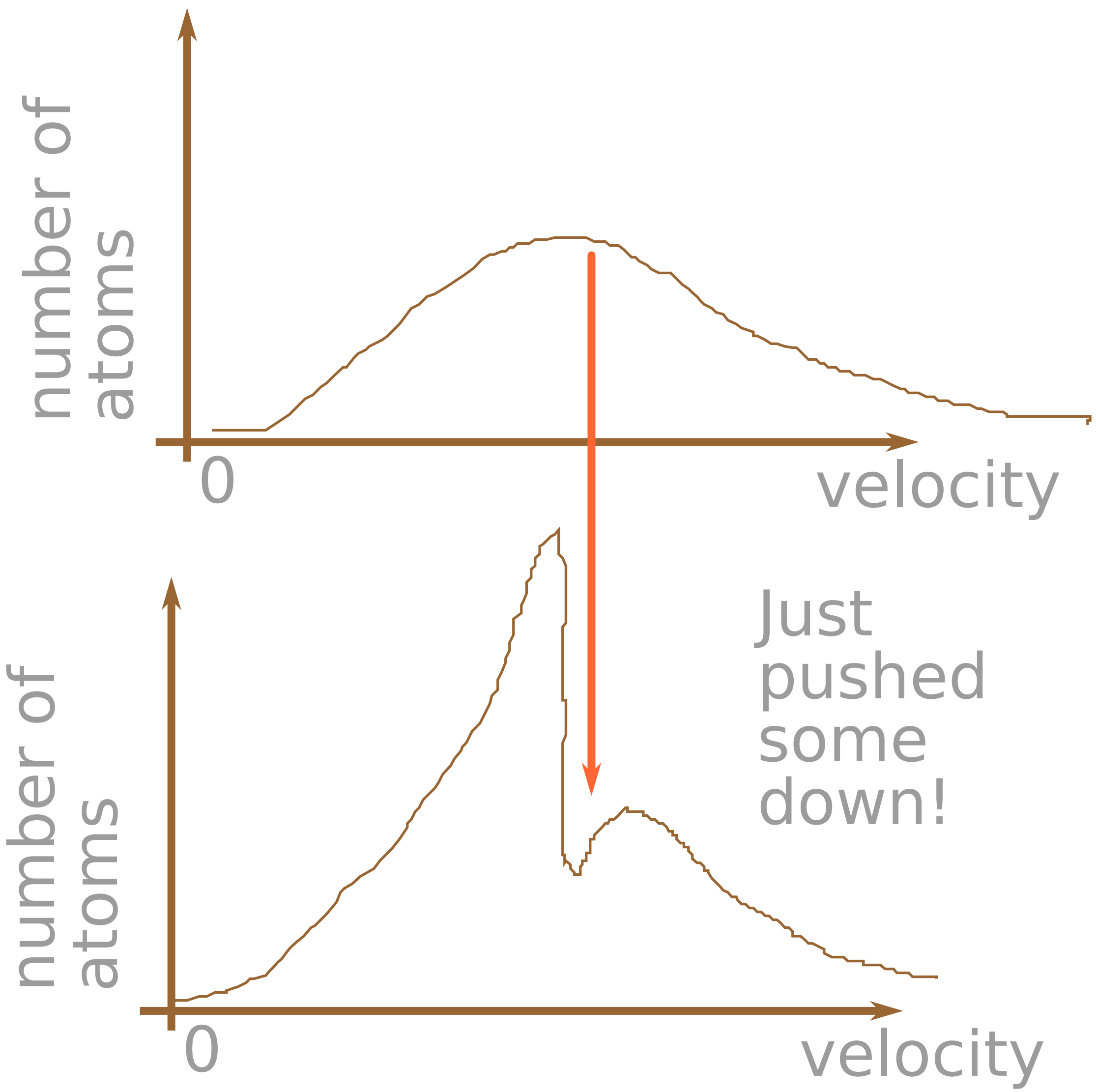
$v^2 = 2as$

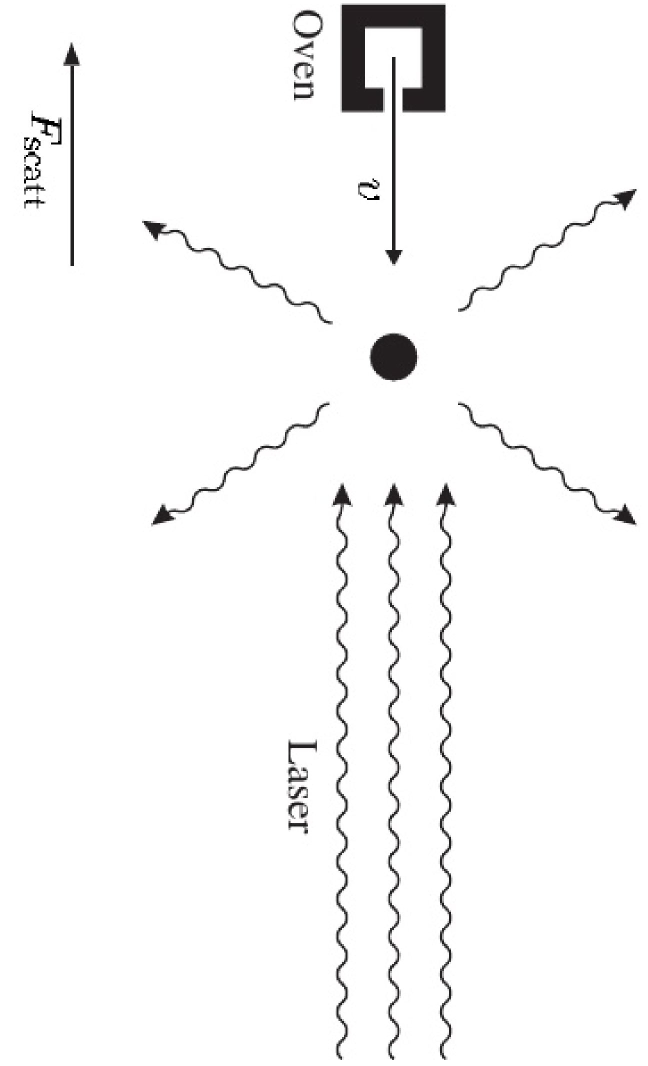
$s = 1\,\mathrm{m}$

for $v(0) = 300\mathrm{m/s}$, $a = a_{max}/2$

Similar distance for other alkali metals: Na, K, Cs

Slowing atoms with laser light





Doppler shift much greater than natural width

$$\frac{\Delta f}{f_0} = \frac{v}{c}$$

Doppler width = velocity / wavelength

$$\Delta f_{Doppler} = \frac{v}{\lambda} = \frac{300}{7.8\times 10^{-7}} = 380\,\mathrm{MHz}$$

(estimate)

Natural width (lifetime broadening)

$$\tau = 28\,\mathrm{ns\ for\ }^{87}\mathrm{Rb}$$

$$\Delta f_N = \frac{1}{2\pi\tau} = 6\,\mathrm{MHz}$$

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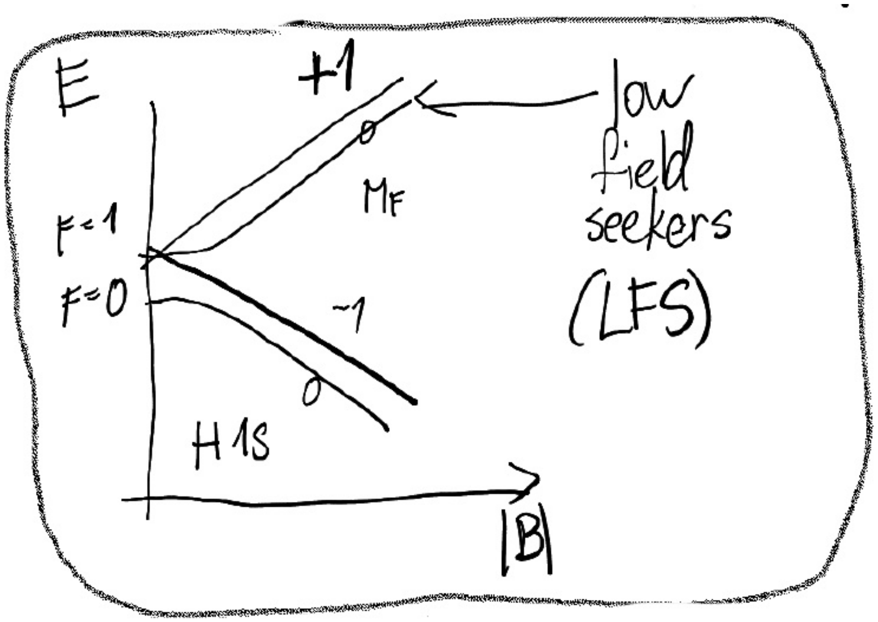
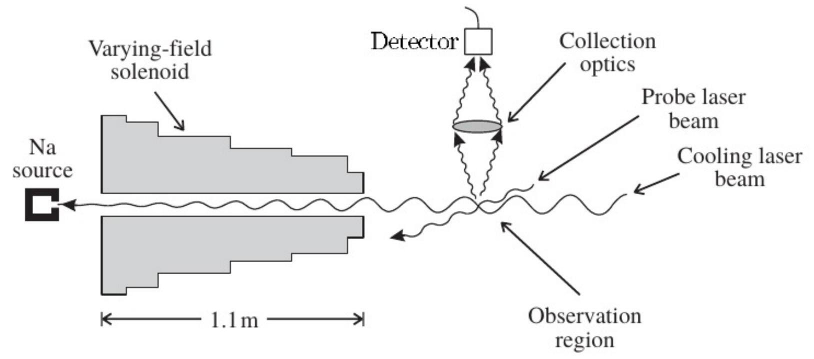
Compensate for the Doppler shift

Shift the wavelength in time: chirp cooling - not popular - cannot do it continuously (pulsed laser)

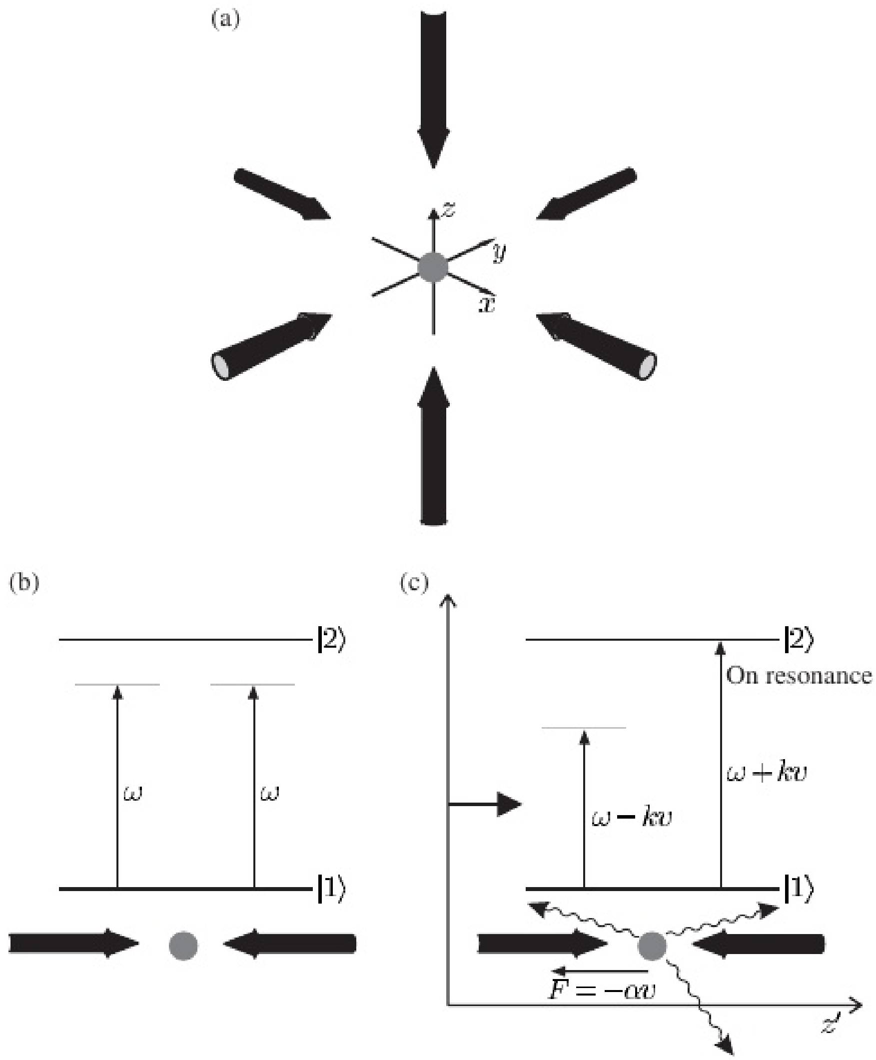
Use Zeeman shift (frequency shift in magnetic field)



Zeeman slower: space-dependent magnetic field



Optical molasses



(a) 3 pairs of counterpropagating beams

(b) atom at rest

(c) moving atom

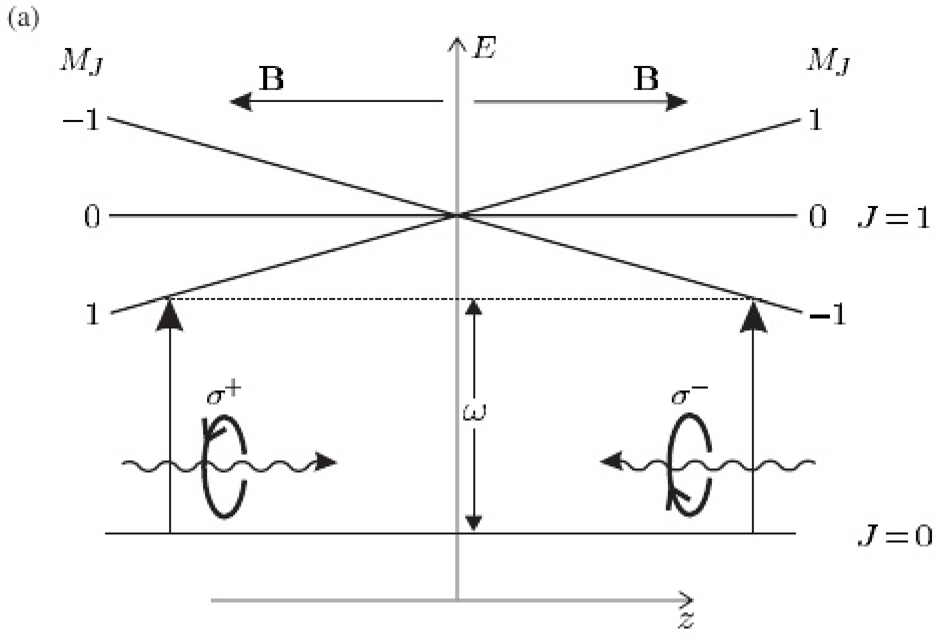
Just damping and cooling. Not confining.

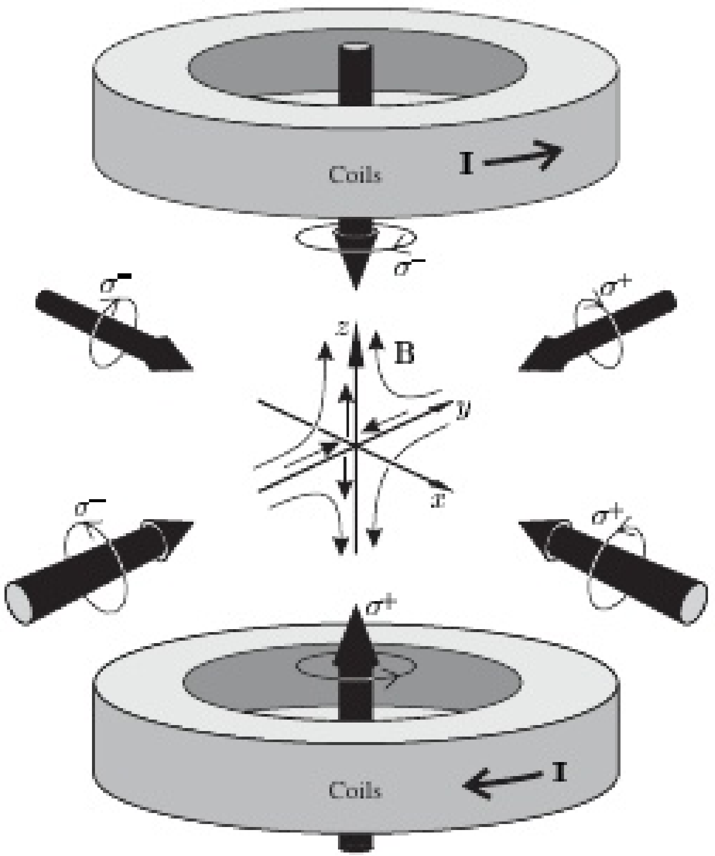
The same for ions, in principle, but no counterpropagating beam is necessary.

