Cooling Methods

AVA International School of Low Energy Antimatter Physics 2018
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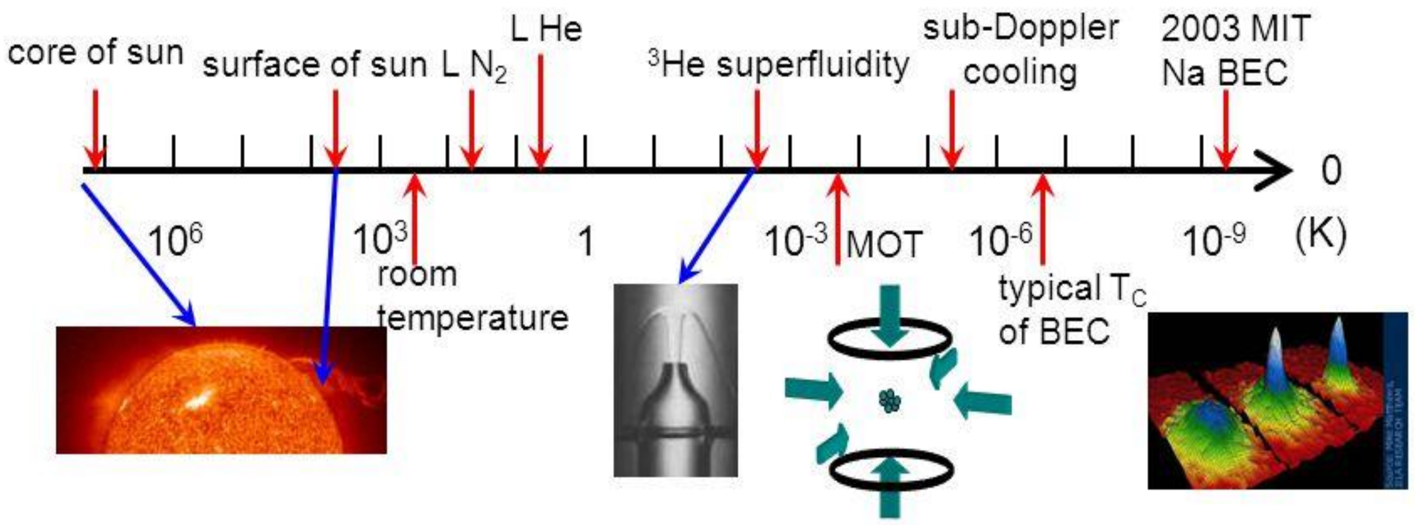
Motivation for cooling $\bar{p}$

Precision experiments need well defined boundary conditions of specimens

- Isolated $\bar{p}$ (Penning trap in vacuum <10^{-11} mbar)
- Small particle numbers require low temperature to gather statistics
- Low $\bar{p}$ temperature (Doppler broadening of $\bar{H}$ internal transitions / de Broglie for gravity exp.)



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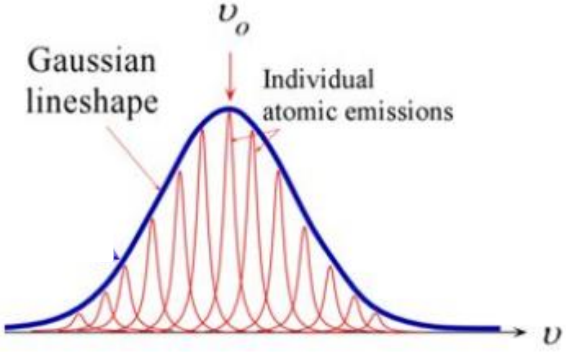
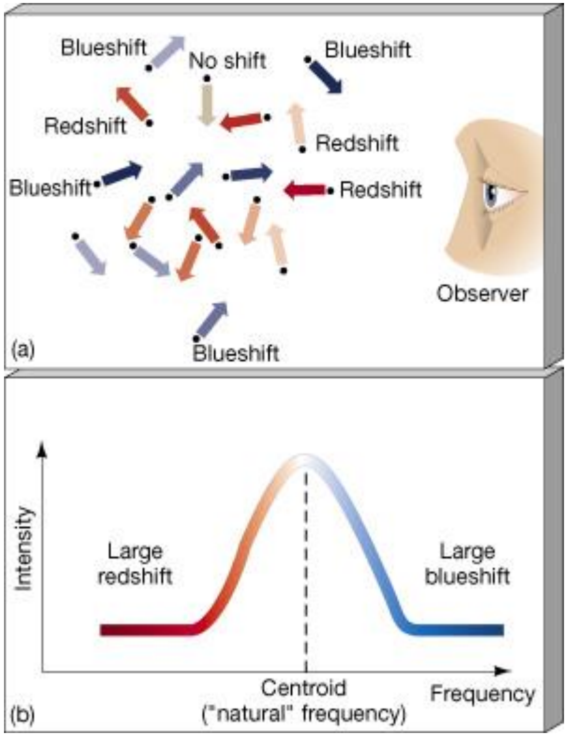
$$\Delta v = v_0 \sqrt{\frac{2\, k_B\, T \ln(2)}{m\, c^2}}$$





Spectroscopy on $\bar{H}$ 1s-2s at 0.54 K, $\Delta v/v = 10^{-13}$ M. Ahmadi et al., *Nature*, **541**, 506 (2017)

Spectroscopy on $\bar{H}$ hyperfine at 0.54 K, $\Delta v/v = 10^{-13}$ M. Ahmadi et al., *Nature*, **548**, 66 (2017)

Spectroscopy on H 1s-2s $\Delta v/v = 10^{-15}$ A. Matveev et al., *Phys. Rev. Lett.*, **110,** 230801 (2013)

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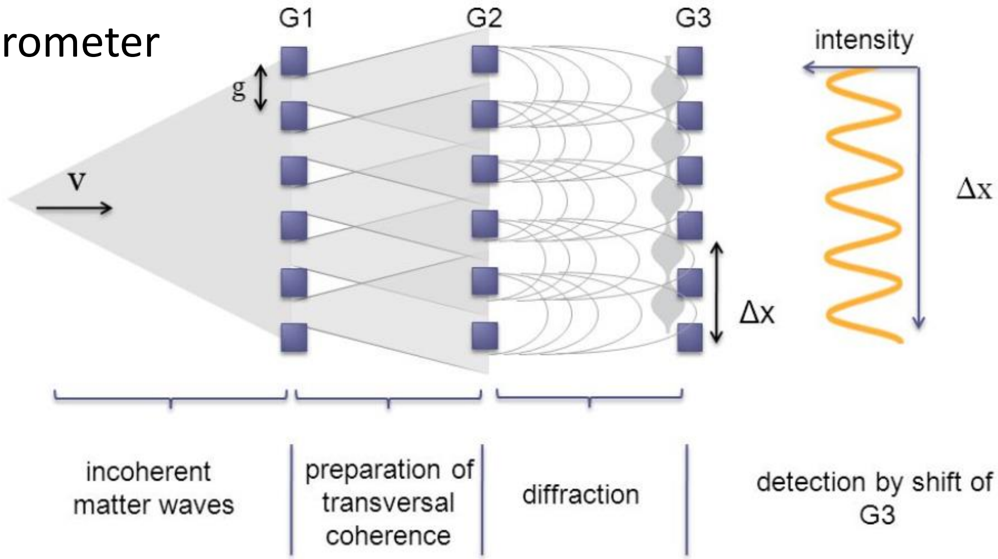
$$\lambda = \frac{h}{m\,v}$$

Talbot-Lau atom interferometer



Currently <u>no experimental WEP test available for antimatter</u> with high precision

normal matter $\Delta g/g$: H. Mueller et al., *Nature*, **463**, 926 (2010)

normal matter WEP: S. Baessler et al., *Phys. Rev. Lett.*, **83**, 3583 (1999)

Antiproton cooling methods

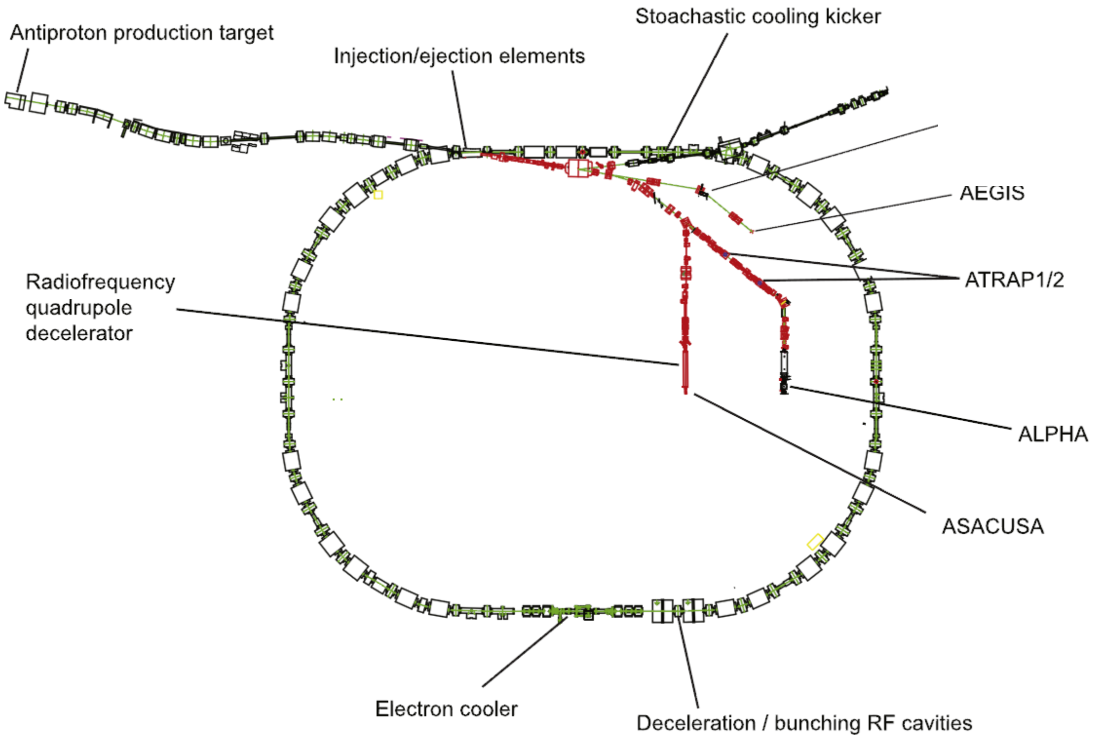
- Cooling in the Antiproton decelerator
  - Stochastic cooling
  - Electron cooling
- Cooling in Penning traps
  - Electron cooling
  - Laser cooling

Antiproton Decelerator (AD)

- Replacement of LEAR (shutdown 1996)
- AD started operation in 1999

Specs:

- Produces $\bar{p}$ of 5.3 MeV energy,
- Cycle time ~100 s,
- Pulsed beams with >3*10^7 $\bar{p}$,
- Emittance ~0.3π mm mrad



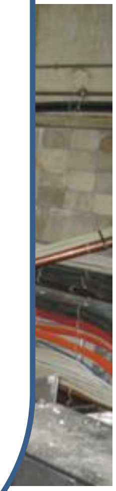
M. Hori and J. Walz, *Progress in Particle and Nuclear Physics* **72**, 206 (2013)

Antiproton Decelerator (AD)

- Replacement of LEAR (shutdown 1996)
- A

Specs:

Hz



What is emittance?

Liouville’s equation.

$$\frac{d\rho}{dt} = \frac{\partial\rho}{\partial t} + \sum_{i=0}^{n}\left(\frac{\partial\rho}{\partial q_i}\dot{q}_i + \frac{\partial\rho}{\partial p_i}\dot{p}_i\right) = 0 \qquad \frac{d\rho}{dt} = -\{\rho,H\}$$

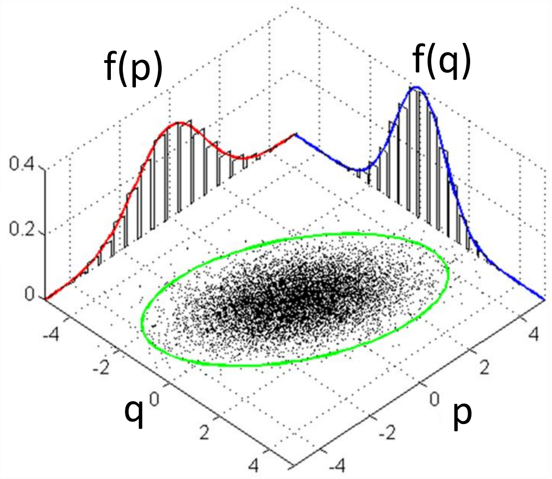
Theorem: Emittance can not be changes by lenses

Emittance only changeable by:

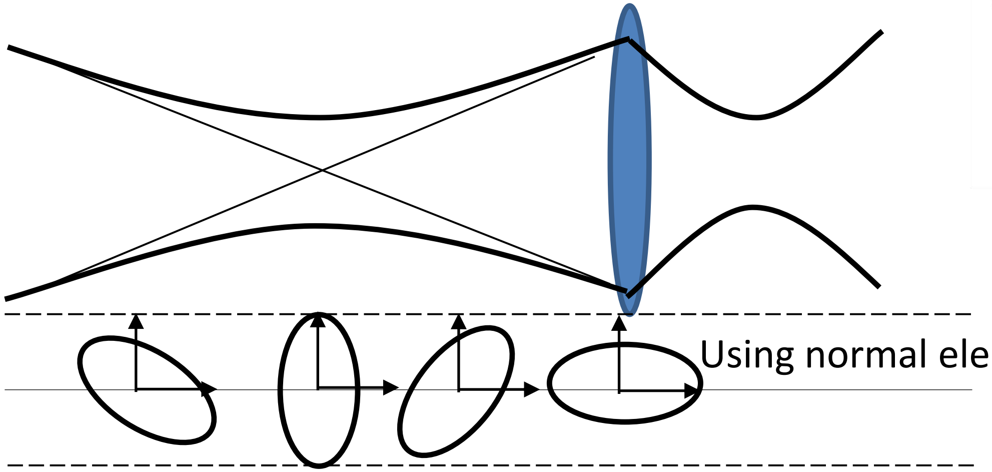
radiation damping, stochastic and electron cooling.

coordinate q – momentum p

phase space ρ at t_0



Emittance=Area



Using normal electrostatic lens, area stays the same

M. Hori and J. Walz, *Progress in Particle and Nuclear Physics* **72**, 206 (2013)

AD, Experiment

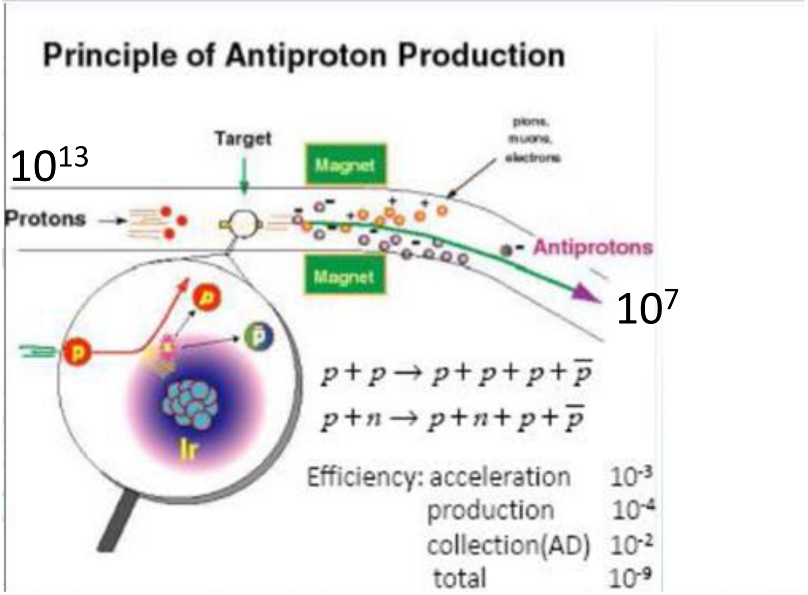
1. Antiproton production

$p(26\,GeV/c) + p_{\text{Ir-target}} \rightarrow p + p + p + \bar{p}\,(3.6\,GeV/c)$

$\bar{p}$ emittance 200 π mm mrad
Δp/p momentum spread ~6%

2. RF bunch rotation:

stretches $\bar{p}$ bunch from 30 m to 190 m
new Δp/p ~1.5% (L∗Δp/p is conserved)



3. $\bar{p}$ cooling energy cascade of RF cavity deceleration, stochastic and electron cooling:

Target: 3.5 GeV/c → AD cooling: 100 MeV/c → 5.3 MeV/c

M. Hori and J. Walz, *Progress in Particle and Nuclear Physics* **72**, 206 (2013)

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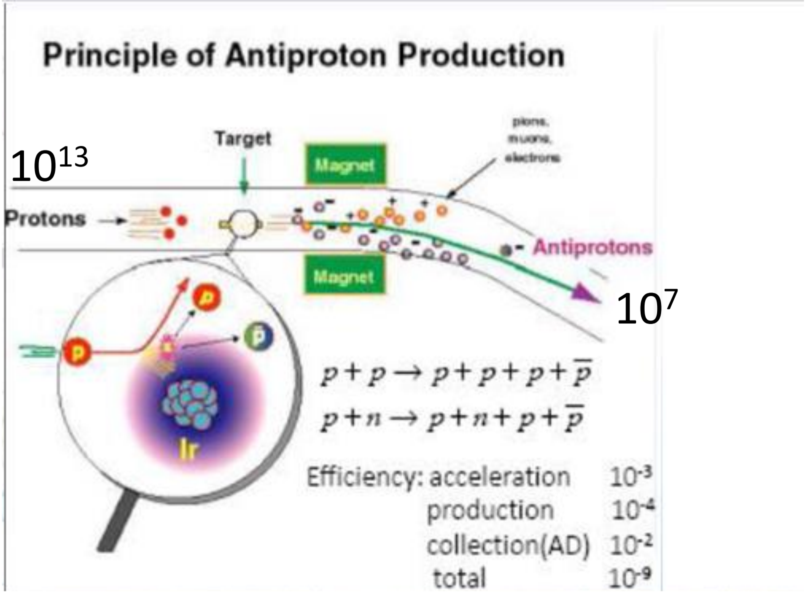


Principle of Antiproton Production

$$p + p \rightarrow p + p + p + \bar{p}$$
$$p + n \rightarrow p + n + p + \bar{p}$$

Efficiency:		
	acceleration	10^{-3}
	production	10^{-4}
	collection(AD)	10^{-2}
	total	10^{-9}

3. $\bar{p}$ cooling energy cascade of
RF cavity deceleration, stochastic and electron cooling:

Target: 3.5 GeV/c → AD cooling: 100 MeV/c → 5.3 MeV/c

Why?

E~3.6 GeV must be reduced by ~10^{6} before $\bar{p}$ are trappable in Penning trap (10 kV electrodes)

E~3.6 GeV must be reduced by ~10^{10} before $\bar{H}$ production can start (~300 K)

E~3.6 GeV must be reduced by ~10^{13} before produced $\bar{H}$ is trappable in magnetic trap (~0.5 K)

E~3.6 GeV must be reduced by ~10^{15} before a future $\bar{H}$ atomic fountain (nK)

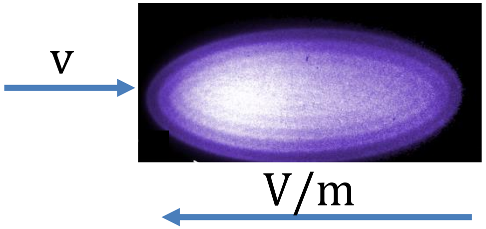
→ **Importance of $\bar{p}$ cooling**

M. Hori and J. Walz, *Progress in Particle and Nuclear Physics* **72**, 206 (2013)

Stochastic cooling

Why is stochastic cooling needed?

A simple deceleration of a cloud N of $\bar{p}$ would lead to an increase in phase-space density D [1]



$$D = \frac{N}{\sqrt{E_h E_v} L \Delta p/p}$$

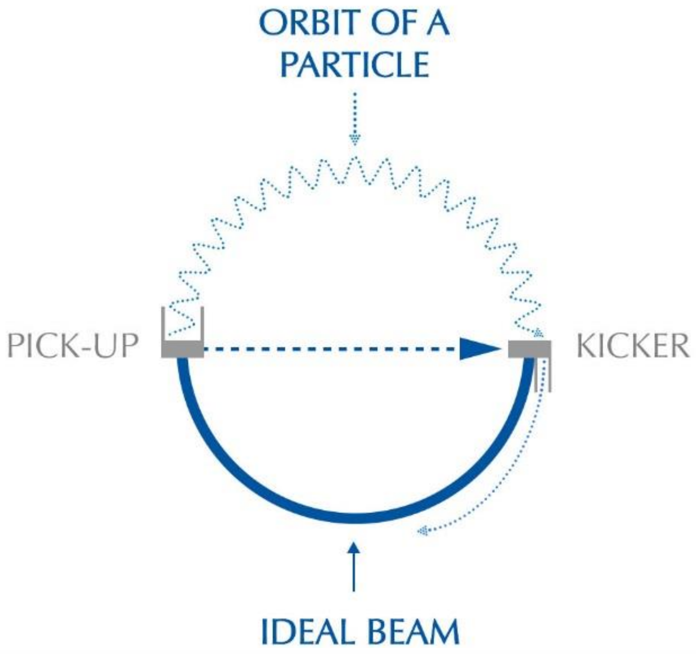
E_h, E_v ...horizontal, vertical emittances
L ...longitudinal spread
N... Number of particles
$\Delta p/p$ ...momentum spread

[1] D. Möhl, Hyperfine Interact. 109 (1997) 33.

Stochastic cooling

Initially wide spread of momentum and angle emission at $\bar{p}$ production.