Doppler cooling limit:

$$k_B T_D = \frac{\hbar\Gamma}{2} = \frac{\hbar}{\tau}$$

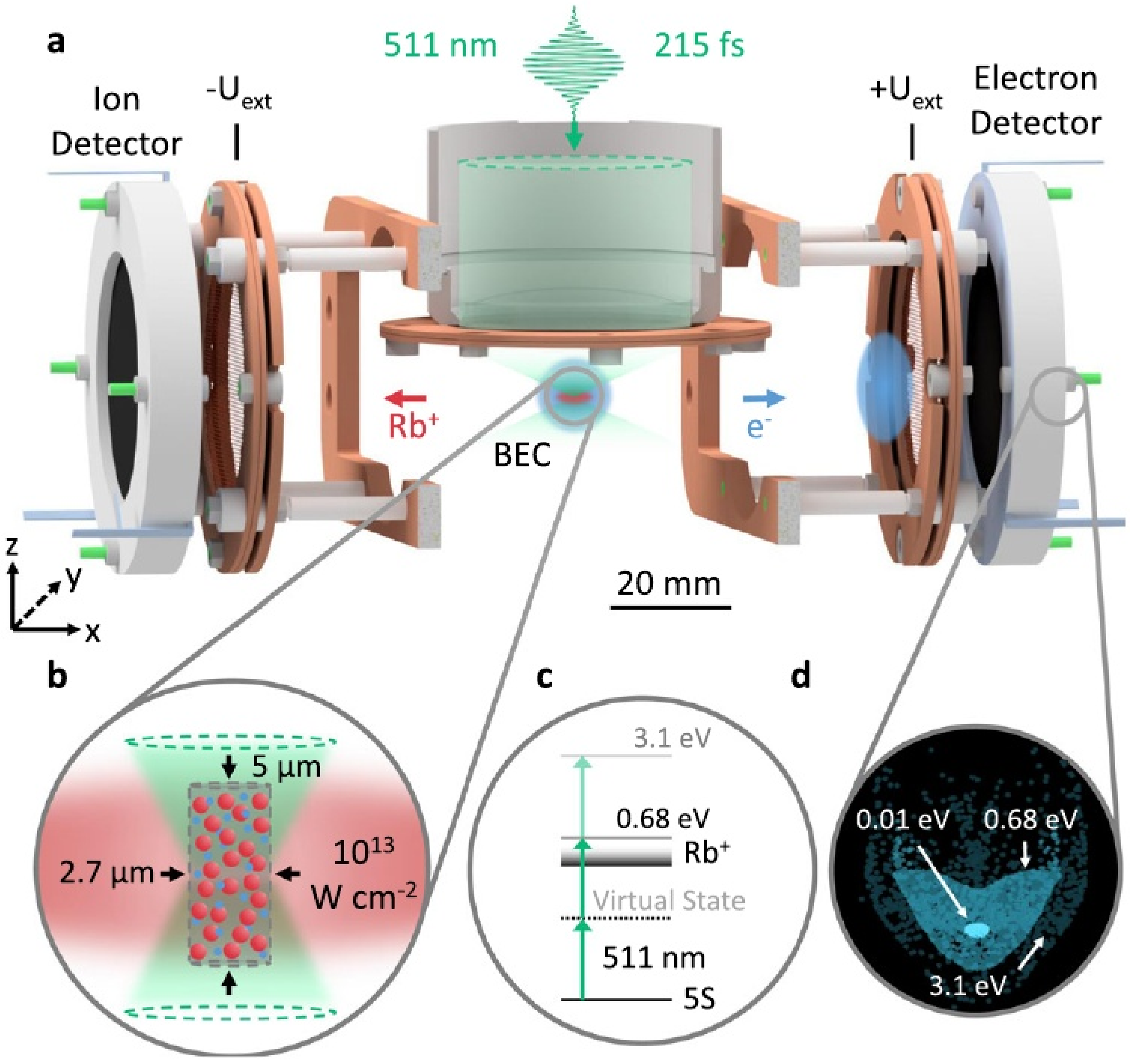
Magneto-Optical Trap (MOT)





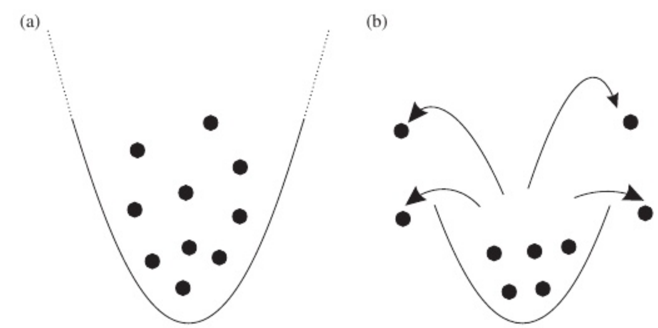
Gas (atoms) pushed to the centre due to force imbalance.

Experiment with Bose-Einstein condensate



$$\lambda_{th} = \sqrt{\frac{2\pi\hbar^2}{mk_BT}}$$

Evaporative cooling



Kroker, T. et al. Ultrafast electron cooling in an expanding ultracold plasma. Nat Commun 12, 596 (2021).

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Atoms do have a magnetic moment

$$\mu_F = g_F \mu_B \sqrt{f(f+1)}$$

$$g_J = 1 + \frac{J(J+1)+S(S+1)-L(L+1)}{2J(J+1)}$$ (Landé g-factor)

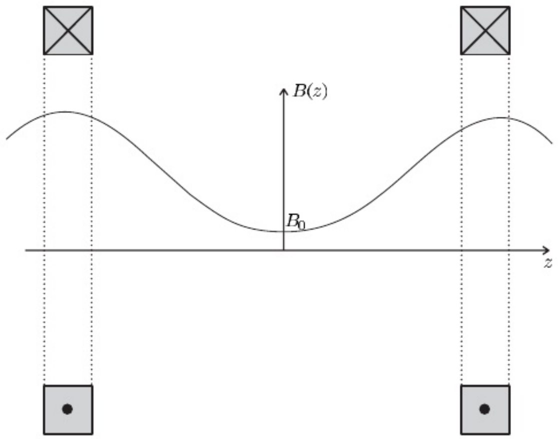
$$g_F \approx= g_J \frac{F(F+1)+J(J+1)-I(I+1)}{2F(F+1)}$$

Energy in magnetic field: $V = -\mu_F \cdot B = m_F g_F \mu_B B$ (Zeeman energy)

Force acting in an inhomogeneous magnetic field:

$$F = -m_F g_F \mu_B \nabla B$$

Larger the J, L, F, stronger the interaction!



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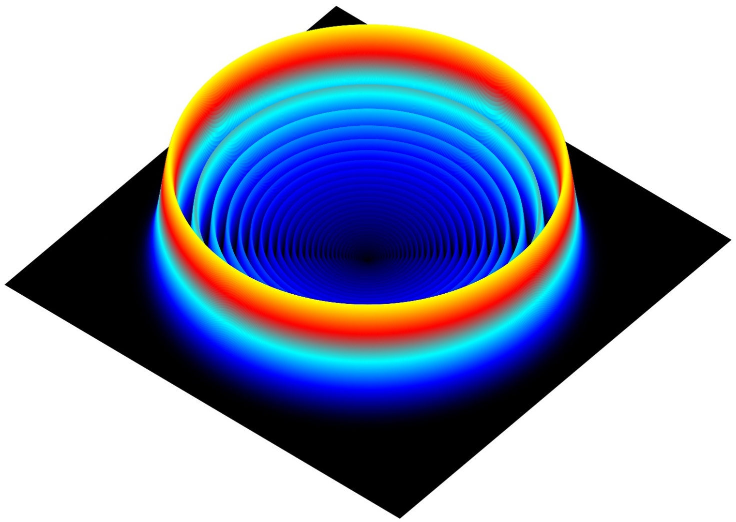
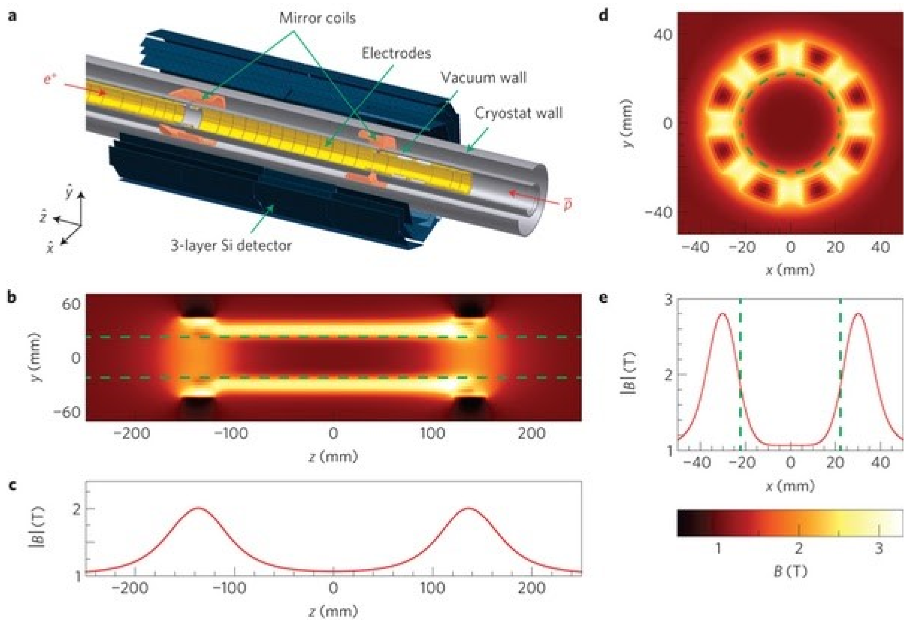
Rydberg atoms

- Born from mutual love - Coulomb interaction - between an electron and an ion.
- Or, between an positron and an antiproton.



35s state of hydrogen



CERN Alpha trap, trapping antimatter in a magnetic bottle

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Interesting things about Rydberg atoms

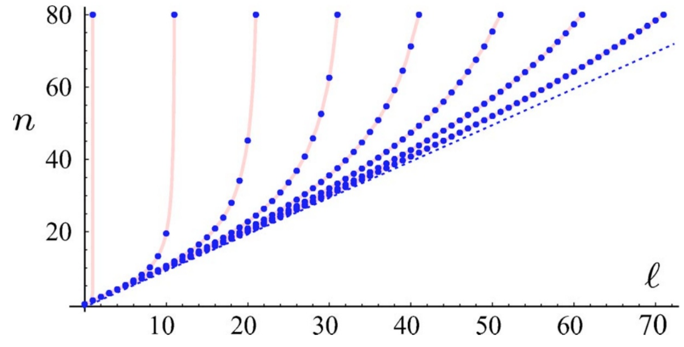
Dimensions: $r = \frac{n^2\hbar^2}{ke^2m}$ microns (like bacteria)

Lifetimes: $\tau \propto n^3(l+1/2)^2$ hundreds of microseconds

Dipole moments: $d \propto n^2$

Radiative cascade, only changes of l by +/−1 allowed.

Energy spacing: $\Delta E \propto \frac{1}{n^3}$



And remember the magnetic moment! Circular states with l=n−1.

$$\mu_F = g_F \mu_{\mathrm{B}} \sqrt{f(f+1)}$$

Flannery, M. R. & Vrinceanu, D. Quantal and classical radiative cascade in Rydberg plasmas. Phys. Rev. A 68, 030502 (2003).

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Antimatter plasma

3-body recombination

$$k \propto T^{-9/2}$$

High Rydberg - reionization

Low-Rydberg - stabilization

Guiding centre atom in magnetic field

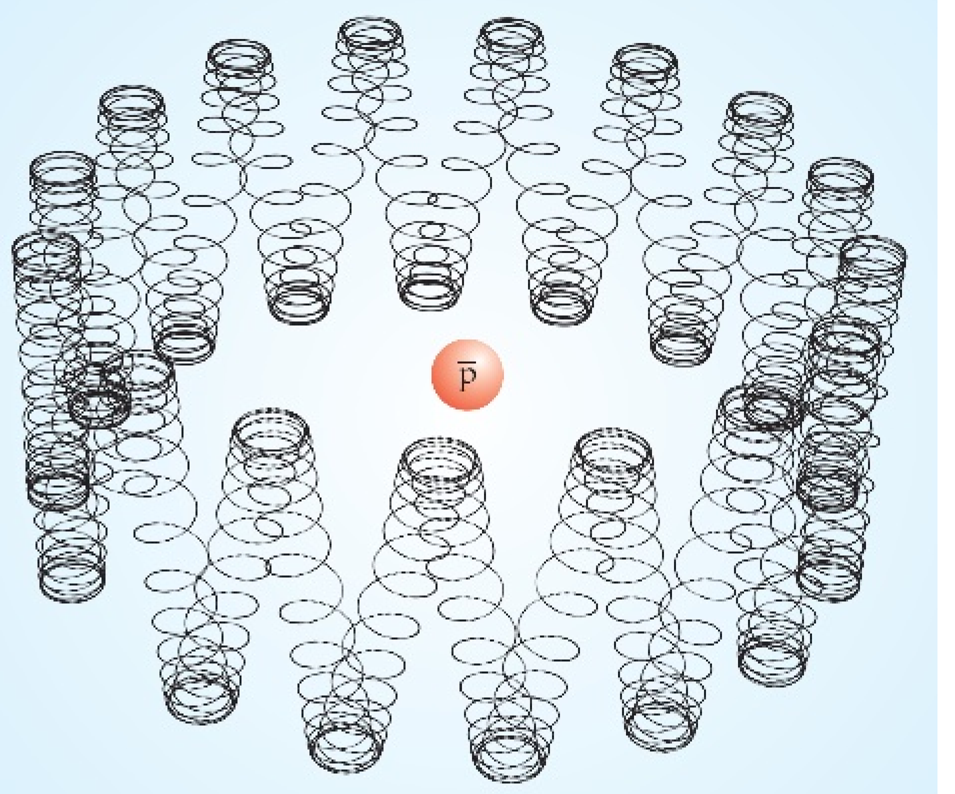

Figure 3. A classical trajectory of a positron in an antihydrogen Rydberg atom in a strong magnetic field. The positron undergoes cyclotron motion with small Larmor radius, bounces back and forth along a field line, and drifts around the antiproton. The complicated motion alters the dynamics of an antimatter plasma containing such atoms.

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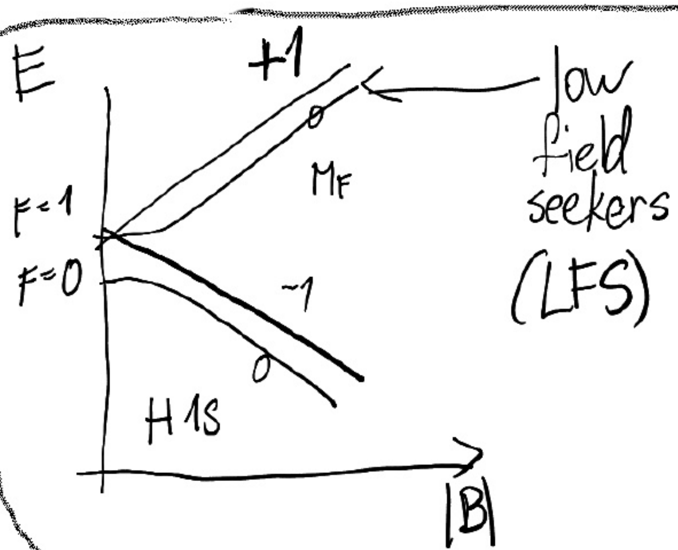
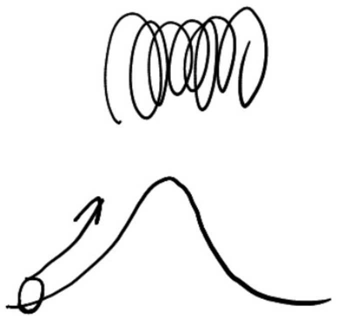
Deceleration without lasers