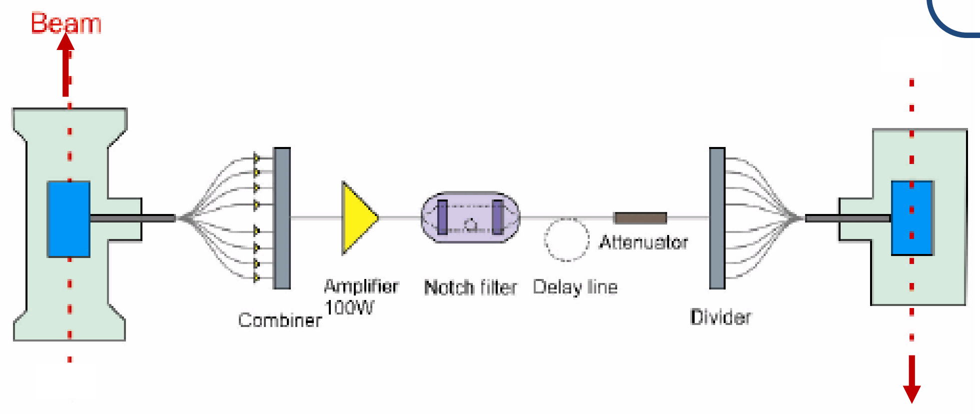
As particles travel around, a detector or "pick up" measures their motion and sends a signal across the ring to a corrector, the kicker, which adjusts their angles.



Pick up electrode:
Detect Δp_i and Δx_i of $\bar{p}$ subgroups i, relative to ideal orbiting $\bar{p}$

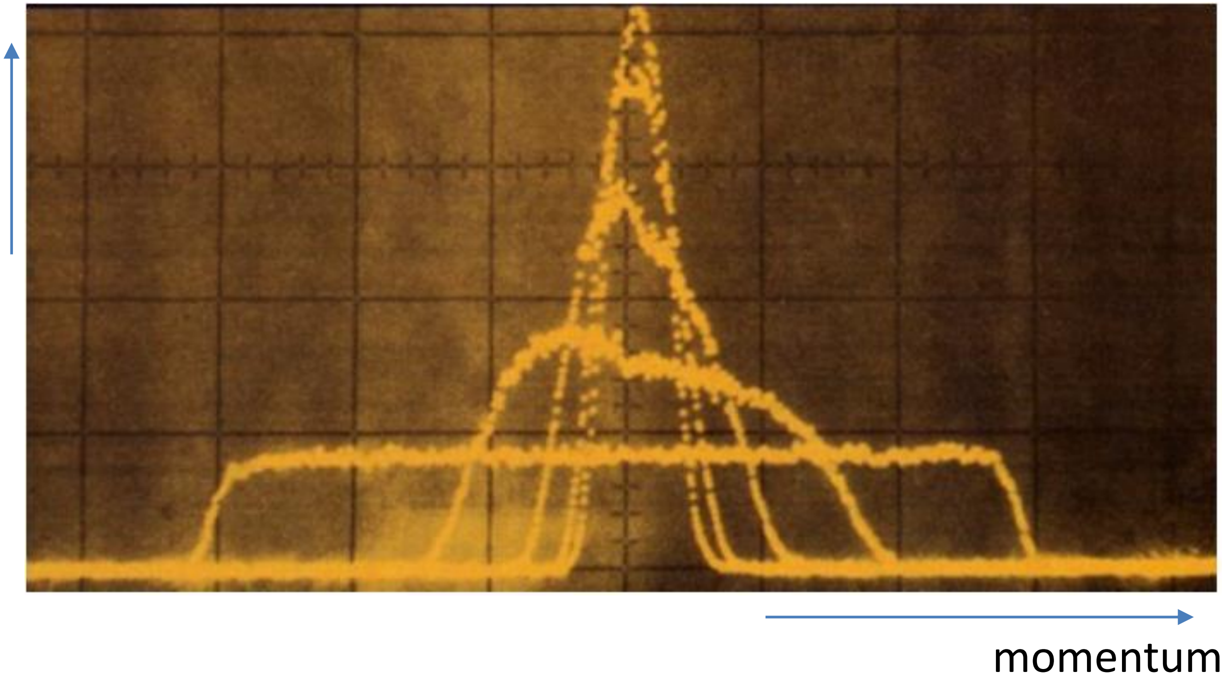
Kicker:
Apply corrective pulses to electrodes

Repeating steps:
$\Delta p/p \sim 0.07\%$ from initially $\sim 1.5\%$
Emittance $\sim 3\pi$ mm mrad from initially $\sim 200\pi$



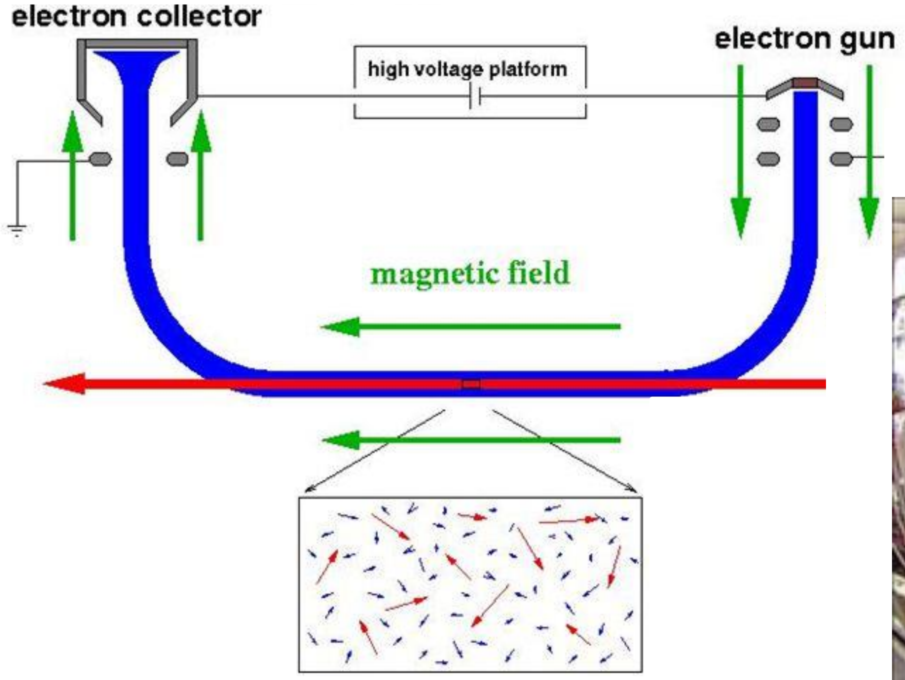
Stochastic cooling

Tested first time 1977 together with electron cooling at CERN in the ICE (initial cooling experiment)



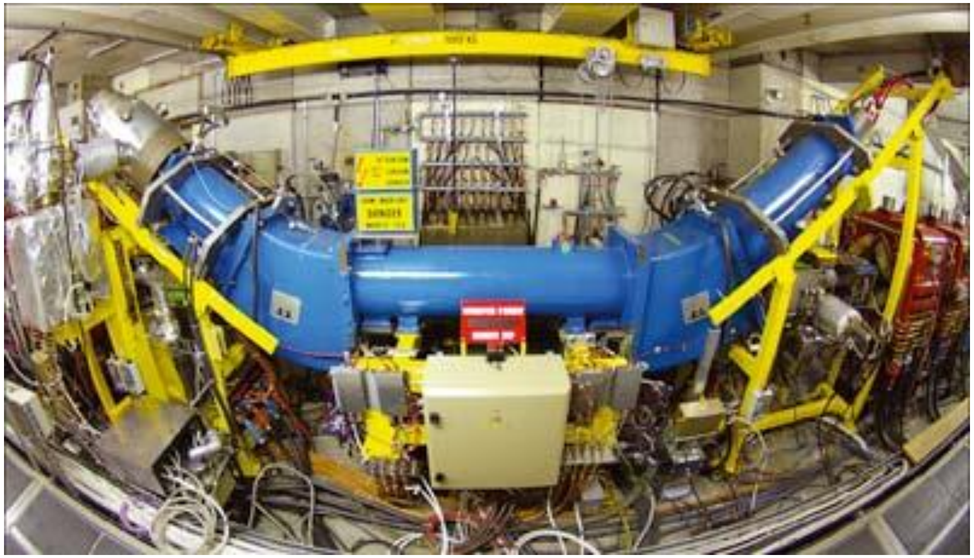
Electron cooling

- **Superposition** of cold intense e$^-$ beam with $\bar{p}$ at **same velocity**
- Momentum transfer by Coulomb collisions
- Cooling results from energy loss in co-moving gas of free electrons



In the beam frame:
Cold electrons interact with
hot $\bar{p}$

In the AD:
$\bar{p}$ beam merged with Ø 20 mm e$^-$ beam of~ 3 A collinearly over 2 m



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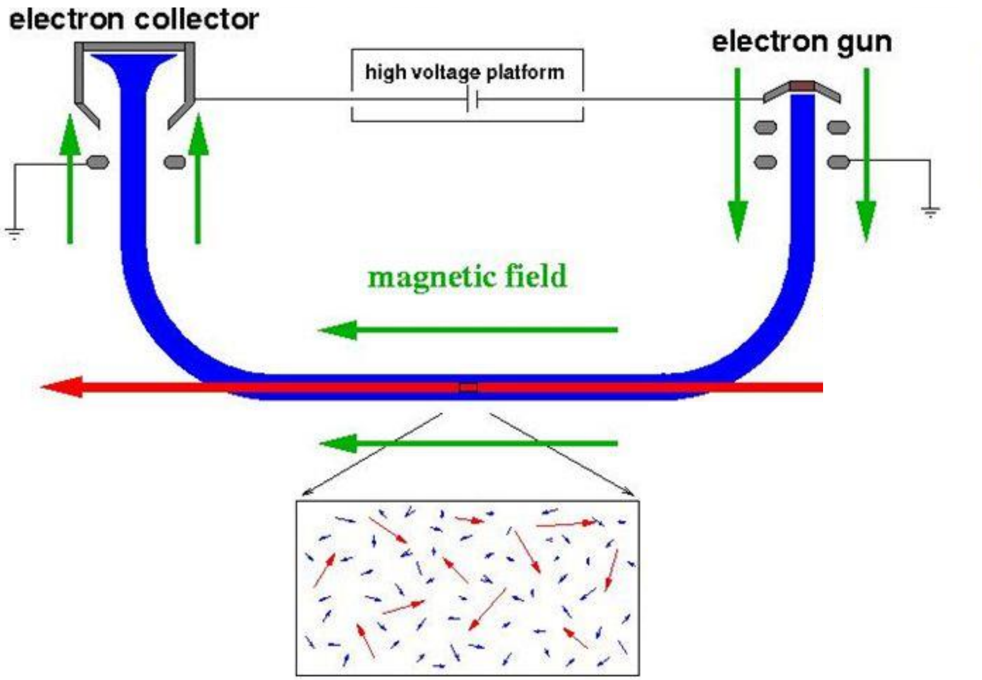


In the beam frame:
Cold electrons interact with
hot $\bar{p}$

$$v_e = \beta_e c = \beta_p c = v_p$$

$$E_e = \frac{m_e}{m_p} E_p$$

m_e…electron mass

m_p…$\bar{p}$ mass

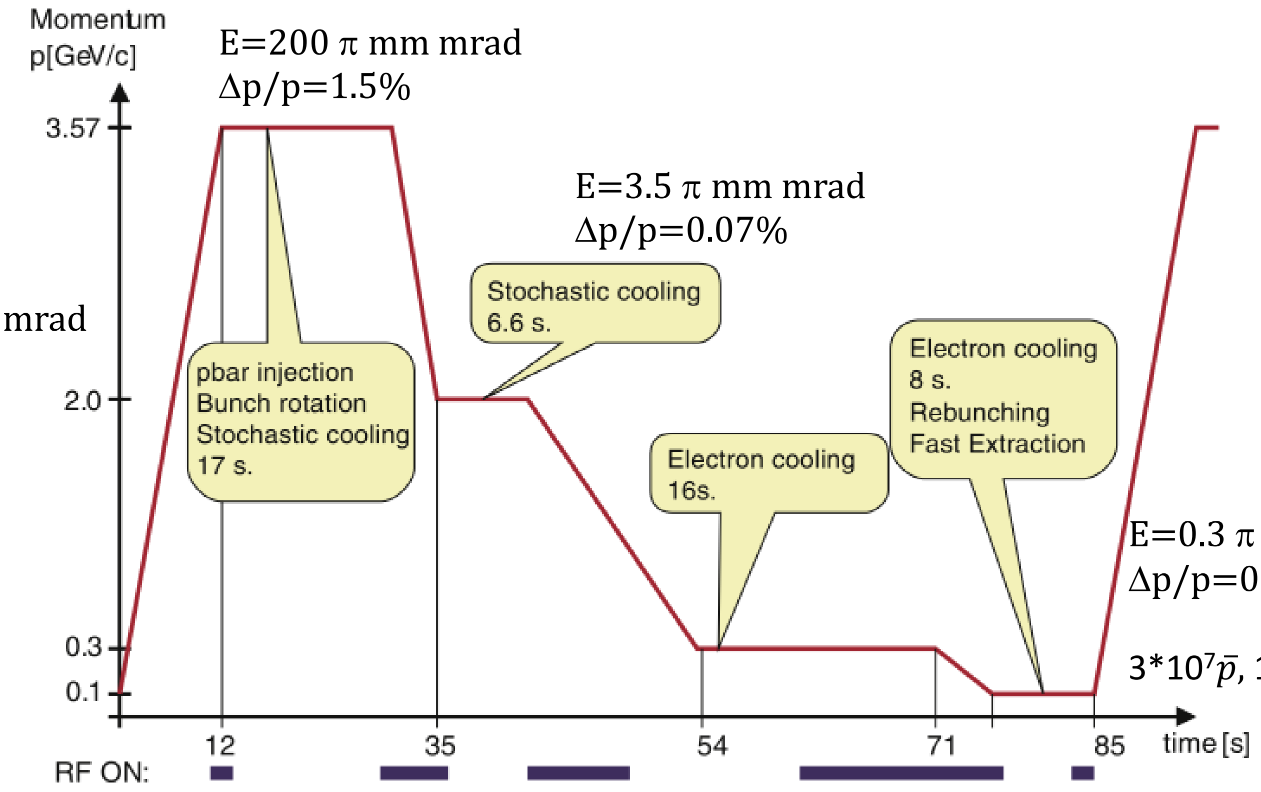
E_e…electron kinetic energy

E_p…$\bar{p}$ kinetic energy

e.g. 220 keV electrons cool 400 MeV $\bar{p}$

AD machine cycle

Bunch rotation: reduce Δp/p
Stochastic cooling: reduce emittance, reduce Δp/p
Deceleration in radiofrequency cavities: reduce p
Electron cooling: reduce emittance, increase D



E=200 π mm mrad
Δp/p=6%

E=200 π mm mrad
Δp/p=1.5%

E=3.5 π mm mrad
Δp/p=0.07%

E=0.3 π mm mrad
Δp/p=0.01%

$3*10^7\bar{p}$, 150 ns long

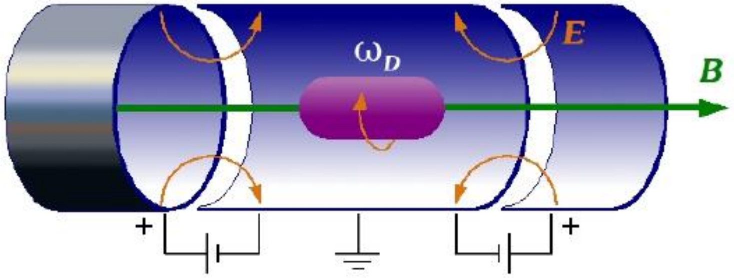
D. Möhl, Hyperfine Interact. 109 (1997) 33.

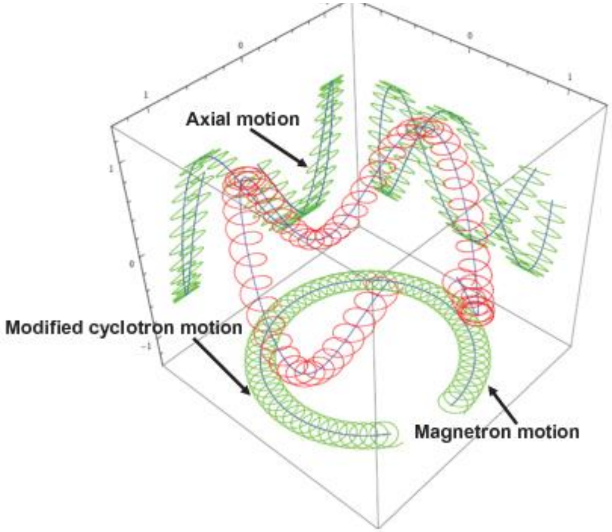
P. Belochitskii et al., Nucl. Instrum. Methods Phys. Res. A 214 (2004) 176.

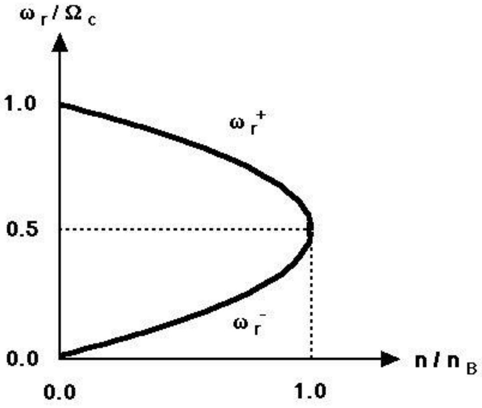
Cooling in Particle Traps

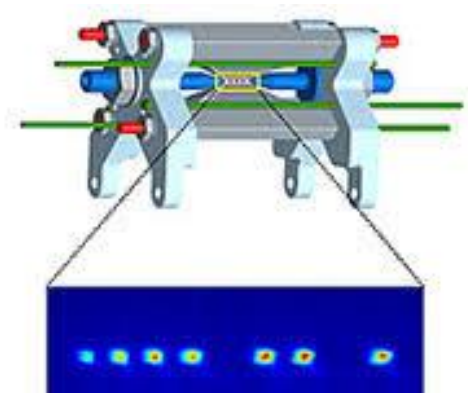
Penning traps, uses E and B fields

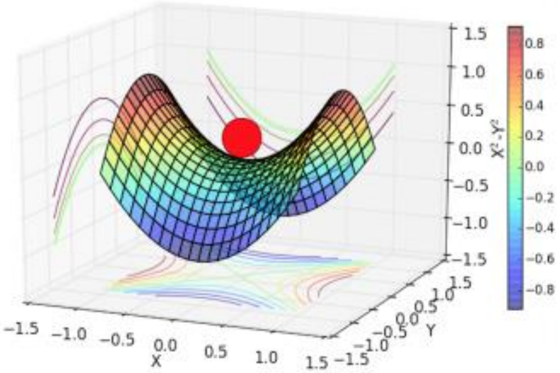
Paul trap, uses rf-E fields











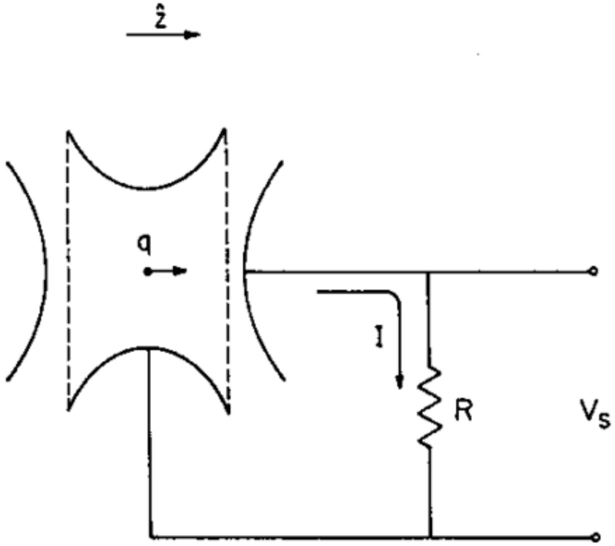
$\omega_c = e\,B/m$ $\qquad \omega_c^2 = \omega_+^2 + \omega_-^2 + \omega_z^2$ $\qquad \omega_c = \omega_+ + \omega_-$

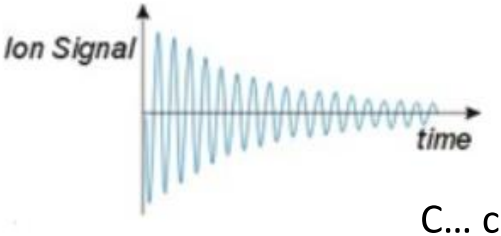
Cooling methods in Penning traps

$\overline{p}$ cooling mechanism in Penning traps:

- ○ **Resistive cooling**
- ○ **Stochastic cooling**
- ○ **Sympathetic radiation electron cooling**
- ○ **Evaporative / adiabatic cooling**
- ○ **Sympathetic laser cooling using anion species:**
  - **Os^-** spectroscopy: *U. Warring et al., Phys. Rev. Lett.* ***102*** *043001 (2009)*
  - **La^-** spectroscopy: *E. Jordan et al., Phys. Rev. Lett.* ***115*** *113001 (2015)*
  - **C_2^-** proposal: *P. Yzombard et al., Phys. Rev. Lett.* ***114*** *213001 (2015)*

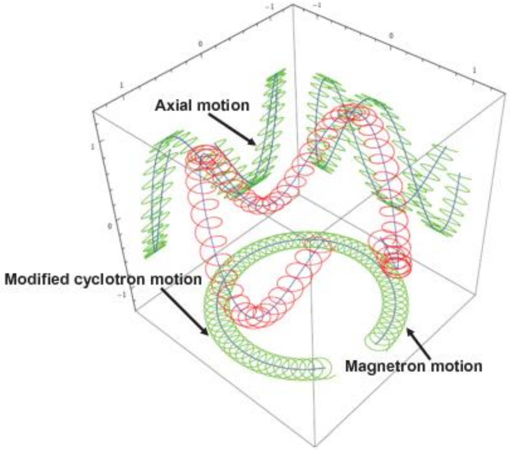
Resistive cooling in Penning traps





$$\tau_R = \left(\frac{2z}{e\,C}\right)^2 \frac{m}{R}$$

C… constant of about unity on trap shape
z…dimension of trap (~1 cm)
R…resistance (100 kOhm gives 270 s for p)