electromagnet



LFS consume the kinetic energy entering the stronger field

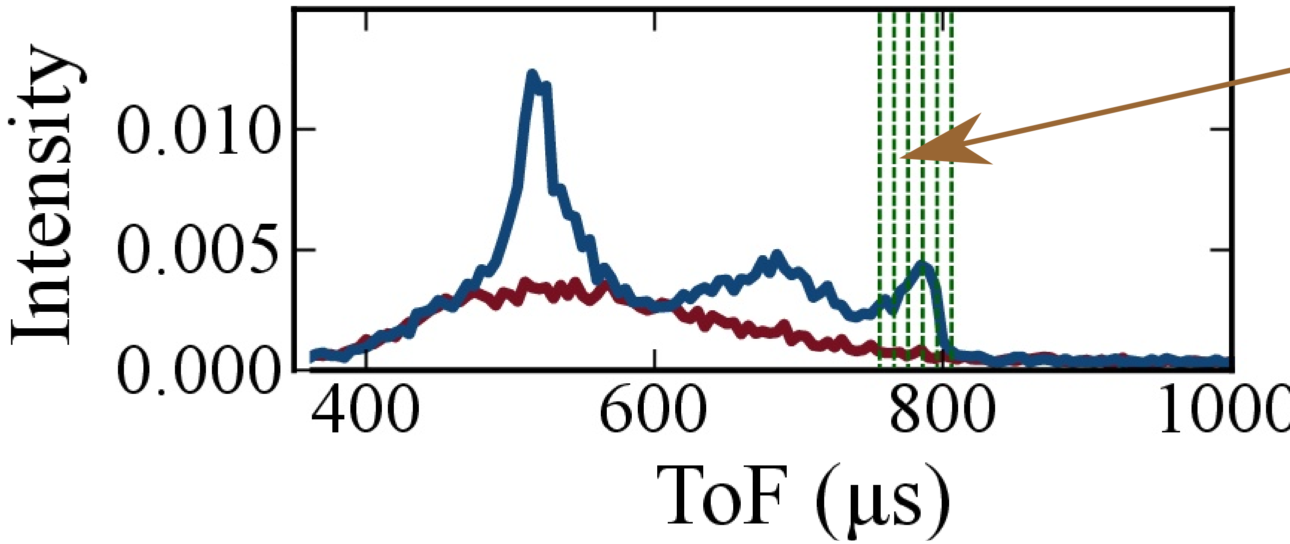
$$F_z = -\mu \nabla_z B(z,t)$$

switching of coils

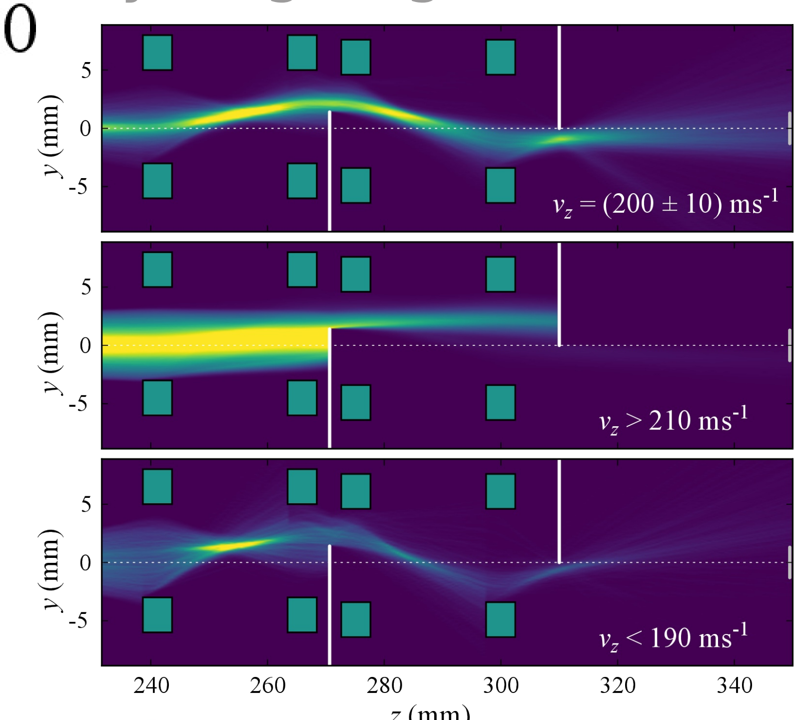
gradual deceleration

There is a catch.

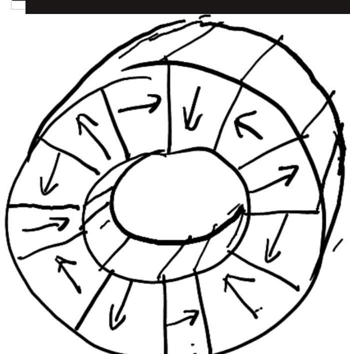
Catch: filtering the velocity

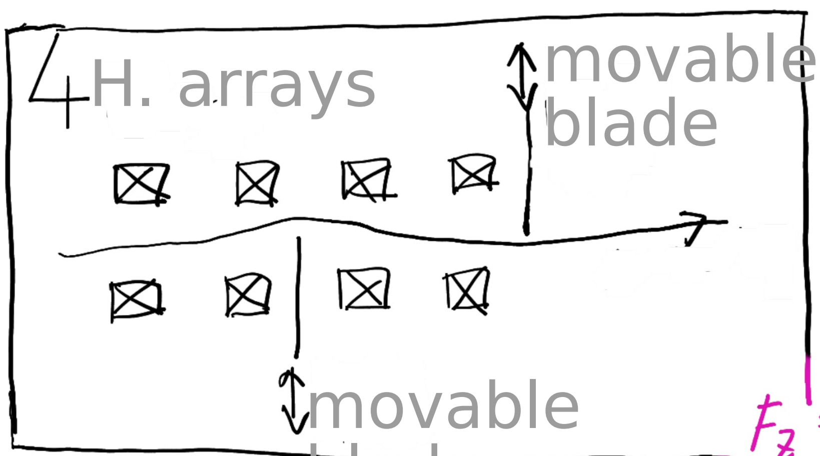


Only this part needed:
70 – 100 m/s, corresponding to mean velocity in 1 K hydrogen gas.



Obstacle course for





$F_z = -\mu \nabla B$

Hallbach array for localised magnetic field

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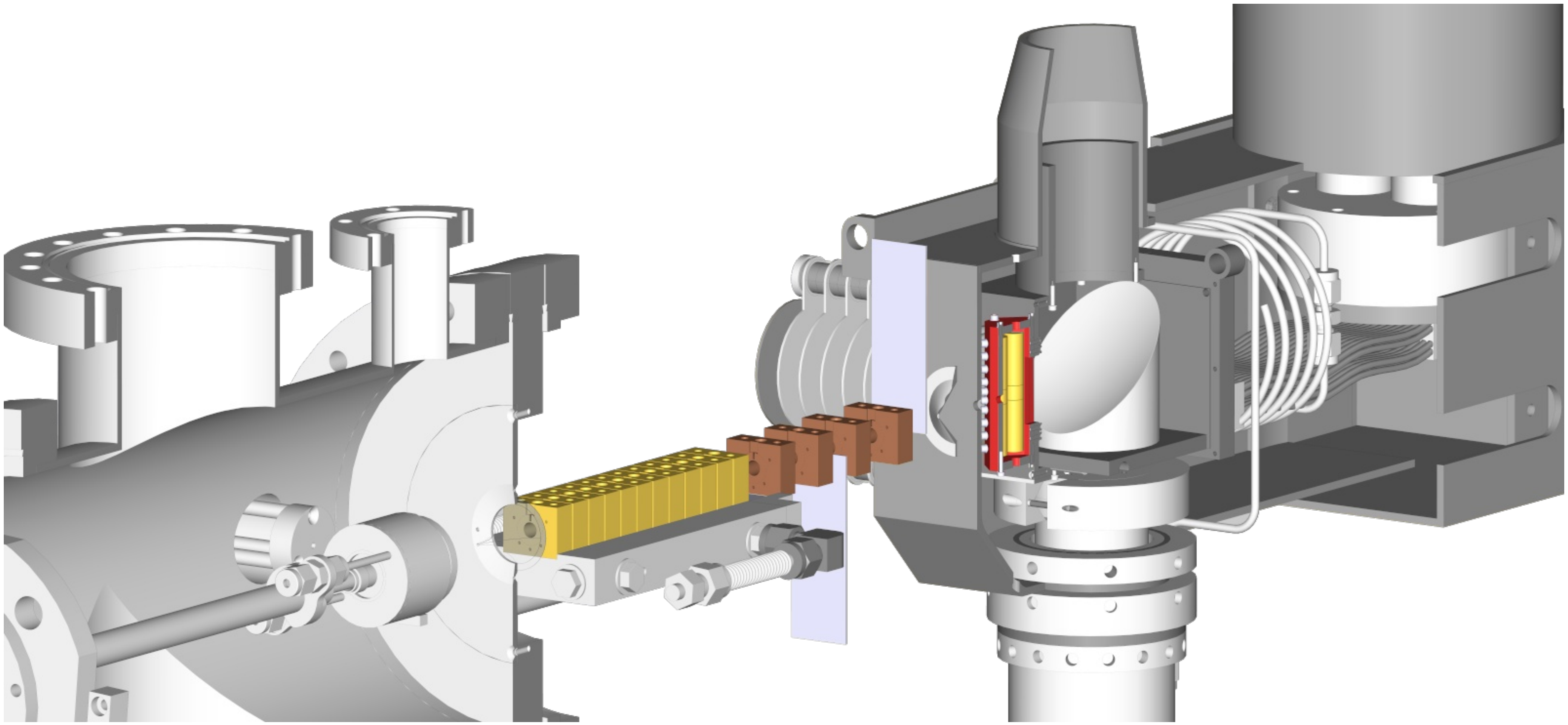
Putting it all together



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What about the ions?

What we have learnt

It is possible to cool, decelerate and trap neutral atoms. Especially easy if they are hydrogen-like.

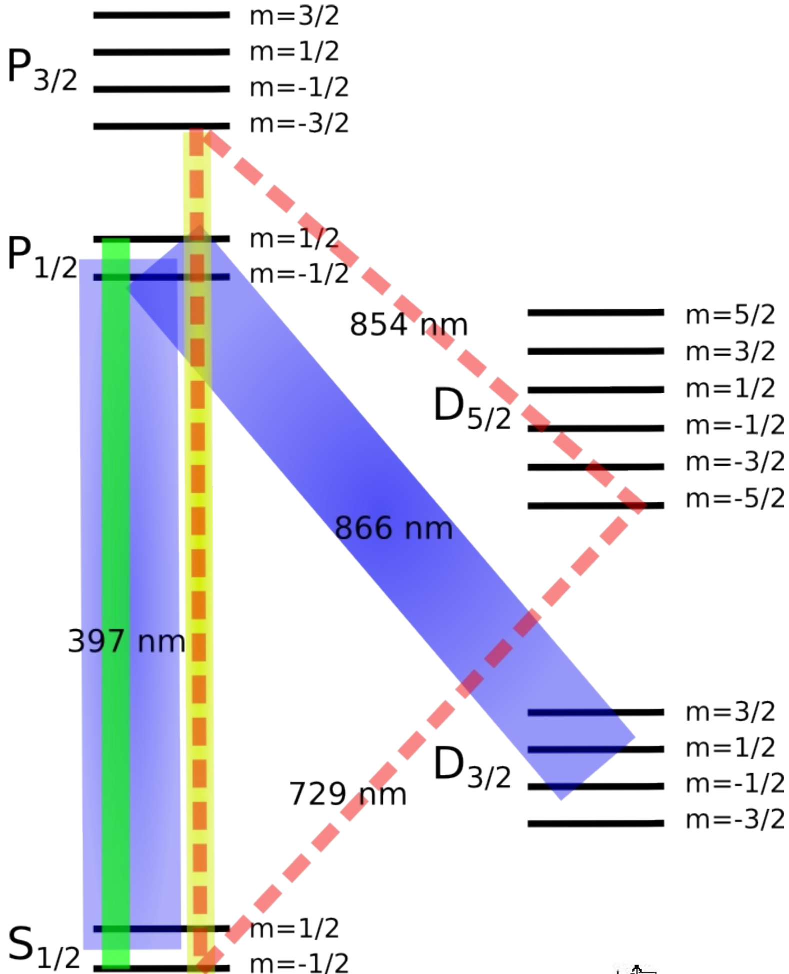
1 H																		**2 He**
3 Li	4 Be													5 B	6 C	7 N	8 O	9 F	**10 Ne**
11 Na	**12 Mg**													13 Al	14 Si	15 P	16 S	17 Cl	**18 Ar**
19 K	**20 Ca**		21 Sc	22 Ti	23 V	**24 Cr**	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	**36 Kr**
37 Rb	**38 Sr**		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	**47 Ag**	**48 Cd**	49 In	50 Sn	51 Sb	52 Te	53 I	**54 Xe**
55 Cs	**56 Ba**	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	**80 Hg**	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	**88 Ra**	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
		*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	**66 Dy**	**67 Ho**	**68 Er**	**69 Tm**	**70 Yb**		
		**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		

1 H																		2 He
3 Li	**4 Be**													5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	**12 Mg**													13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	**20 Ca**		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	**30 Zn**	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	**38 Sr**		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	**48 Cd**	**49 In**	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	**56 Ba**	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	**80 Hg**	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
		*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	**70 Yb**		
		**	89 Ac	**90 Th**	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		

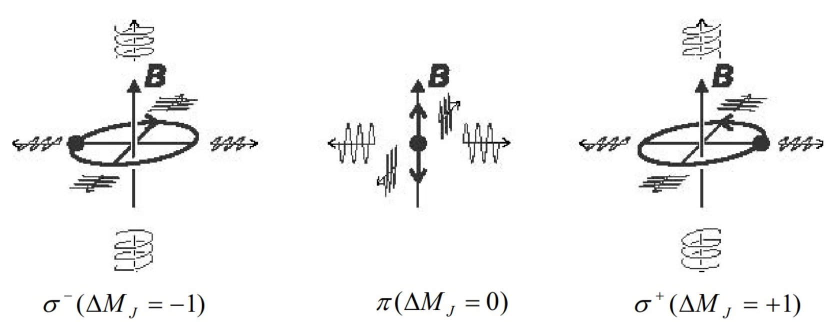
Atoms of alkaline earth metals that have lost one electron are also hydrogen-like.

Ions are friends with benefits: the electric charge allows them to be confined.

Cooling of calcium ions



Allowed transitions		Electric dipole (E1)	Magnetic dipole (M1)
Rigorous rules	**(1)**	$\Delta J = 0, \pm 1$ ($J = 0 \not\leftrightarrow 0$)	
	(2)	$\Delta M_J = 0, \pm 1$ ($M_J = 0 \not\leftrightarrow 0$ if $\Delta J = 0$)	
	(3)	$\pi_f = -\pi_i$	$\pi_f =$
LS coupling	**(4)**	One electron jump $\Delta L = \pm 1$	No electron jump $\Delta L = 0$, $\Delta n = 0$
	(5)	If $\Delta S = 0$ $\Delta L = 0, \pm 1$ ($L = 0 \not\leftrightarrow 0$)	If $\Delta S = 0$ $\Delta L = 0$
Intermediate coupling	**(6)**	If $\Delta S = \pm 1$ $\Delta L = 0, \pm 1, \pm 2$	



polarisation matters

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Trapping ions - Penning traps

$\bar{U} \propto ax^2 + by^2 + cz^2$

$\Delta \bar{U} = 0$

$a + b + c = 0$

$a = -1,\ b = -1,\ c = +2$

Lorentz force:

$\vec{F} = -q\vec{\nabla}\bar{U} + q(\vec{v} \times \vec{B}_0)$

Electrostatic field:

$E_z = -\frac{\bar{U}}{d^2}z$ and $E_\rho = +\frac{\bar{U}}{2d^2}\rho$

where characteristic trap dimension $2d^2 = z_0^2 + \rho_0^2/2$

Energy require to move fron the centre

in electric field

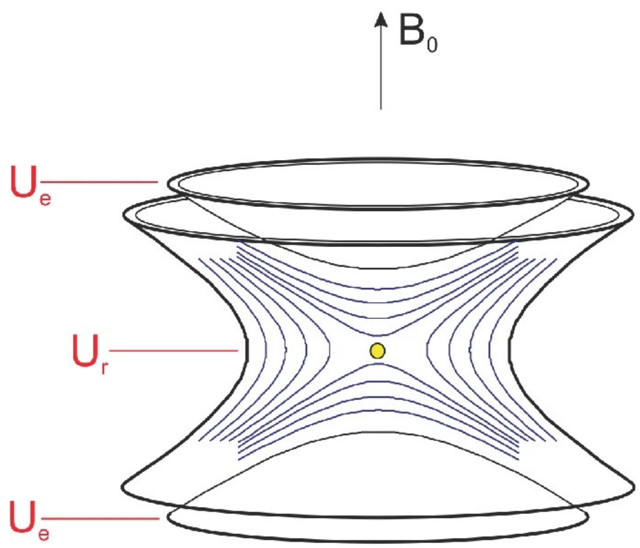
$E_B = \frac{1}{2m}\rho^2 q^2 B_0^2$

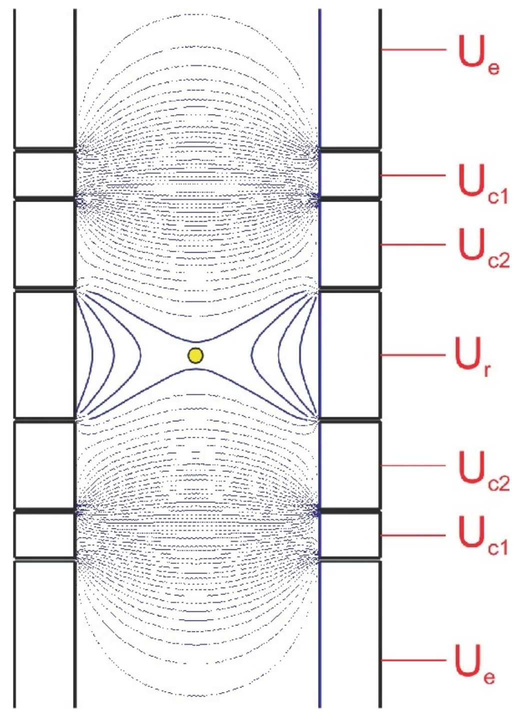
in magnetic field

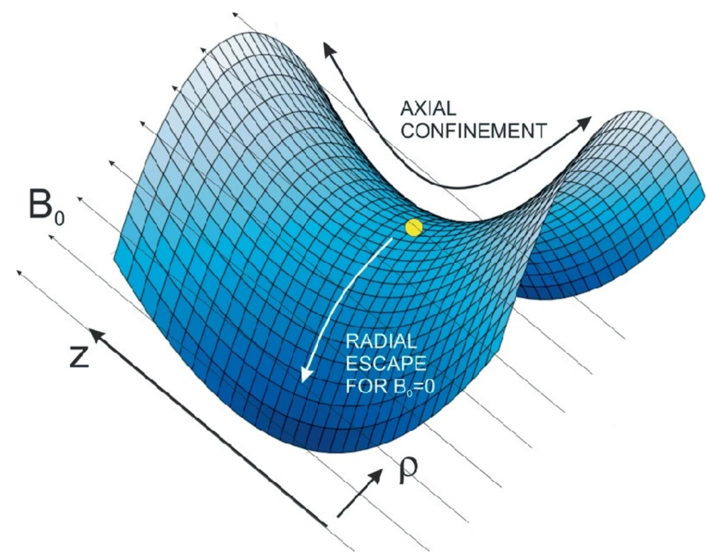
$E_E = q\bar{U}\frac{z^2}{d^2}$

ratio:

$\frac{E_B}{E_E} = \frac{1}{2m}d^2 q \frac{B_0^2}{\bar{U}}$







hyperbolic trap, cylindrical trap

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Vogel, M. (2024). Penning Trap Concept. In: Particle Confinement in Penning Traps. Springer Series on Atomic, Optical, and Plasma Physics, vol 126. Springer, Cham. https://doi.org/10.1007/978-3-031-55420-9_2

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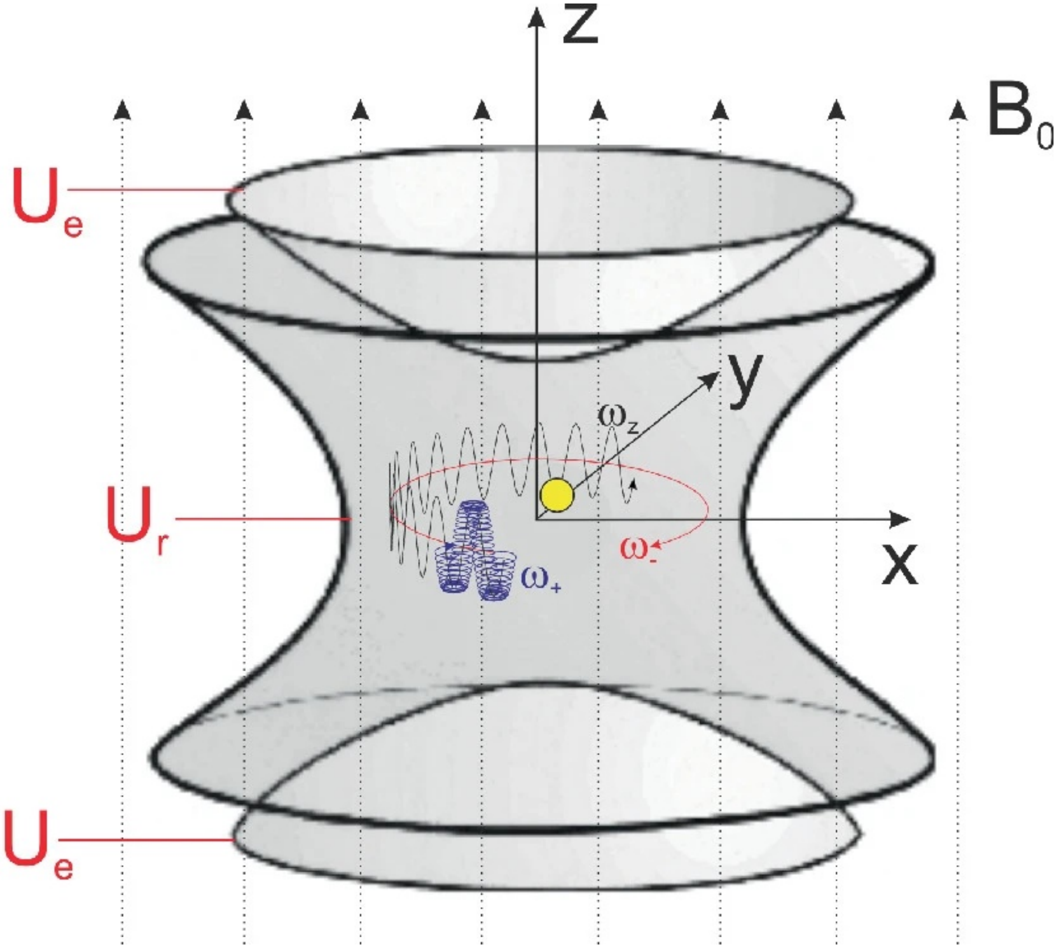
Trapping ions - ion in Penning trap



Stability condition:

$$\omega_c^2 > 2\omega_z^2$$

$$B > \sqrt{2\frac{m}{q}\frac{\bar{U}}{d^2}}$$

$$\ddot{\vec{r}} = \frac{q}{m}(\dot{\vec{r}} \times \vec{B} + \vec{E})$$

$$\begin{pmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{pmatrix} = \frac{q}{m}B_z \begin{pmatrix} \dot{y} \\ -\dot{x} \\ 0 \end{pmatrix} + \frac{q\bar{U}}{2md^2} \begin{pmatrix} x \\ y \\ -2z \end{pmatrix}$$

Solutions:

$z(t) = \hat{z}_0 e^{i\omega_z t}$ with $\omega_z = \sqrt{\frac{q\bar{U}}{md^2}}$

- axial frequency

$$\begin{pmatrix} \ddot{x} \\ \ddot{y} \end{pmatrix} = \omega_c \begin{pmatrix} \dot{y} \\ -\dot{x} \end{pmatrix} + \frac{1}{2}\omega_z^2 \begin{pmatrix} x \\ y \end{pmatrix},$$

where $\omega_c = qB/m$.

Use $u(t) = x(t) + iy(t)$ and rewrite to

$\ddot{u} = -i\omega_c\dot{u} + \frac{1}{2}\omega_z^2 u$.

Then solutions $u(t) = u_0 e^{-i\omega t}$ with

$$\omega_\pm = \frac{1}{2}(\omega_c \pm \sqrt{\omega_c^2 - 2\omega_z^2})$$

ω_+ ... modified cyclotron frequency

ω_- ... magnetron frequency

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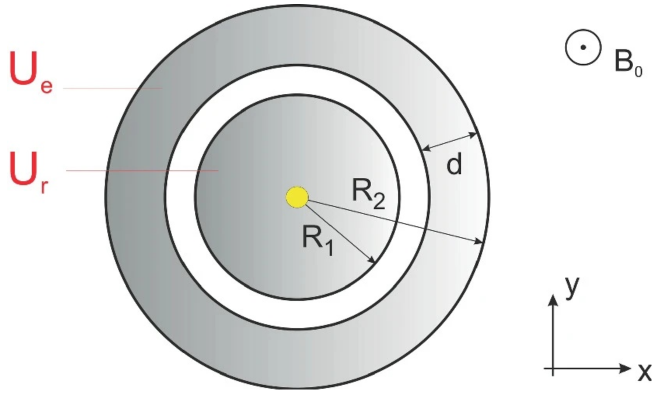
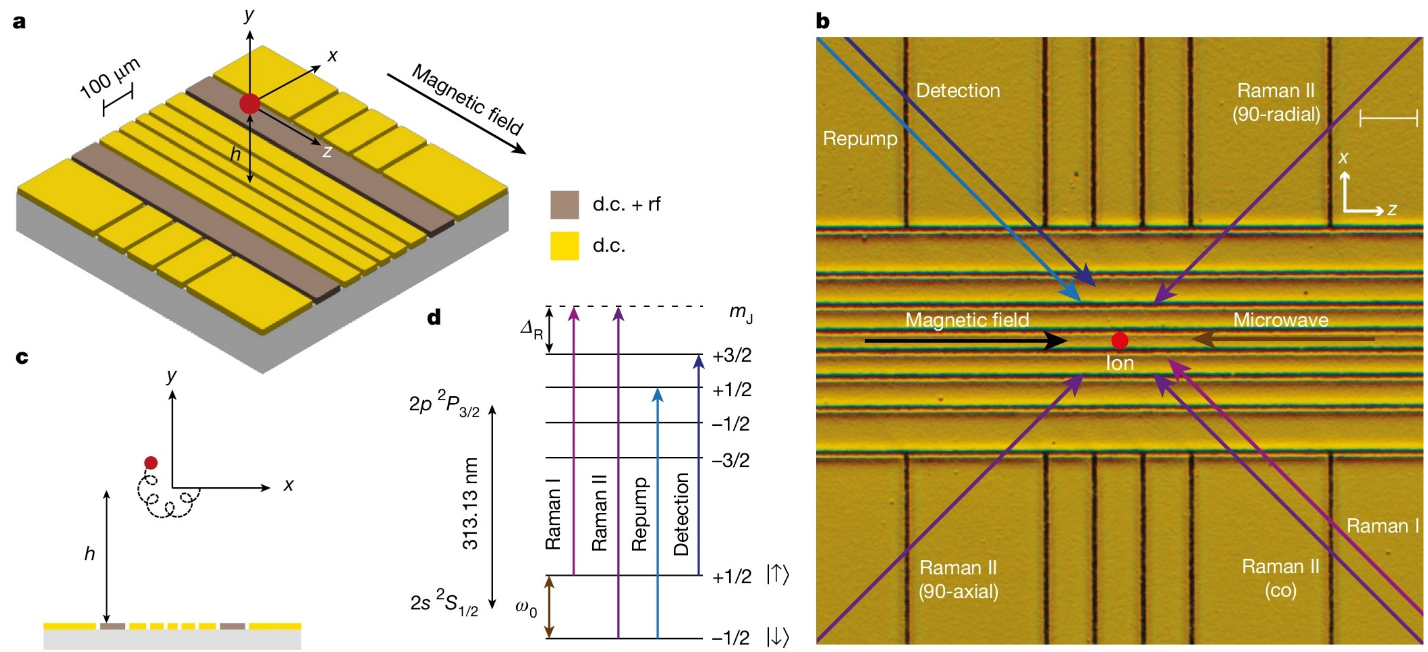
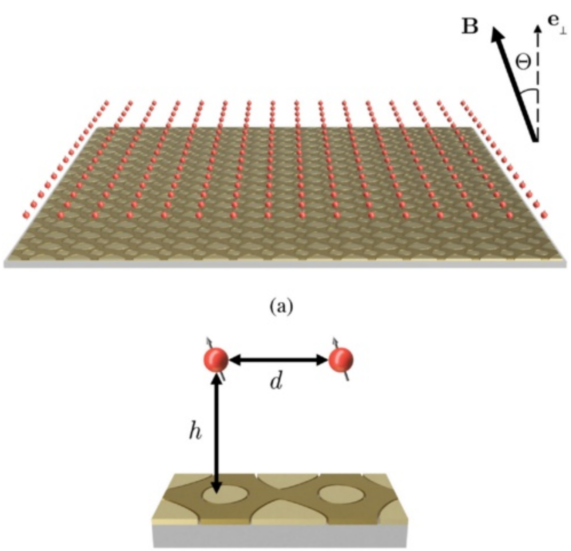
Trapping ions - Penning trap in Quant-tech







(a)

(b)

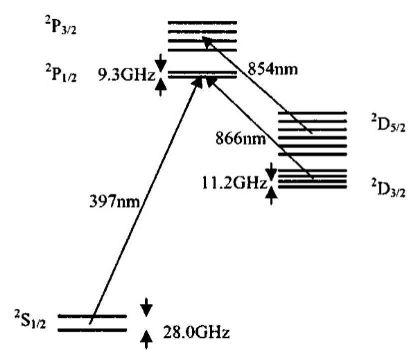
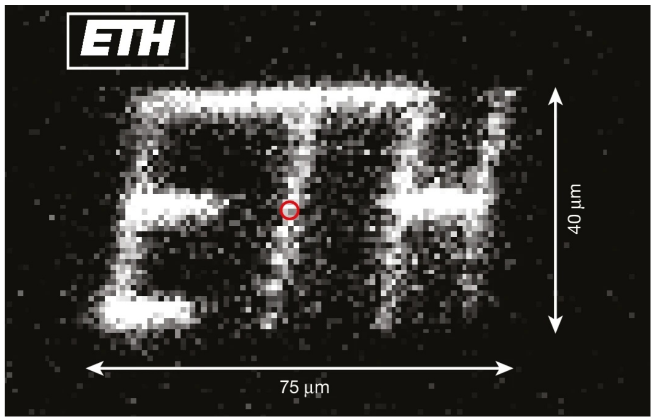


FIG. 1. Partial energy level diagram for Ca^+ showing Zeeman sublevels for a magnetic field of 1 T.



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DOI: https://doi.org/10.1103/PhysRevX.10.031027, DOI: https://doi.org/10.1038/s41586-024-07111-x, DOI: https://doi.org/10.1103/PhysRevA.69.043402

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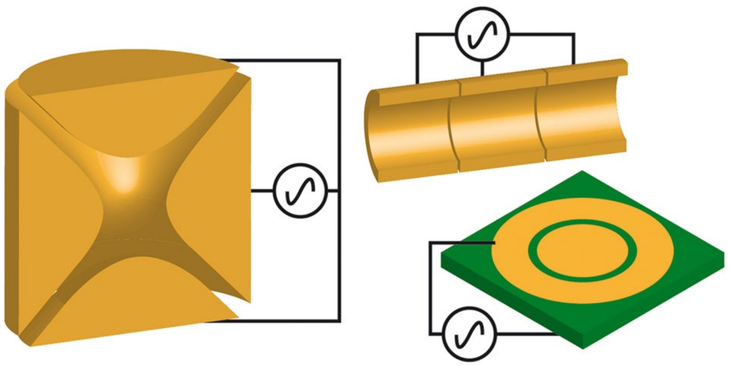
Trapping ions - Paul traps



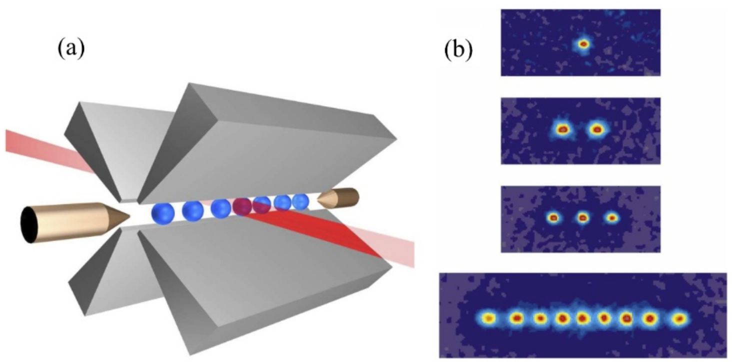


Fig. 1 The canonical four-rod Paul trap has been a workhorse for early demonstrations of QIP with ions. (a) Schematic of a Paul trap consisting of four radiofrequency (RF) electrodes and two end-cap (DC) electrodes to confine ions in a linear chain. A laser beam is shown applying a gate pulse to a single ion. (b) Camera images of few ions in a Paul trap. Images courtesy of University of Innsbruck.

$$\Phi(x,y,z,t) = U\frac{1}{2}(\alpha x^2+\beta y^2+\gamma z^2) + \tilde{U}\cos(\omega_{\mathrm{rf}}t)\frac{1}{2}(\alpha' x^2+\beta' y^2+\gamma' z^2).$$

$$\alpha=\beta=\gamma=0,$$

$$\alpha'+\beta'=-\gamma',$$

$$\ddot{x} = -\frac{Z|e|}{m}\frac{\partial\Phi}{\partial x} = -\frac{Z|e|}{m}[U\alpha+\tilde{U}\cos(\omega_{\mathrm{rf}}t)\alpha']x$$

Mathieu differential equation

$$\frac{d^2x}{d\xi^2}+[a_x-2q_x\cos(2\xi)]x=0$$

by the substitutions

$$\xi=\frac{\omega_{\mathrm{rf}}t}{2}, \quad a_x=\frac{4Z|e|U\alpha}{m\omega_{\mathrm{rf}}^2}, \quad q_x=\frac{2Z|e|\tilde{U}\alpha'}{m\omega_{\mathrm{rf}}^2}.$$