→ proven method for single particles in Penning traps

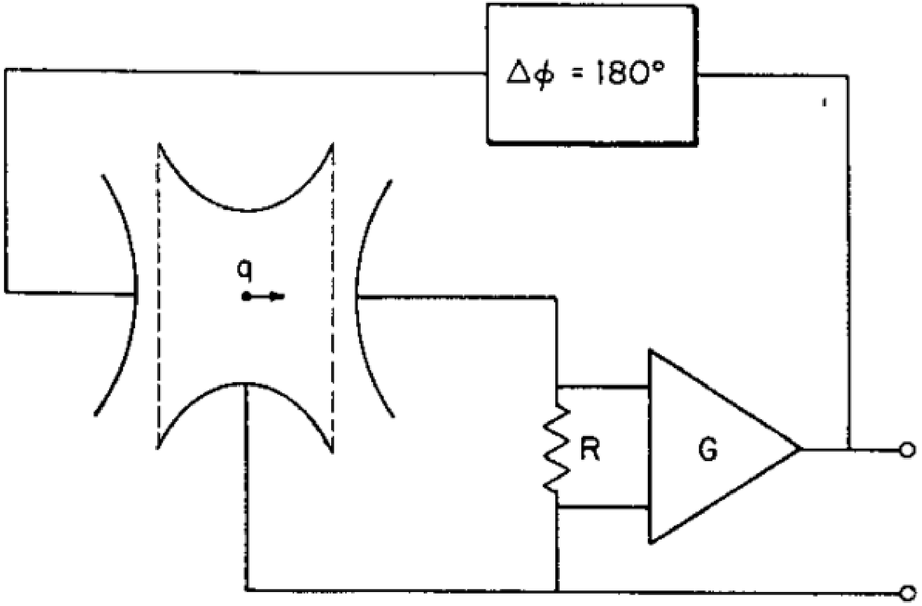
→ difficult for many particles because of broad plasma modes

i.e. weak coupling to high-Q LRC circuit

S. Rolston, G. Gabrielse, *Hyperf. Int.* **44**, 233 (1988)

Stochastic cooling in Penning traps

Stochastic cooling, negative feedback cooling
Signal from particle is amplified and fed back onto trap electrodes with 180° phase shift



$$\tau_{St} = \frac{1}{1+G}\tau_R$$

G… amplifier gain

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Electron cooling in Penning traps

Electron cooling using coupled rate equations:

$$\frac{d}{dt}T_p = -\frac{1}{\tau_{elcool}}\left(T_p - T_e\right)$$

$$\frac{d}{dt}T_e = \frac{N_p}{N_e}\frac{1}{\tau_{elcool}}\left(T_p - T_e\right) - \frac{1}{\tau_{rad}}\left(T_e - T_{trap}\right)$$

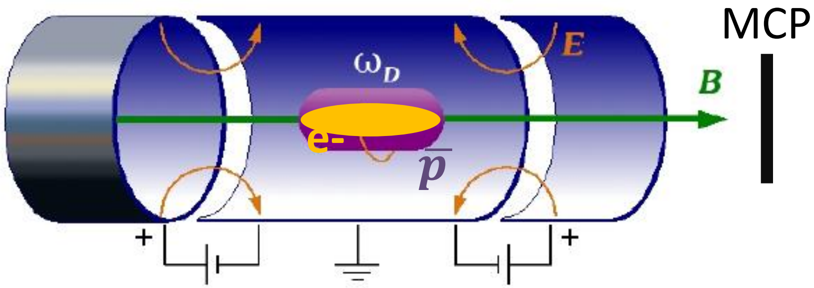
T_p… $\bar{p}$ temperature

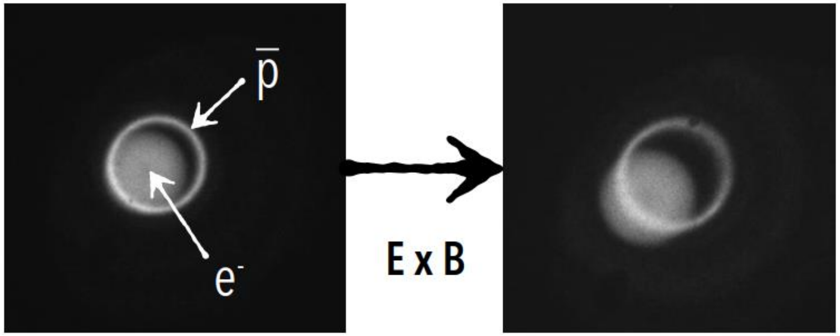
T_e…electron temperature

T_{trap}…temperature of trap electrodes

N_p…nr. of $\bar{p}$

N_e…nr. of electrons





Centrifugal separation, causes e^- to be on axis

S. Rolston, G. Gabrielse, *Hyperf. Int.* **44**, 233 (1988)

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T_p... $\overline{p}$ temperature

T_e...electron temperature

T_{trap}...temperature of trap electrodes

N_p...nr. of $\overline{p}$

N_e...nr. of electrons

$$\tau_{rad} = \frac{3\pi\, {m_e}^3 c^3 \varepsilon_0}{B^2 e^4}$$

Synchrotron radiation term

B... magnetic field of Penning trap

$$\tau_{elcool} = \frac{3 m_p m_e c^3 (4\pi\varepsilon_0)^4}{8\sqrt{2\pi} n_e e^4} \frac{1}{ln\left(4000\, n_e^{-1/2} T_e^{1/2}\left(T_e + \frac{T_p}{1836} + \frac{\sqrt{T_e T_p}}{21}\right)\right)} \left(\frac{kT_p}{m_p c^2} + \frac{kT_e}{m_e c^2}\right)^{3/2}$$

n_e...density of electrons

m_e...electron mass

m_p...$\overline{p}$ mass

S. Rolston, G. Gabrielse, *Hyperf. Int.* **44**, 233 (1988)

Electron cooling in Penning traps

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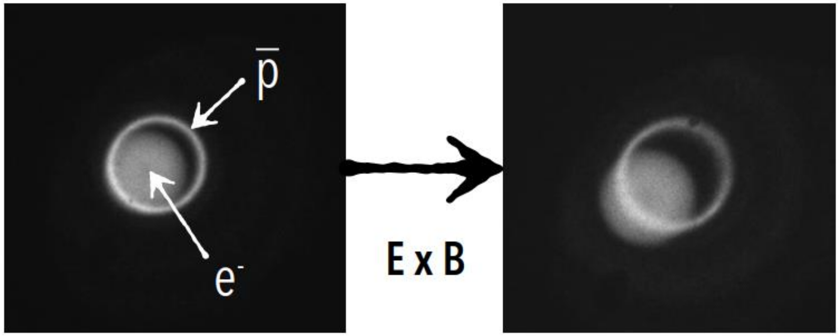
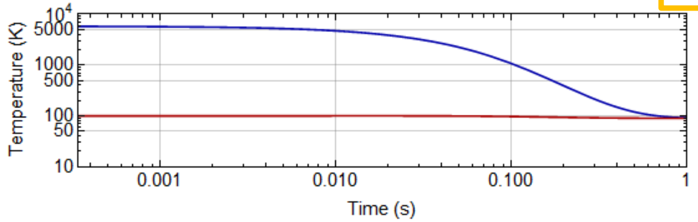
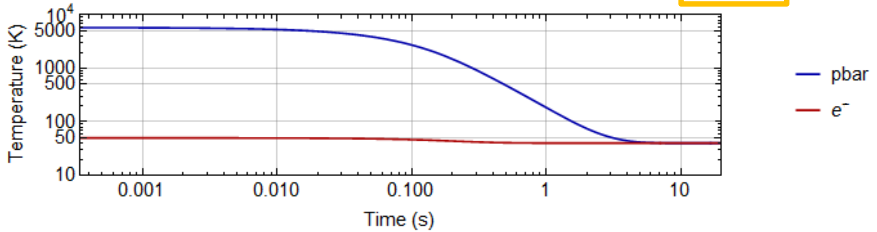


$T_{inject-pbar}=0.5$ eV, $T_{e^-}=100$ K, $n=1\text{x}10^{13}\ \text{m}^{-3}$, $B=4.5$ T, $T_{elec.}=40$ K, $\frac{N_{e+}}{N_{pbar}}=10^3$



$T_{inject-pbar}=0.5$ eV, $T_{e^-}=50$ K, $n=1\text{x}10^{12}\ \text{m}^{-3}$, $B=4.5$ T, $T_{elec.}=40$ K, $\frac{N_{e+}}{N_{pbar}}=10^3$



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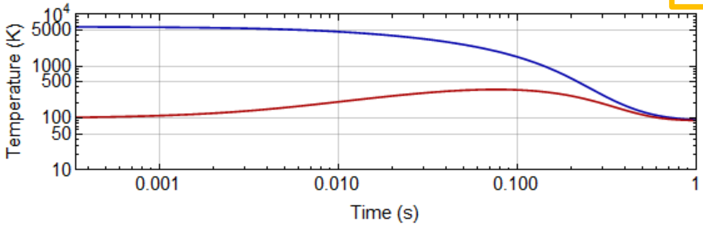

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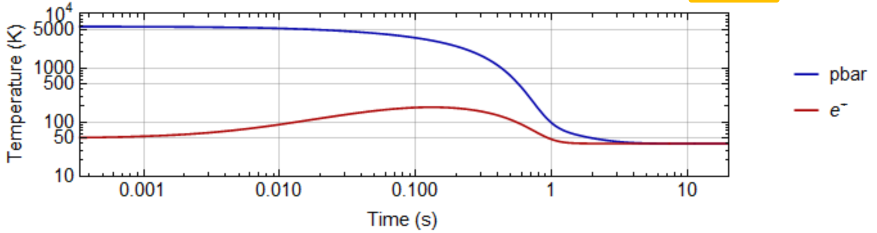
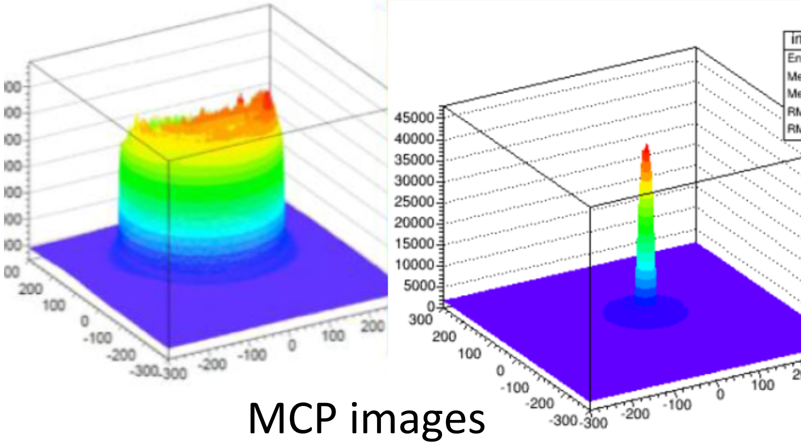


→ Great method for many particles, limited by B field and environmental temperature