Trapping ions - Stability of trapping Paul traps

Floquet theorem

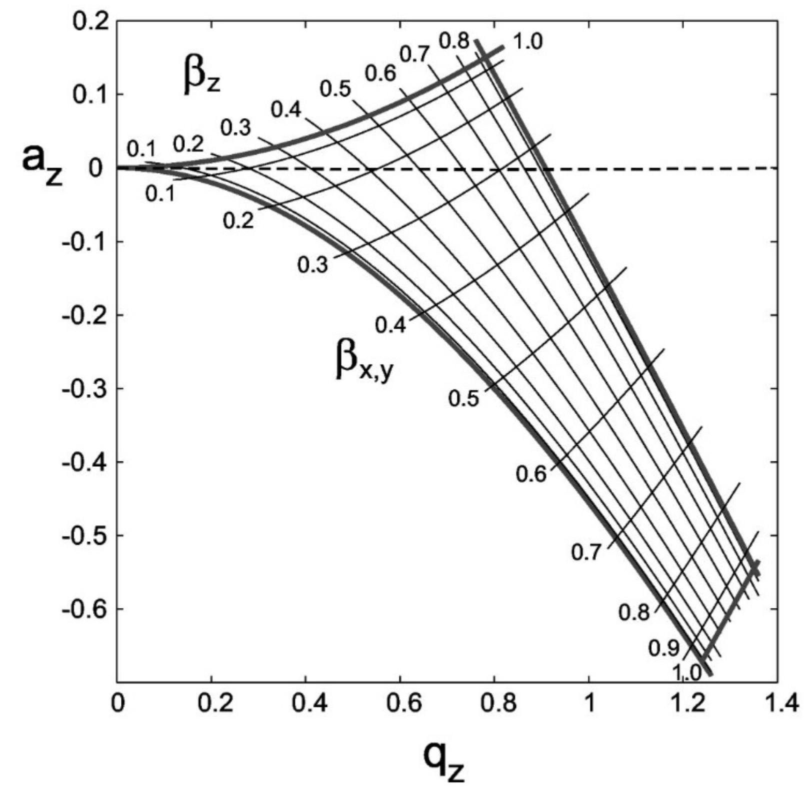
$$x(\xi)=Ae^{i\beta_x\xi}\sum_{n=-\infty}^{\infty}C_{2n}e^{i2n\xi}$$

$$+Be^{-i\beta_x\xi}\sum_{n=-\infty}^{\infty}C_{2n}e^{-i2n\xi},$$

$$C_{2n+2}-D_{2n}C_{2n}+C_{2n-2}=0,$$

$$D_{2n}=[a_x-(2n+\beta_x)^2]/q_x,$$

$$\beta_x^2=a_x-q_x\left(\frac{1}{D_0-\frac{1}{D_2-\frac{1}{\cdots}}}+\frac{1}{D_0-\frac{1}{D_{-2}-\frac{1}{\cdots}}}\right)$$



$$C_{2n+2}=\frac{C_{2n}}{D_{2n}-\frac{1}{D_{2n+2}-\frac{1}{\cdots}}},$$

$$C_{2n}=\frac{C_{2n-2}}{D_{2n}-\frac{1}{D_{2n-2}-\frac{1}{\cdots}}},$$

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Trapping ions - ion in Paul trap

Lowest-order approximation

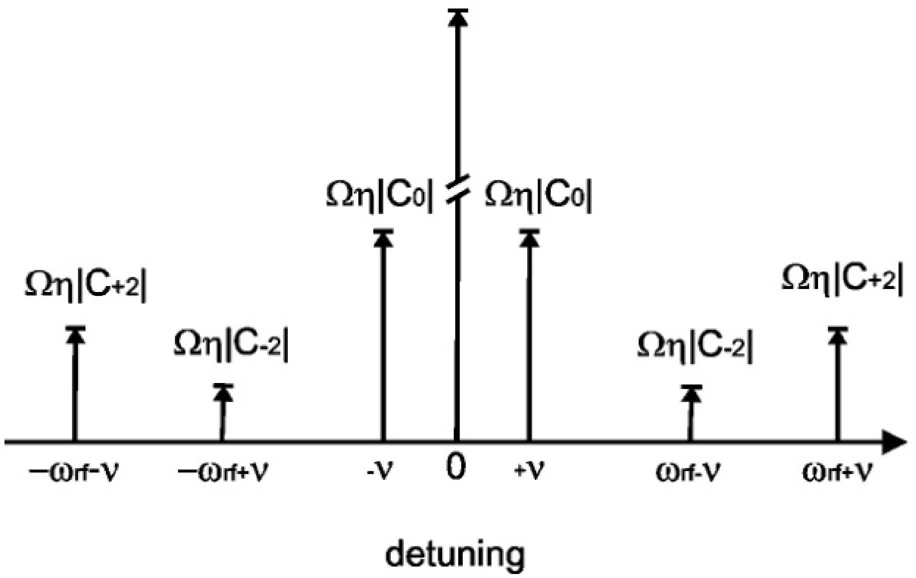
$$(|a_x|, q_x^2) \ll 1 \qquad C_{\pm 4} \simeq 0$$

$$\beta_x \approx \sqrt{a_x + q_x^2/2},$$

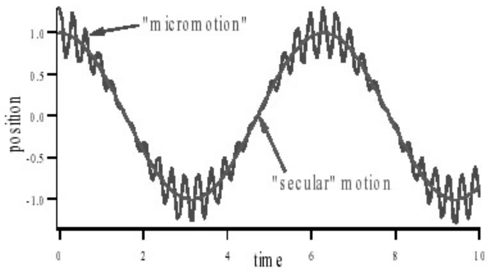
$$x(t) \approx 2AC_0 \cos\left(\beta_x \frac{\omega_{\rm rf}}{2} t\right)\left[1 - \frac{q_x}{2}\cos(\omega_{\rm rf} t)\right]$$

$$\nu = \beta_x \omega_{\rm rf}/2 \ll \omega_{\rm rf}$$

Spectrum of a fluorescing ion



secular motion, micromotion



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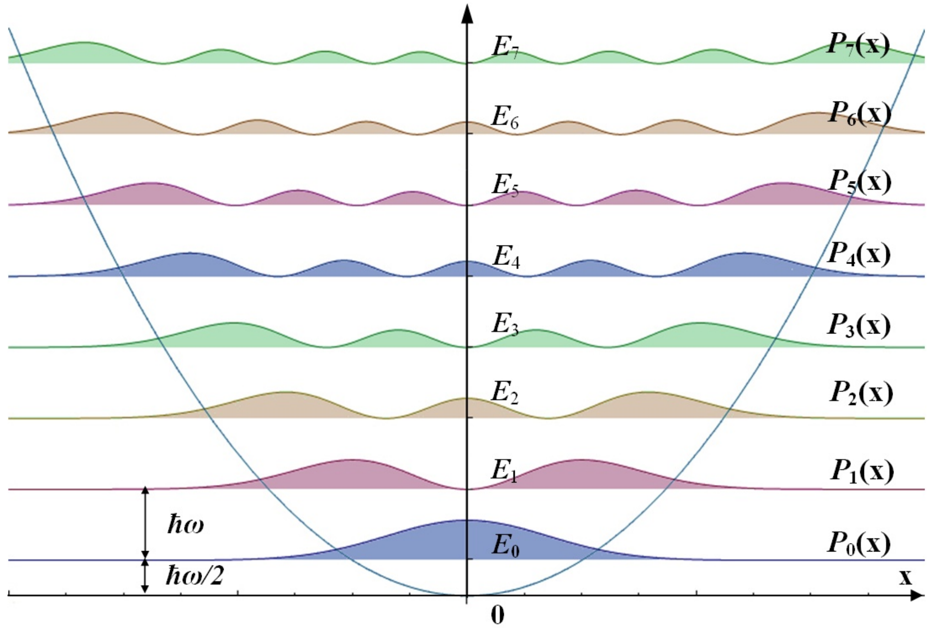
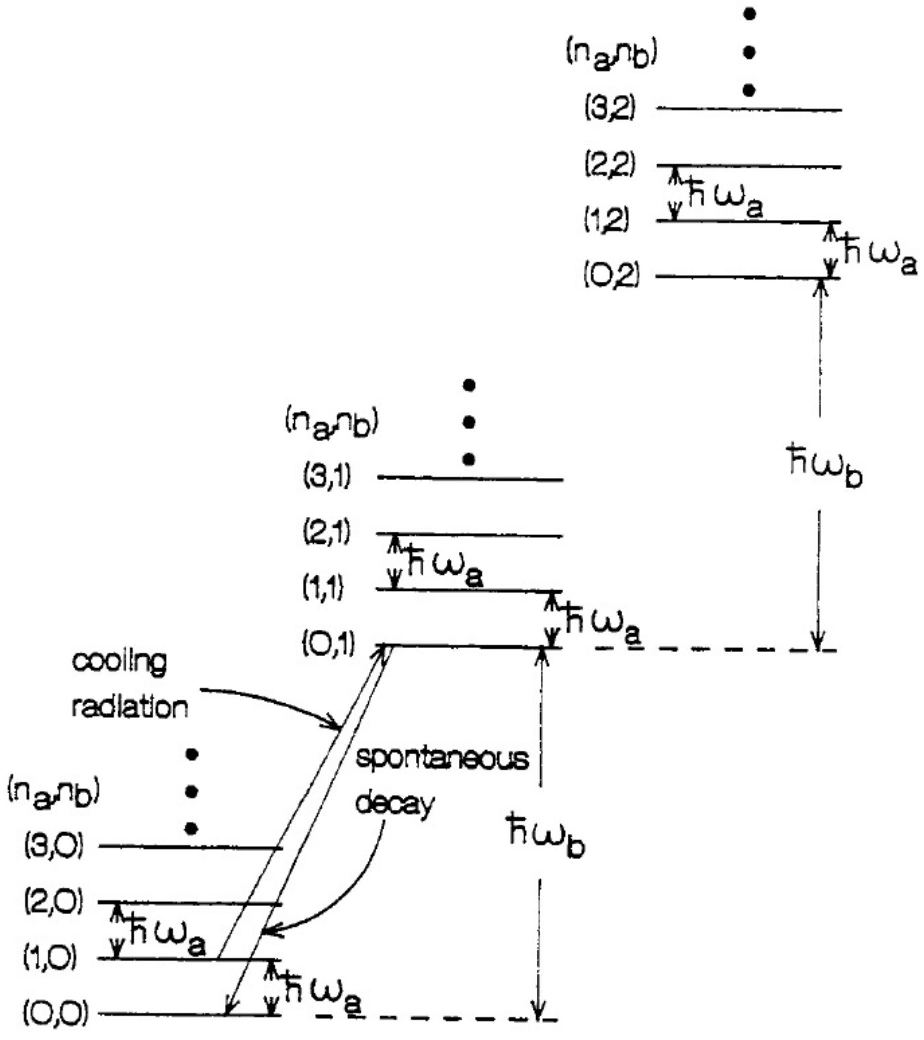
Quantum states of trapped ions

The trap generates a harmonic potential well.





$\omega_a \equiv \nu$, $n\omega_{\rm rf}+\nu$ sidebands lead to heating

For N particles

$$\omega_k = \sqrt{2\nu^2(1-\cos(ka))}$$

where $k = 2n\pi/Na$.

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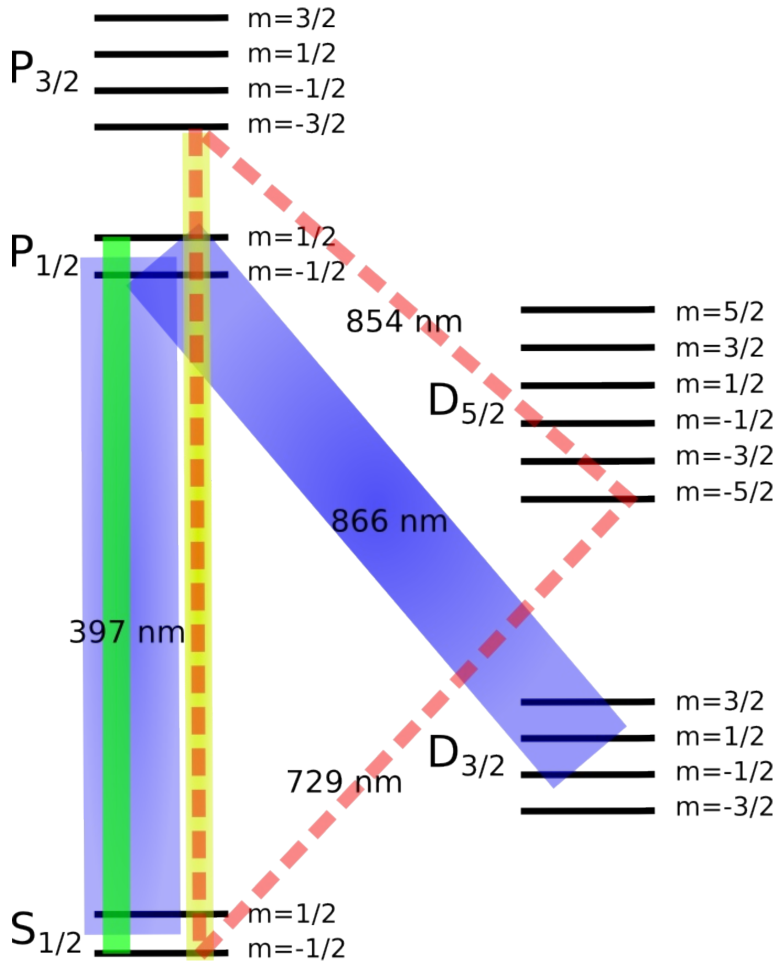
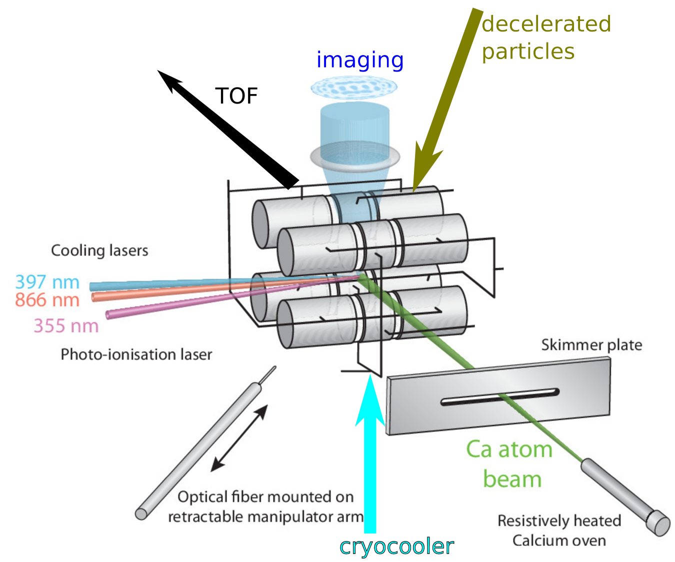
Production of ion Coulomb crystal



Doppler cooling limit: 0.5 mK
for calcium S-P transition



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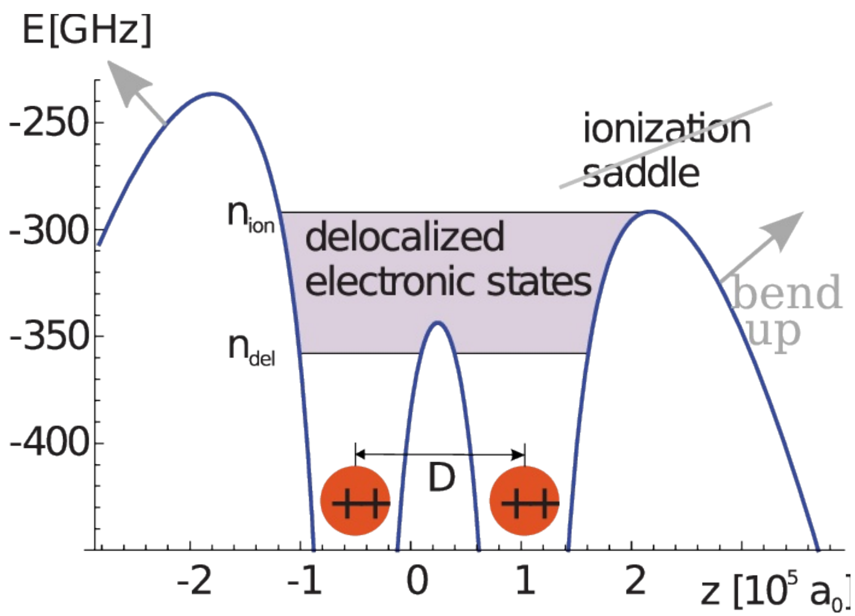
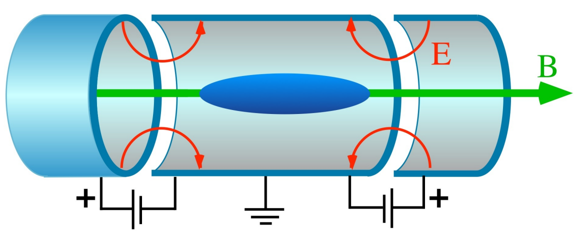
Oppositely charged particles in traps

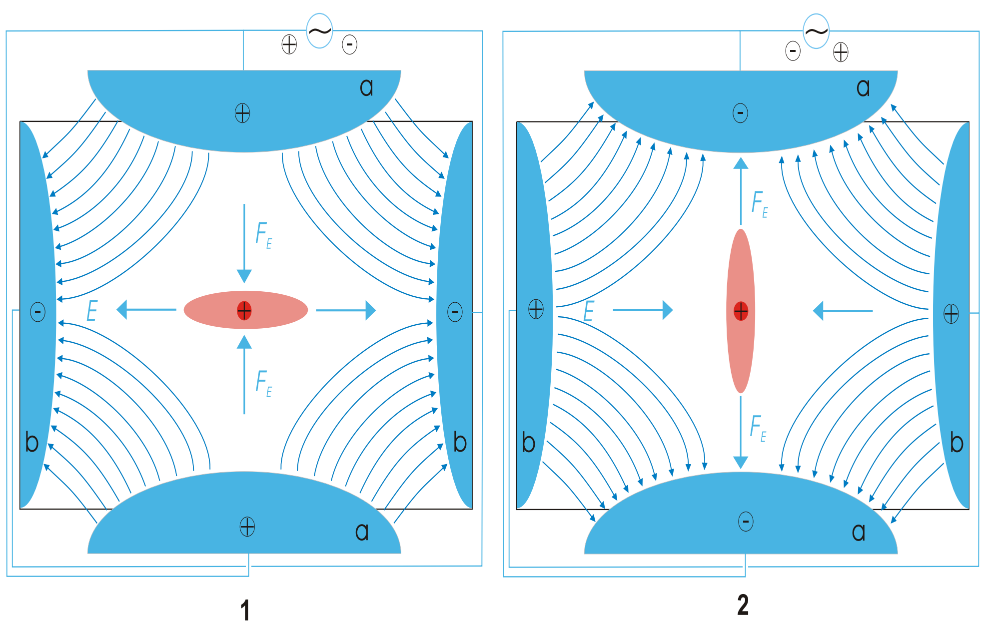


Not Penning but Paul

Penning: mass-agnostic

Paul: charge-agnostic (ponderomotive potential)





Lesanovsky, I., Müller, M. & Zoller, P. Trap-assisted creation of giant molecules and Rydberg-mediated coherent charge transfer in a Penning trap. Phys. Rev. A 79, 010701 (2009).

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Two-frequency Paul trap

Normal Paul trap not directly applicable: large m:q ratio difference between ions and electrons

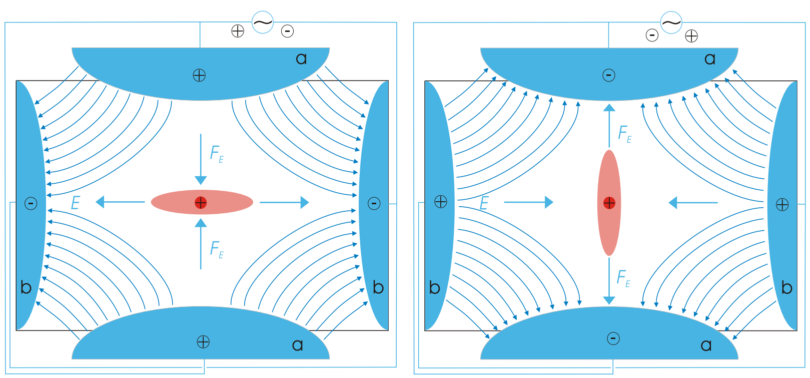
$$V(t) = V_e \cos \Omega_e t + V_i \cos \Omega_i t$$

Mathieu differential equation

$$\frac{d^2 x}{d\xi^2} + [a_x - 2q_x \cos(2\xi)]x = 0$$

by the substitutions

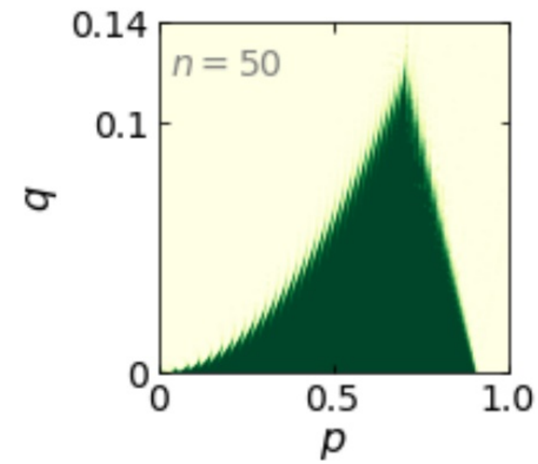
$$\xi = \frac{\omega_{\rm rf} t}{2}, \quad a_x = \frac{4Z|e|U\alpha}{m\omega_{\rm rf}^2}, \quad q_x = \frac{2Z|e|\tilde{U}\alpha'}{m\omega_{\rm rf}^2}.$$



1 2

Requirements for stability

$$V_e \gg V_i \qquad \Omega_e \gg \Omega_i$$



p, q - normalised amplitudes

Our choice:

V_e=100 V, f_e= 2.5 GHz, V_i=1 V, f_i=1 MHz

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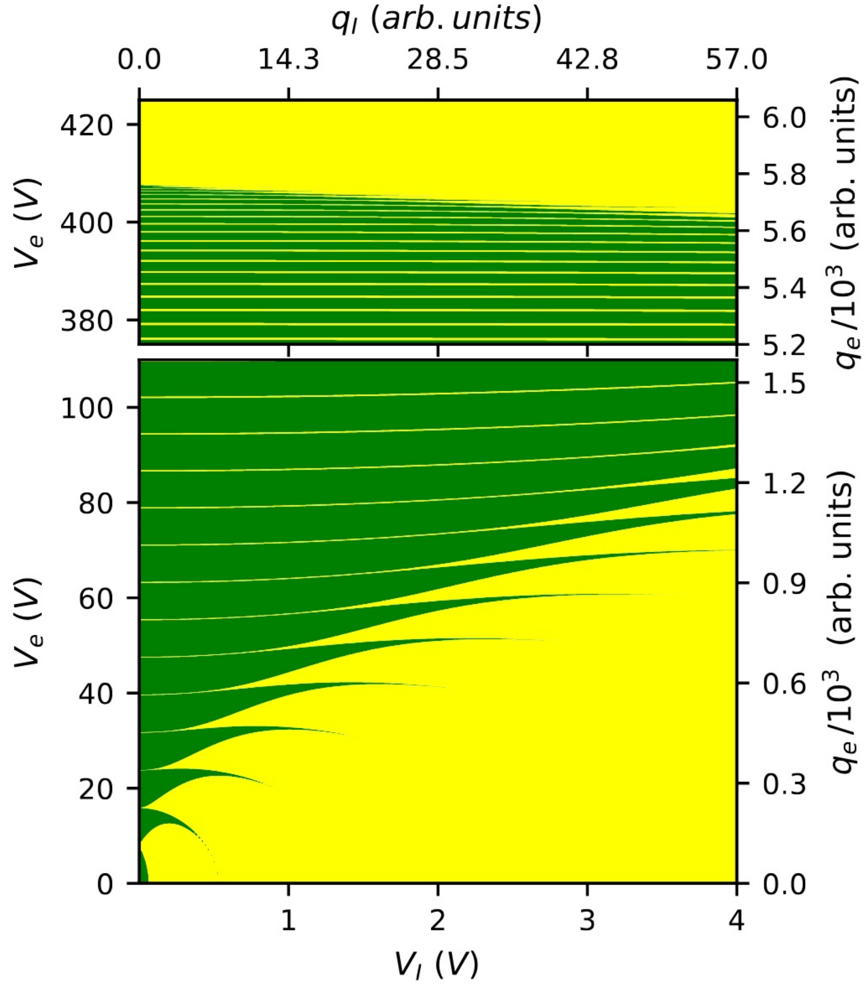
Motion of electron in two-frequency Paul trap

$$q_I = \frac{2|e|V_I}{m_e r_0^2 \Omega_I^2}, \quad q_e = \frac{2|e|V_e}{m_e r_0^2 \Omega_e^2}.$$



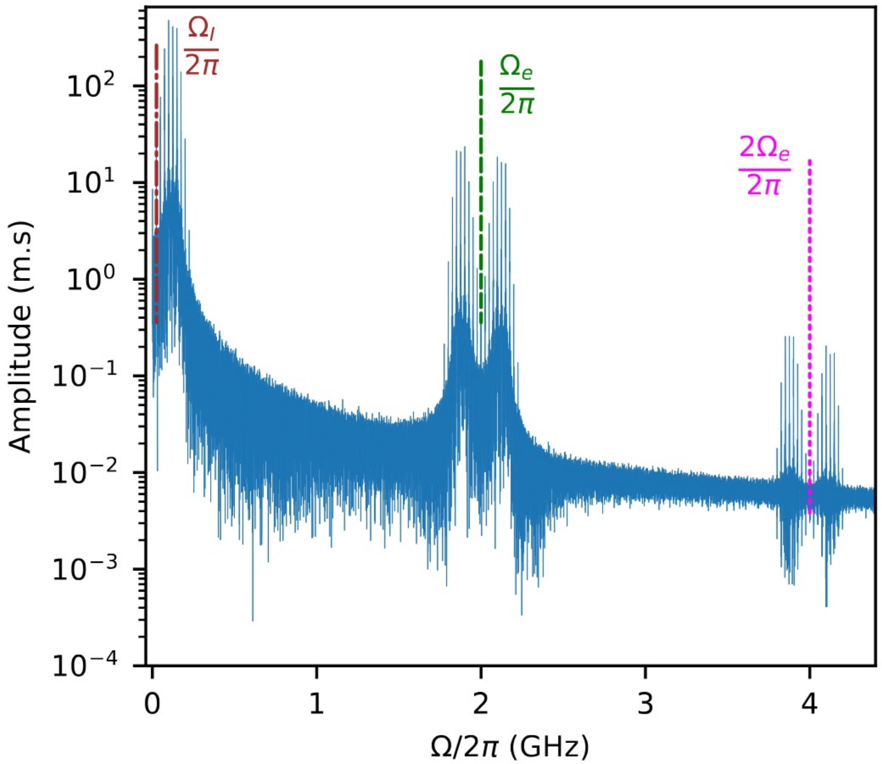


FIG. 7. Frequency spectrum of the trajectory in the x-direction, including the fixed ion in the center of the trap for $V_I = 2\,\mathrm{V}$ and $V_e = 80\,\mathrm{V}$ within the stable region. The series of the dominant peaks are located around the angular frequency of the ion trap Ω_I, electron trap Ω_e and around $2\Omega_e$.

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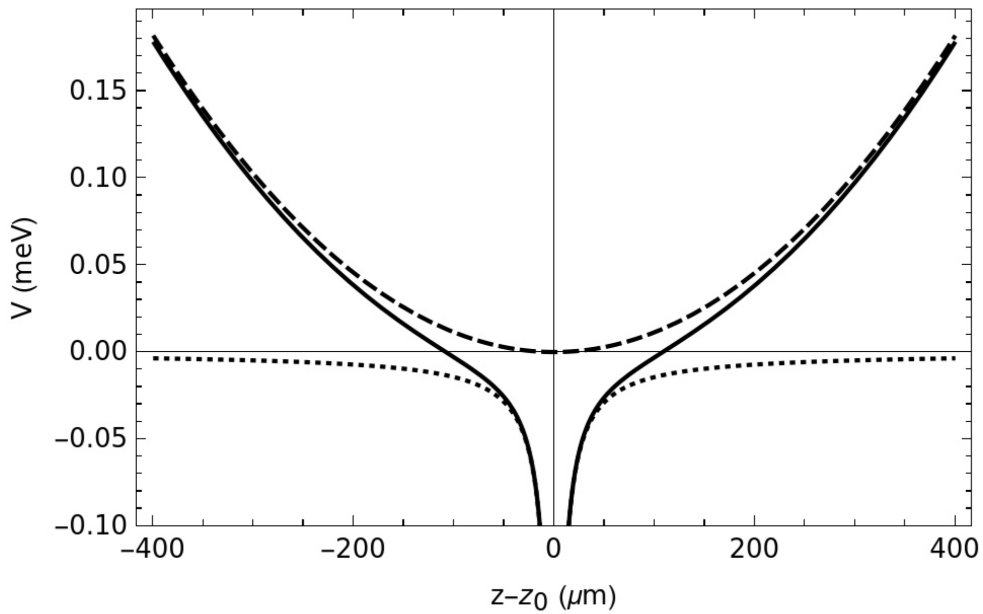
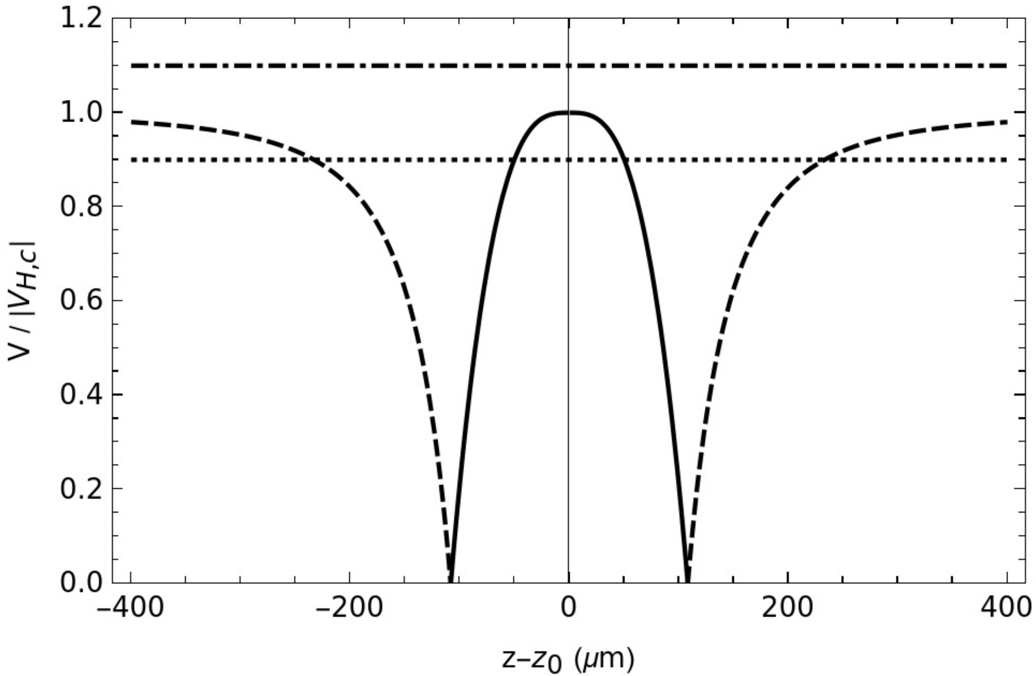
Quantum states of electrons in 2f-trap

Potential with ion





Bound states

Transitional region

Quantum harmonic oscillator-like states

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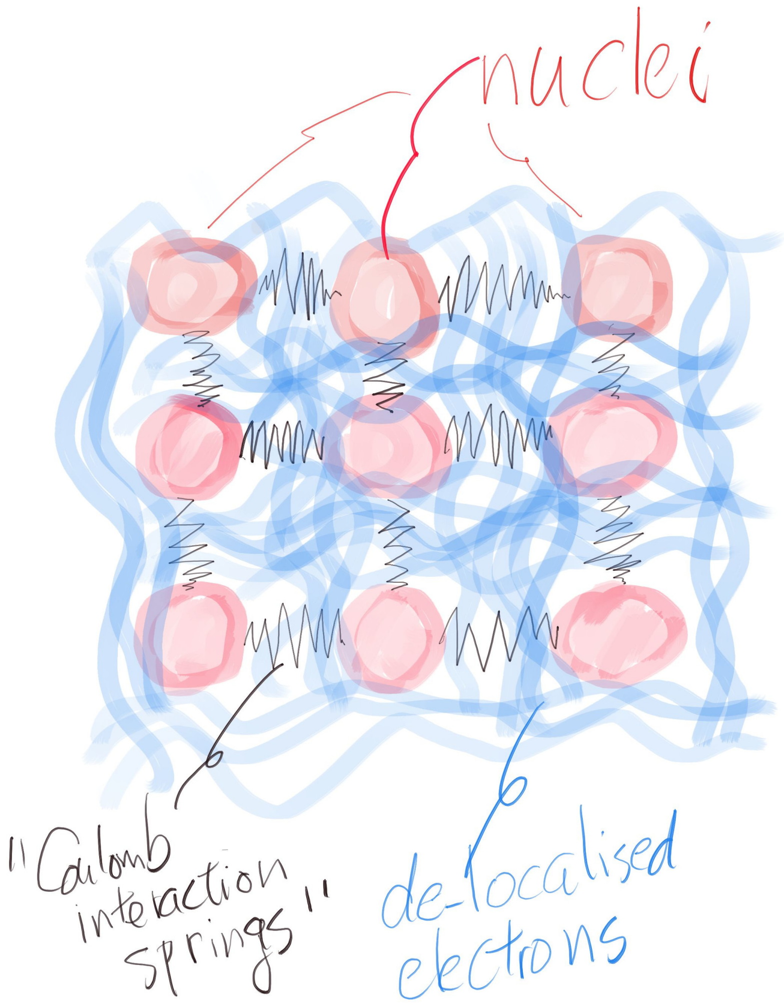
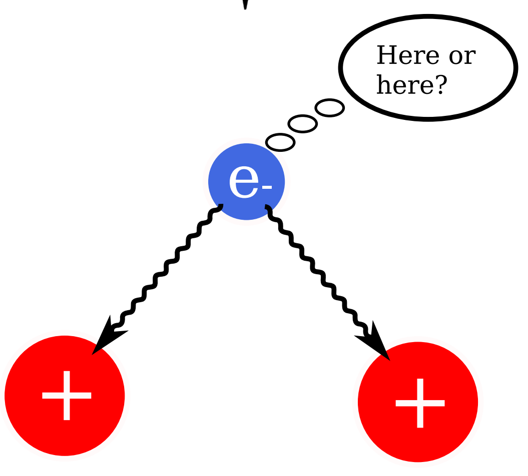
What we are up to: Promiscuous electrons



Electron delocalisation

$$\lambda_{th} = \sqrt{\frac{2\pi\hbar^2}{m_e k_B T_e}}$$



So, how do we cool the electrons?