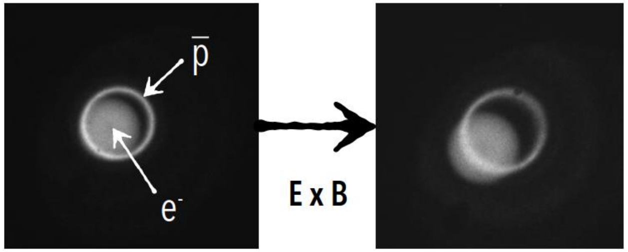
Electron cooling in Penning traps

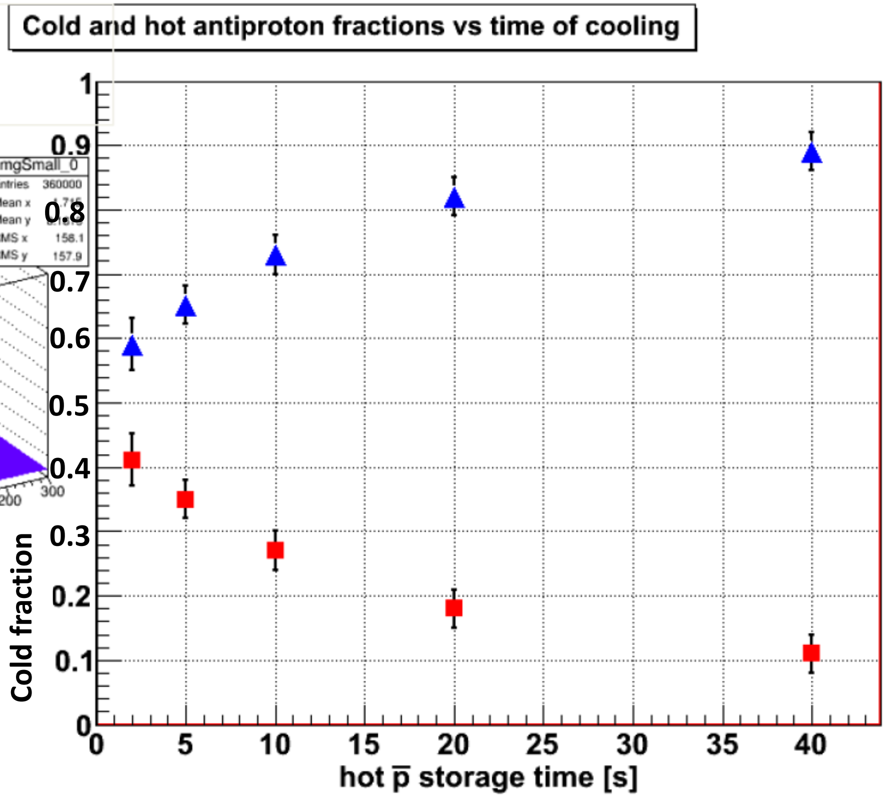
Example of a measurement:

Radial compression of the
Trapped plasma with RF field: Rotating Wall



MCP images





$$\tau_{rad} \propto \frac{m^3}{B^2}$$

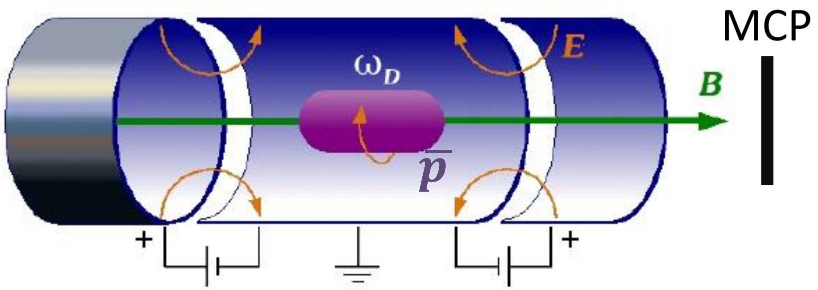
$$\boxed{\begin{array}{ll} e^-, e^+ & \tau_{rad} \cong 0.1\sec @ 5T \\ \bar{p} & \tau_{rad} \cong 10^9 \sec @ 5T \end{array}}$$

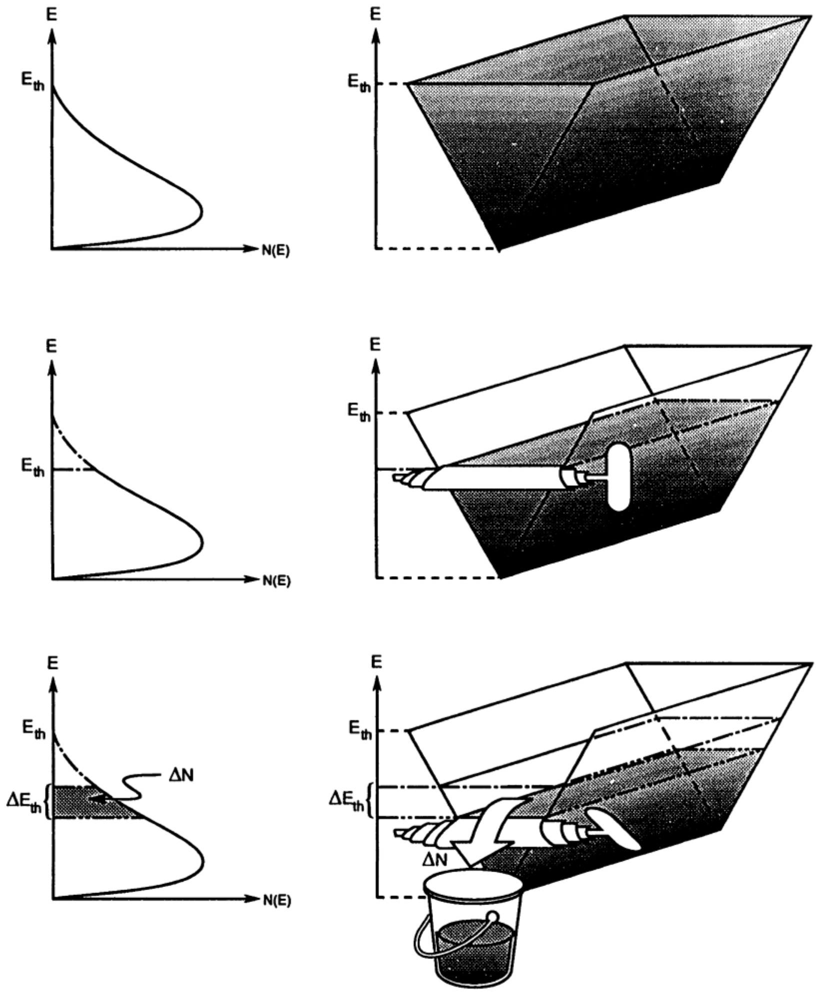
Cyclotron radiation + Coulomb collisions
= thermal equilibrium for e- and pbar

Final energy estimation: about 100 K

Evaporative cooling in Penning traps

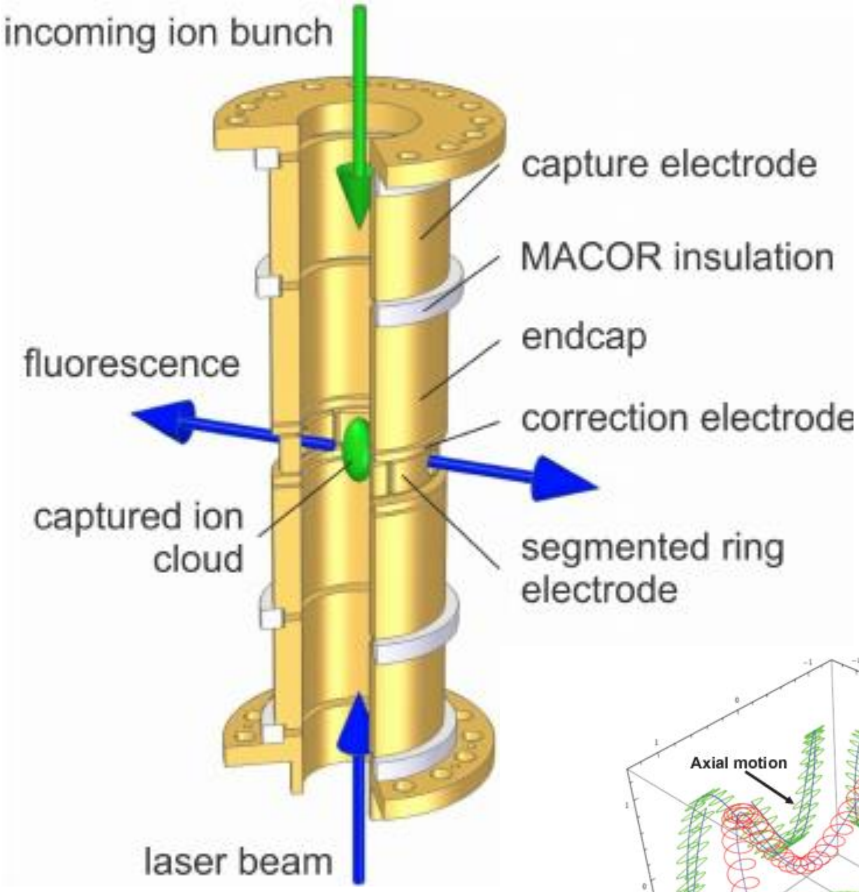
Lower axial confinement voltage to open trap

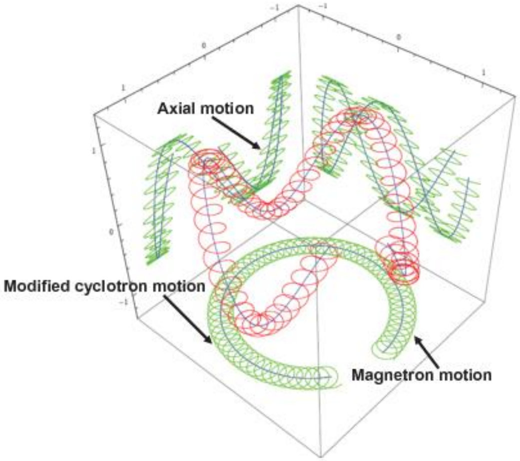


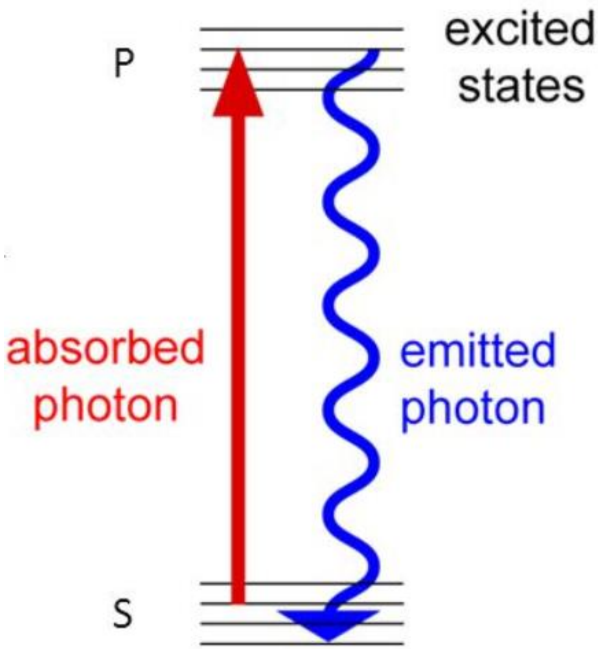


- → Often used in AD experiments
- → Limited by p̄ numbers and axial confinement
- → Reach typically ~100 K

Laser cooling in Penning traps







$$\hbar\omega_{\mathrm{abs}} < \hbar\omega_{\mathrm{em}}$$

=> COOLING !