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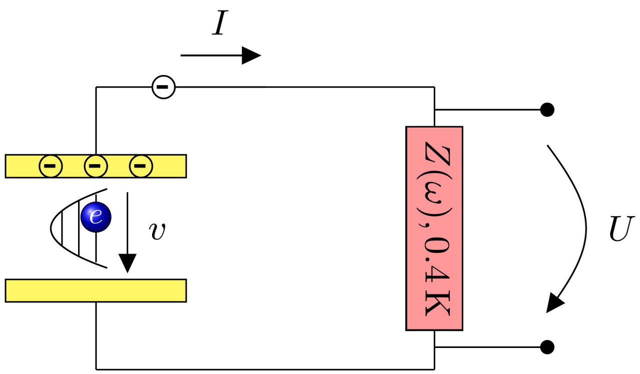
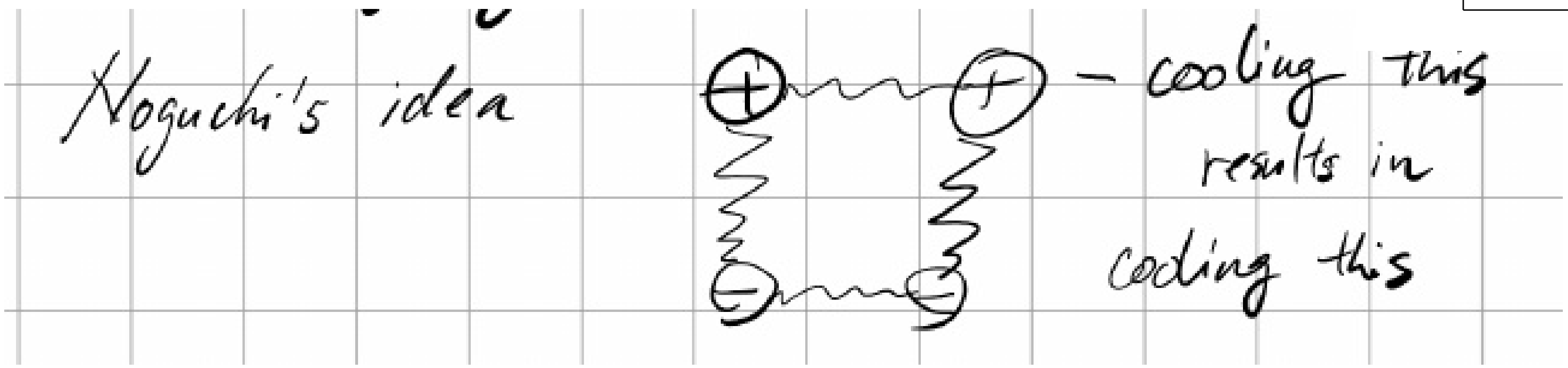
Production of low-energy electrons

Near-threshold photo-ionisation of trapped ion

Cooling in interaction with super-conducting (cryogenic) circuits





Sympathetic cooling in interaction with ions

Electrons are "invisible", ions fluoresce!

Recombination is the unsolved problem

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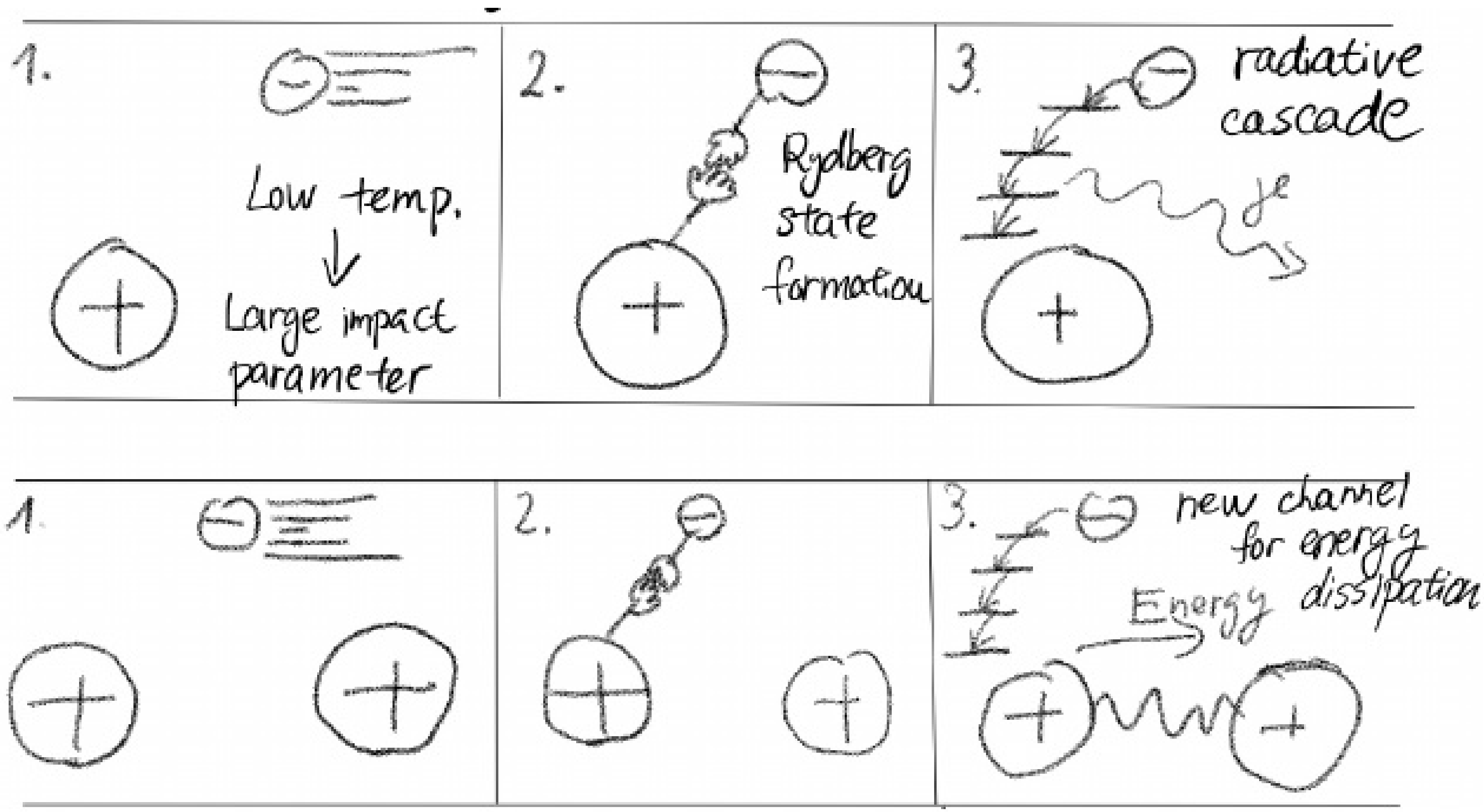
Recombination problem



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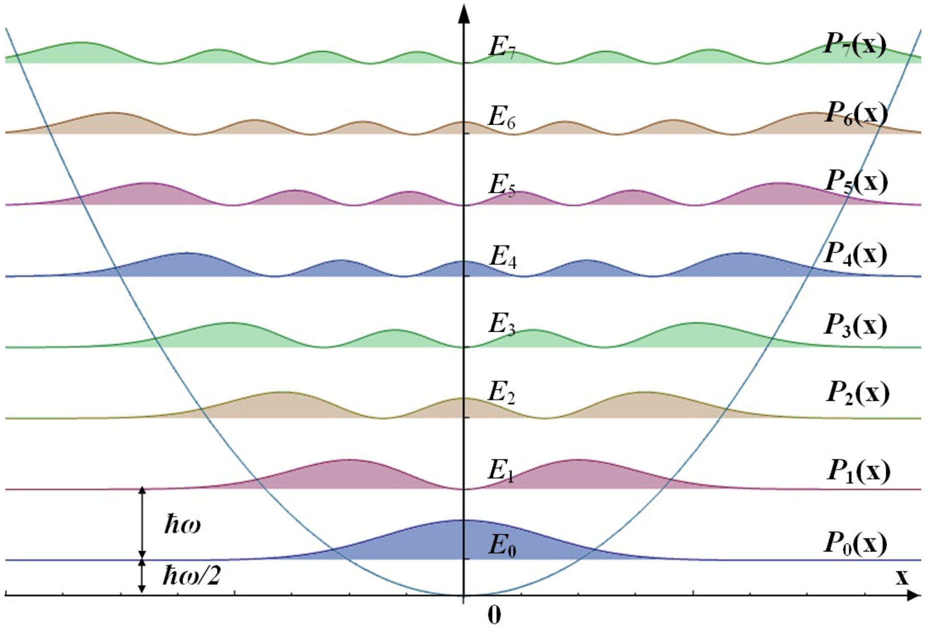
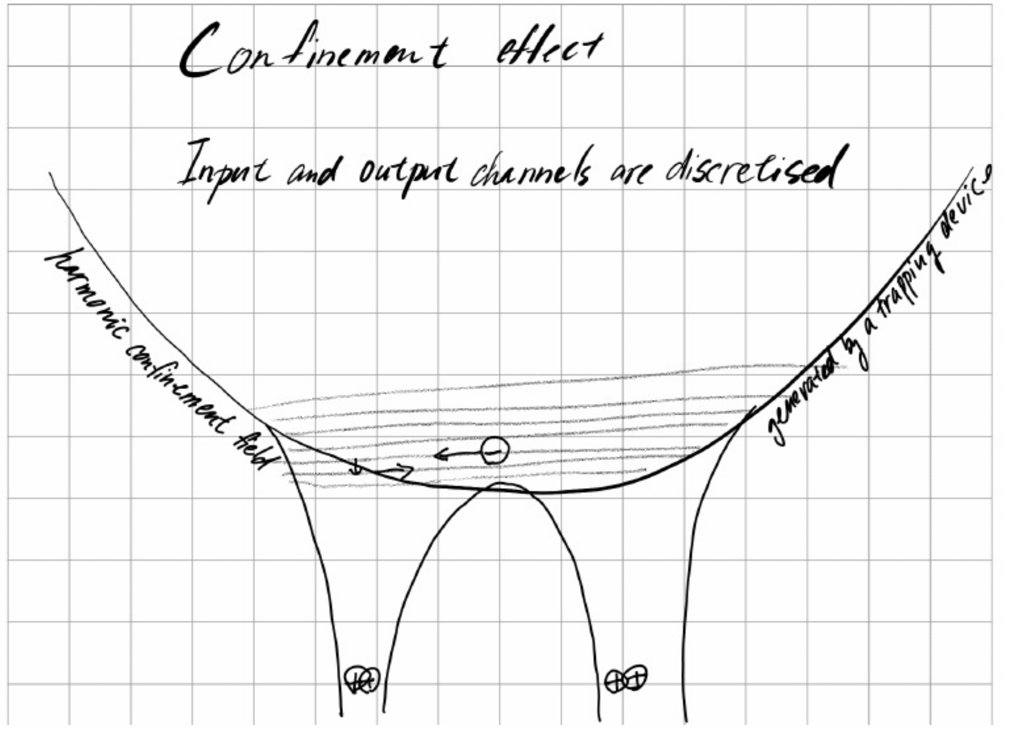
Confinement effect

In transversal dimension



prominent for electrons

In longitudinal dimension



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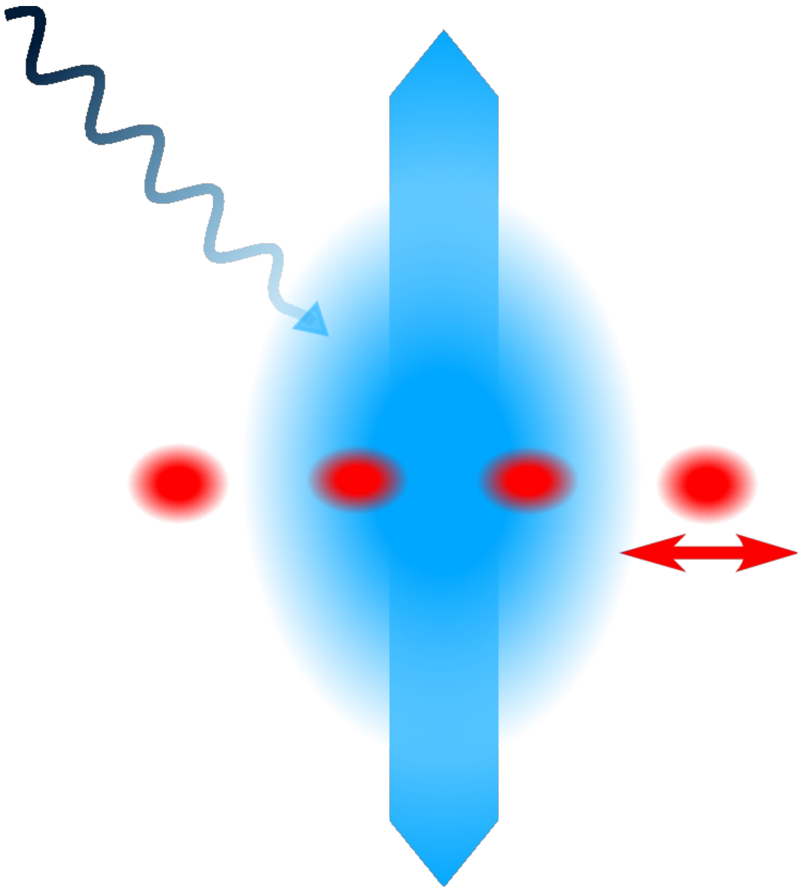
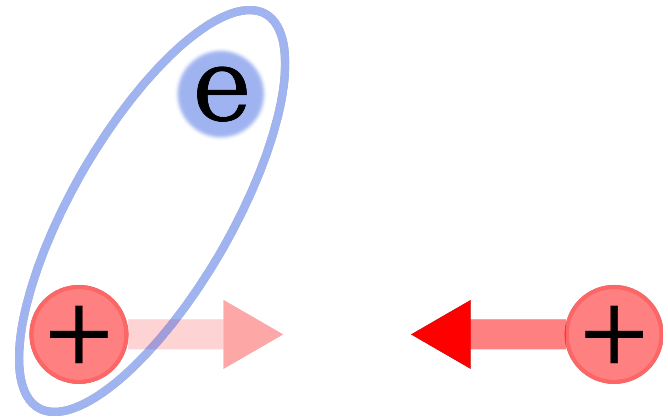
Exploitation of the system