(Need a 2 level system)

Laser cooling in Penning traps

Three possible laser cooling methods for anions (to sympathetically cool $\overline{p}$) :

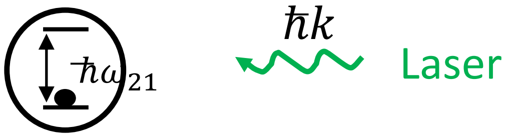
1)…Doppler laser cooling

2)…photodetachment cooling

3)…dipole force Sisyphus cooling

Laser cooling in Penning traps

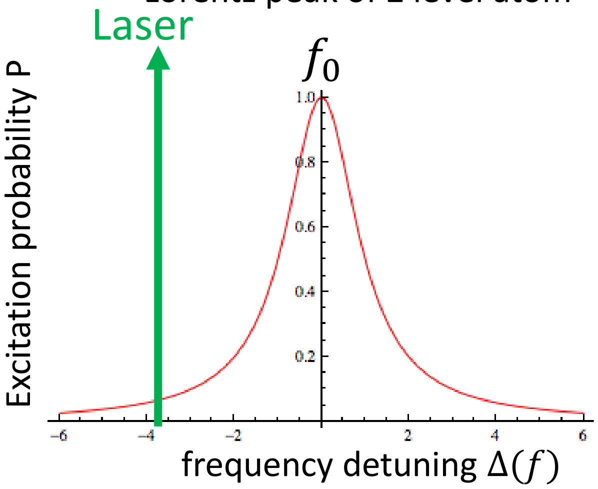
Doppler laser cooling



Atom stands still, **no excitation**

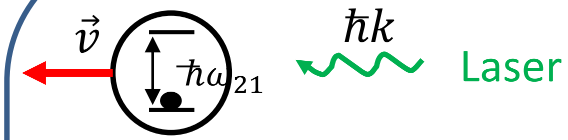
Atom sees laser without Doppler shift

$$f_D = \frac{2\,f_0}{c}\vec{v} = 0$$


Lorentz peak of 2 level atom

Laser cooling in Penning traps

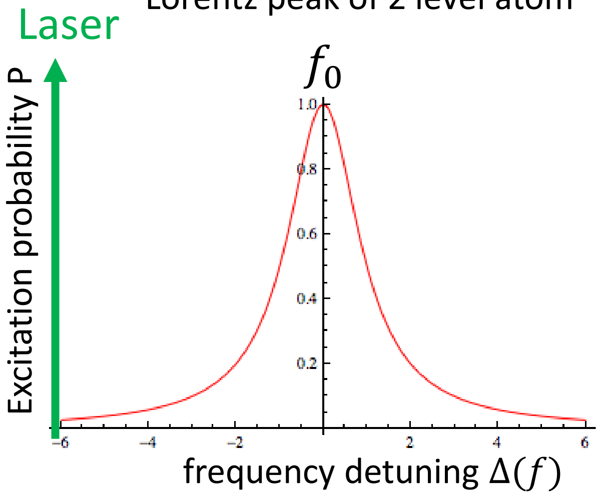
Doppler laser cooling



Atom moves away from the laser,
no excitation

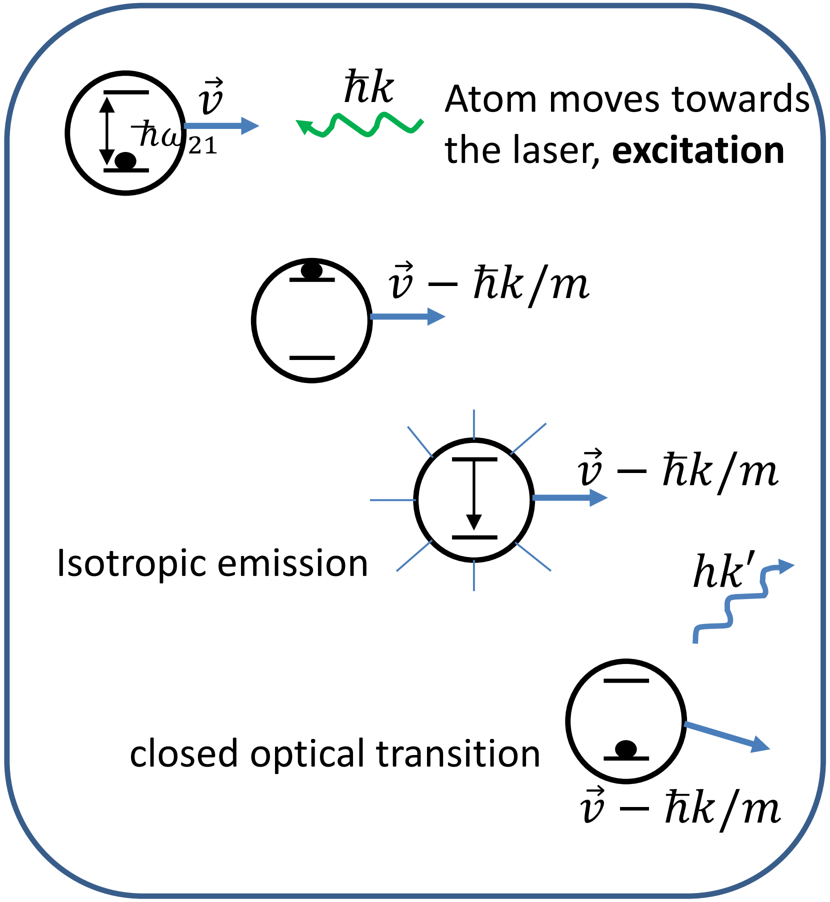
Atom sees laser red Doppler shifted

$$f_D = \frac{2\,f_0}{c}\,\vec{v}$$


Lorentz peak of 2 level atom

Laser cooling in Penning traps

Doppler laser cooling

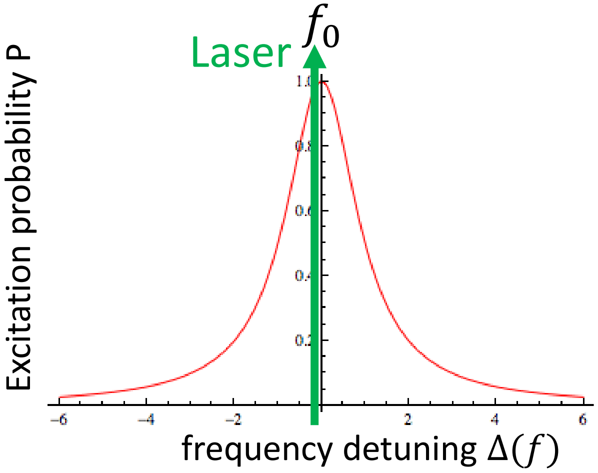


Atom moves towards the laser, **excitation**

Isotropic emission

closed optical transition

Lorentz peak of 2 level atom

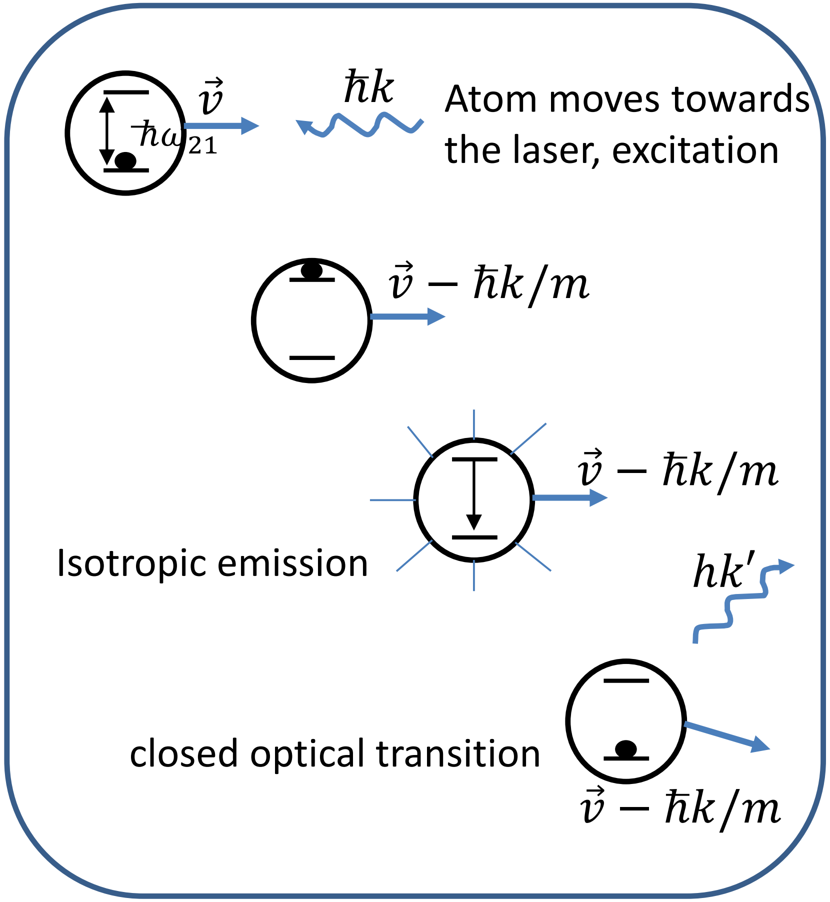


Atom sees laser blue Doppler shifted

$$f_D = \frac{2\,f_0}{c}\,\vec{v}$$

Laser cooling in Penning traps

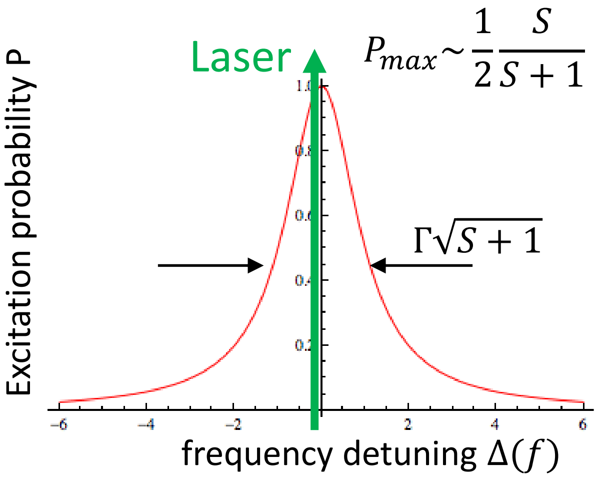
Doppler laser cooling



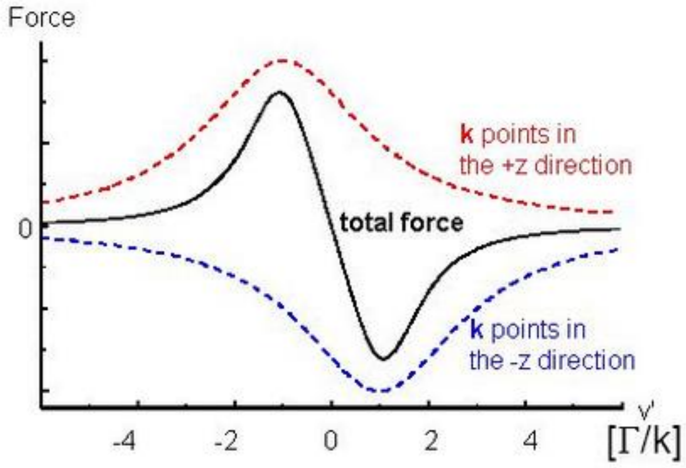
Atom moves towards the laser, excitation