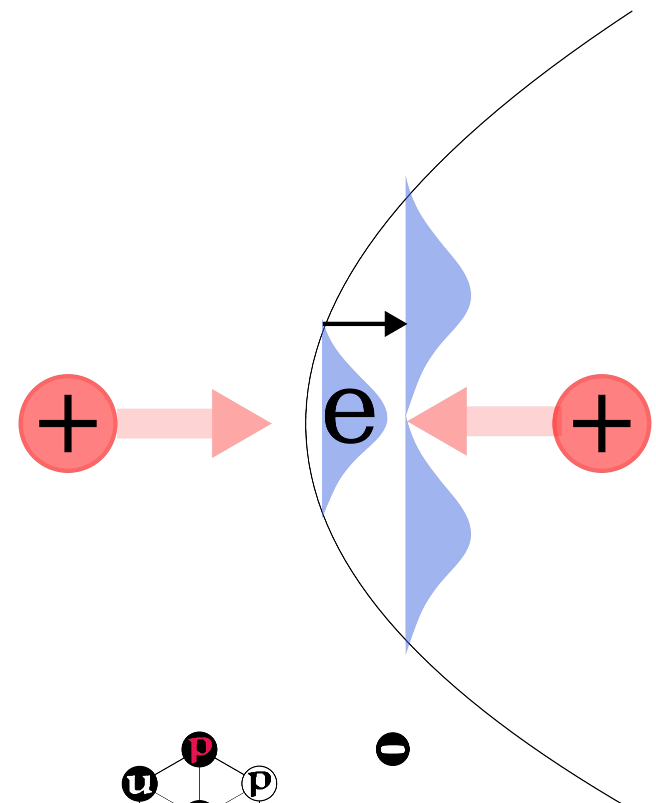
Single photon detection



classical,
localised



quantum
mechanical,
delocalised



change in the screening

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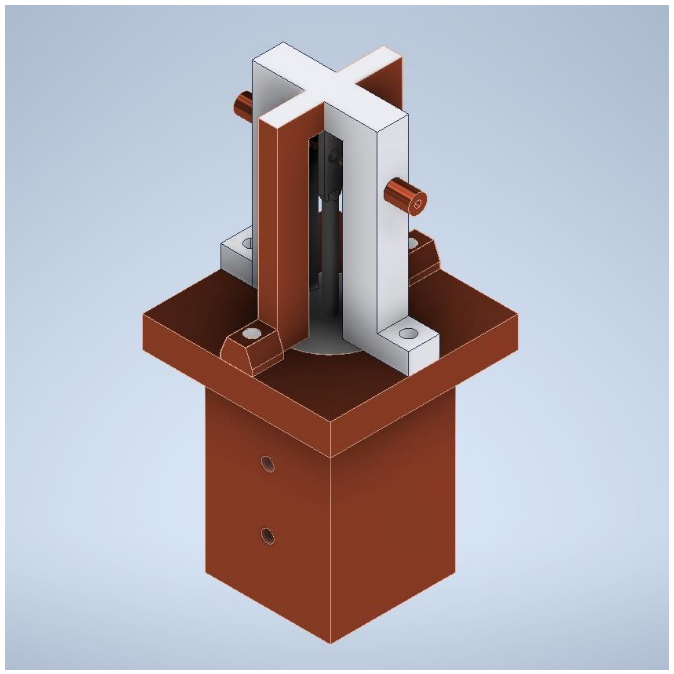
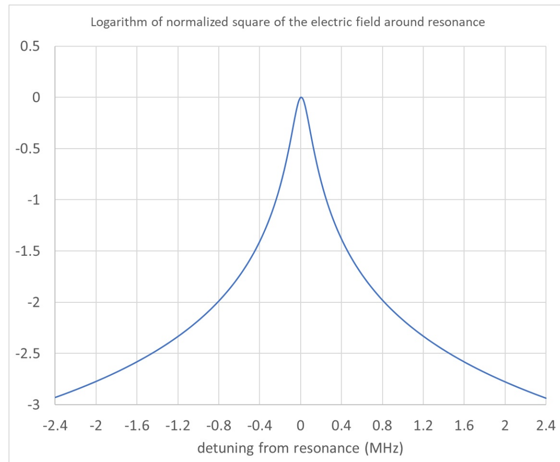
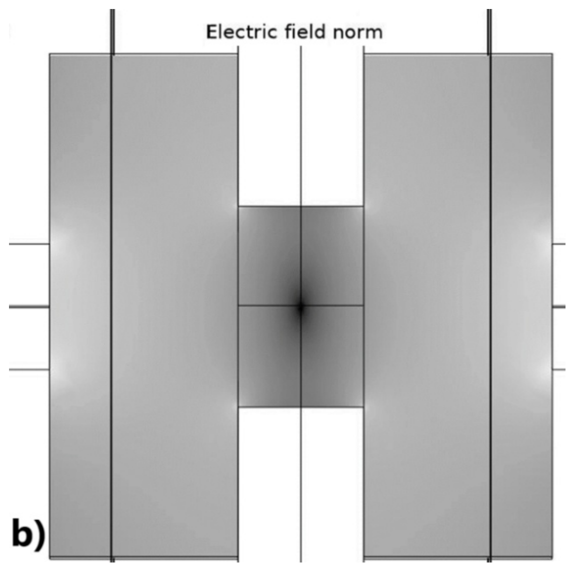
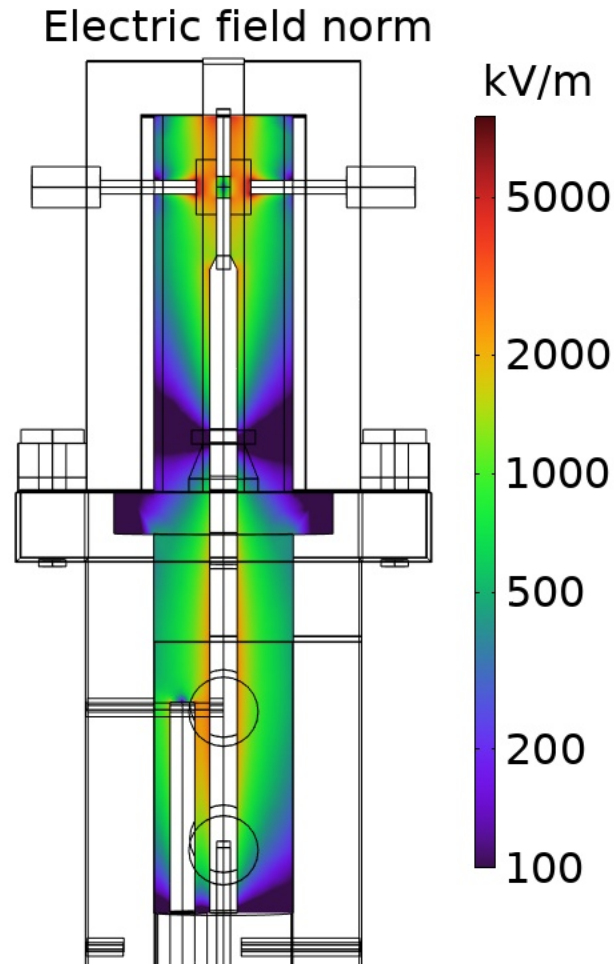
Realisation

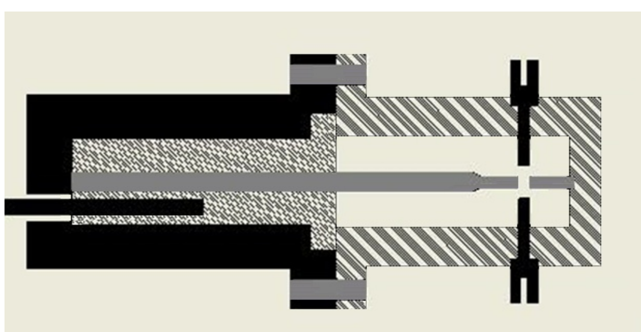
Our choice: V_e=100 V, f_e= 2.5 GHz, V_i=1 V, f_i=1 MHz











coaxial resonator

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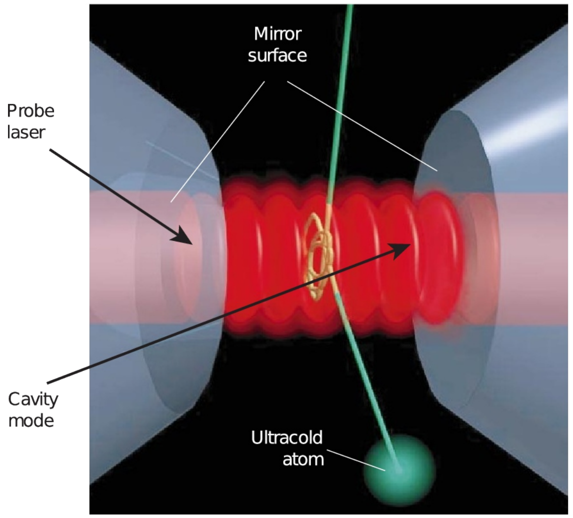
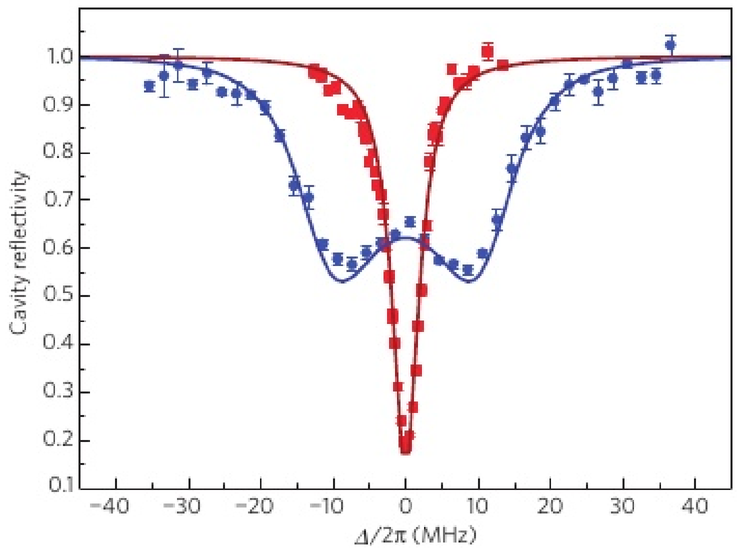
Ion vibration detection

Fluorescence imaging by microscope (slow, low resolution, possible to detect vibration modes in Coulomb crystal)

Interaction with an optical resonator (fast, high sensitivity, integral, state preparation necessary)

Photon collection using cavities, self-interference ...

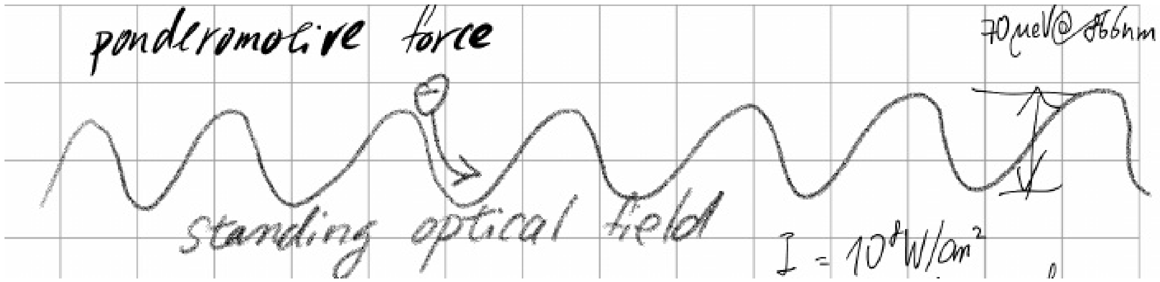


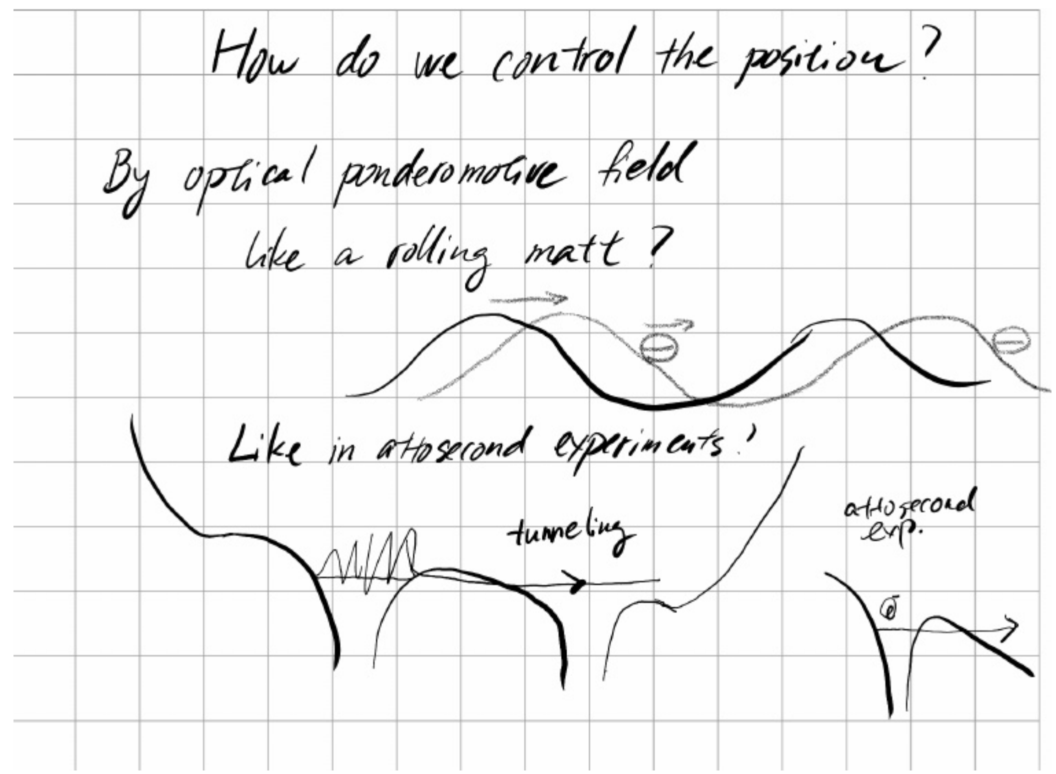


Vahala, K. J. Optical microcavities. Nature 424, 839–846 (2003).

Herskind, P. F., Dantan, A., Marler, J. P., Albert, M. & Drewsen, M. Realization of collective strong coupling with ion Coulomb crystals in an optical cavity. Nat. Phys. 5, 494–498 (2009).

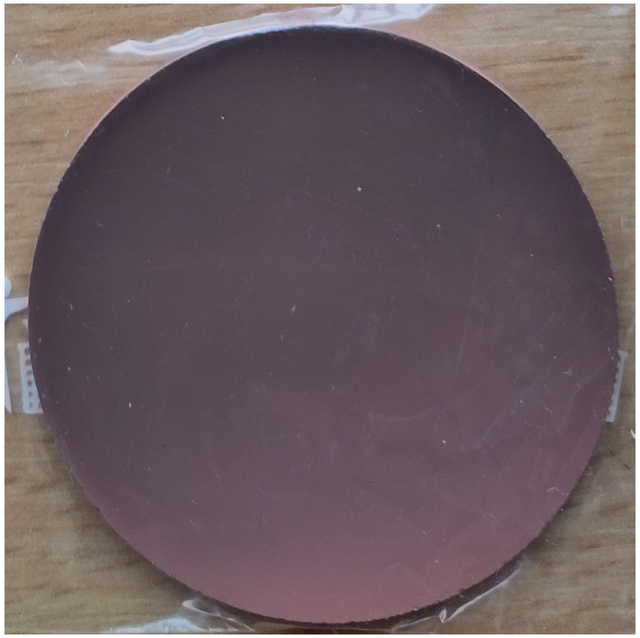
Other physics

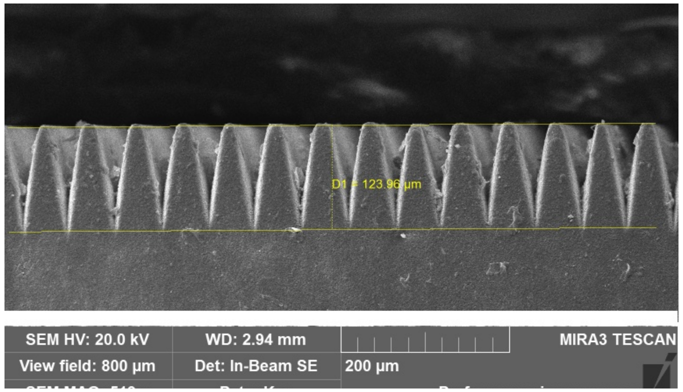




Preparing for application

Fabrication of high-power microwave circtuit boards





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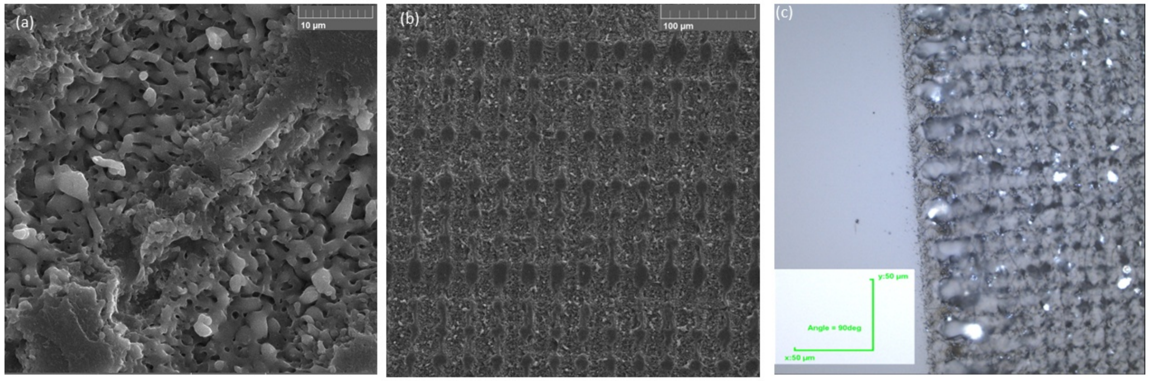
Surface roughening, metallization, circuit carving



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Thank you

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Trap design:

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Experiment preparation:

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Fibre cavity development:

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