Isotropic emission

closed optical transition

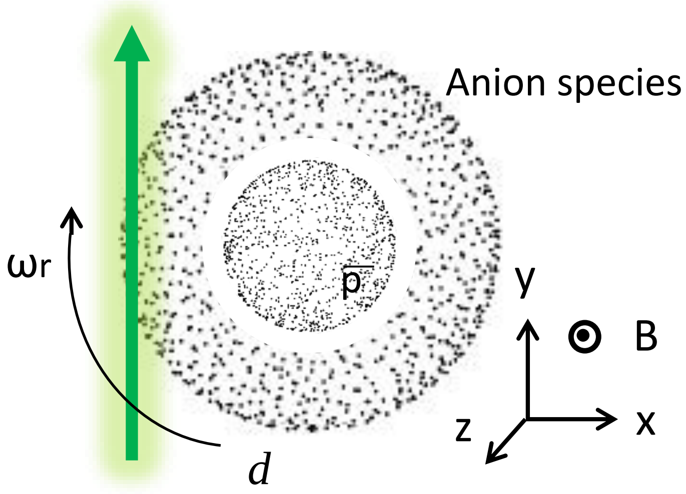


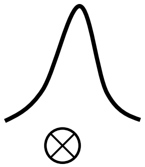
Cooling force
$$F = \pm \frac{\hbar\vec{k}}{2} S\Gamma \frac{(\Gamma/2)^2}{(\omega - \omega_{21} - \vec{v}\vec{k}) + (\Gamma/2)^2(1+S)}$$



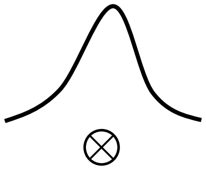
Minimal Doppler temperature
$$T_D = \frac{\hbar\Gamma}{2\,k_B}$$

Doppler cooling in Penning traps





Plasma rotation ~ 1 MHz



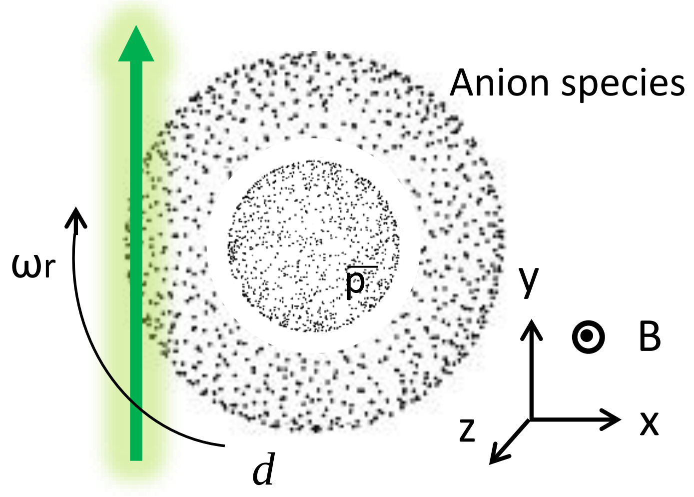
Transition linewidth ~ 3 MHz

Laser linewidth ~ 10 kHz

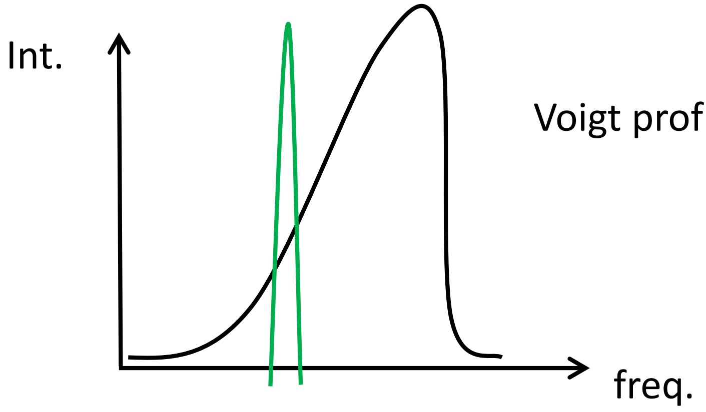
Laser interacts both with 'magnetron' and 'cyclotron'

- If $\omega_L < \omega_0$ and laser put to receding position
  → Plasma size reduced
- If $\omega_L < \omega_0$ and laser put to the approaching side
  → Plasma size increased
- Cyclotron is laser cooled and plasma forms nearly circular magnetron shape.
- Transition blue Doppler shifted prop. to the distance from trap centre

Doppler cooling in Penning traps

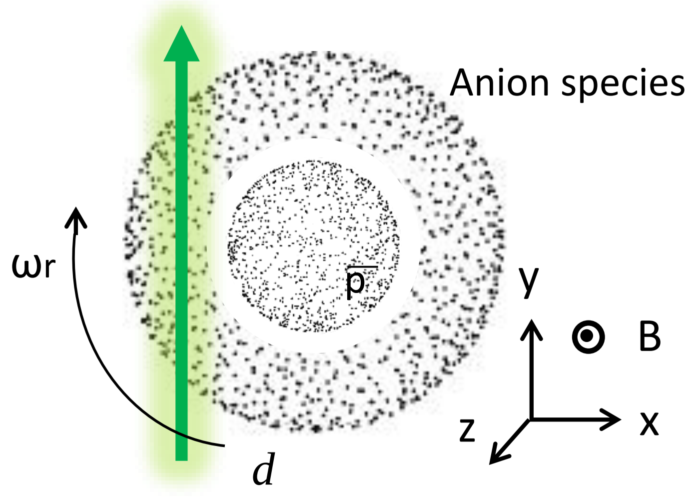


Laser on cooling transition:

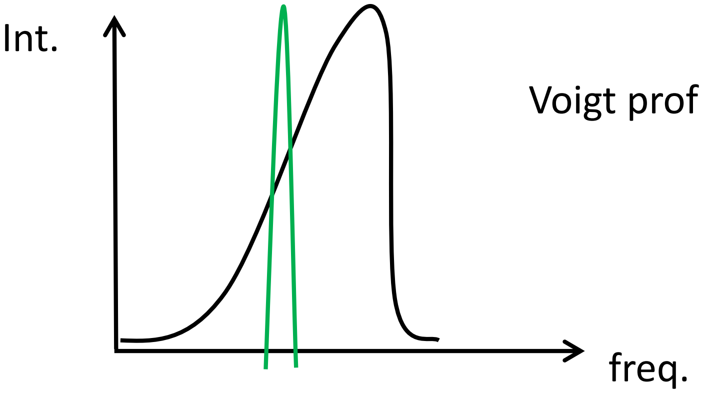


Voigt profile ~7 MHz

Doppler cooling in Penning traps

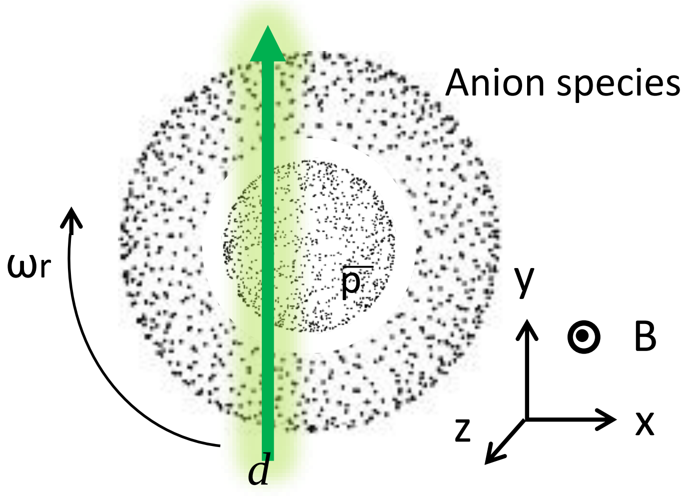


Laser on cooling transition:

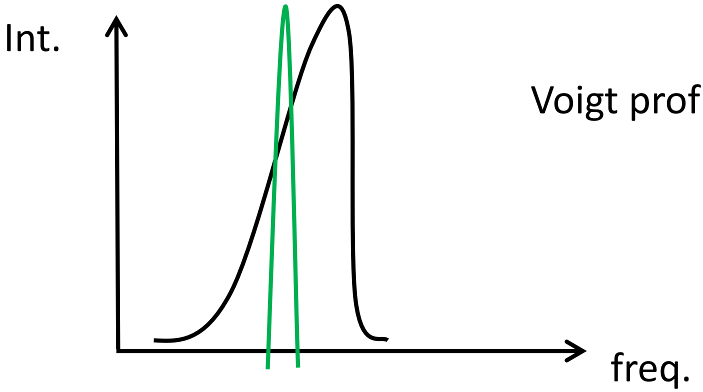


Voigt profile ~5 MHz

Doppler cooling in Penning traps

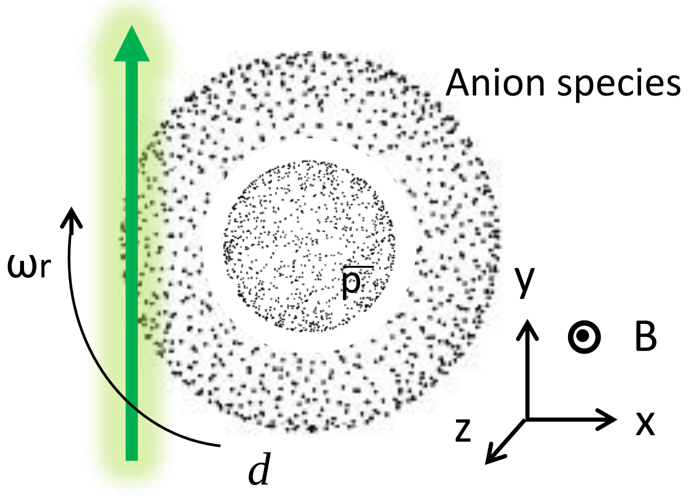


Laser on cooling transition:

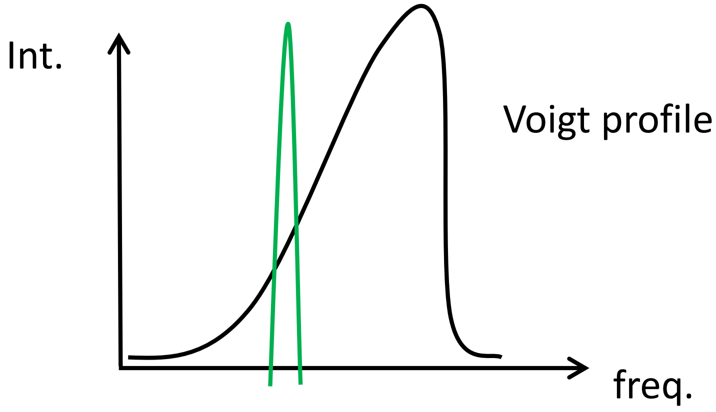


Voigt profile ~3 MHz

Doppler cooling in Penning traps

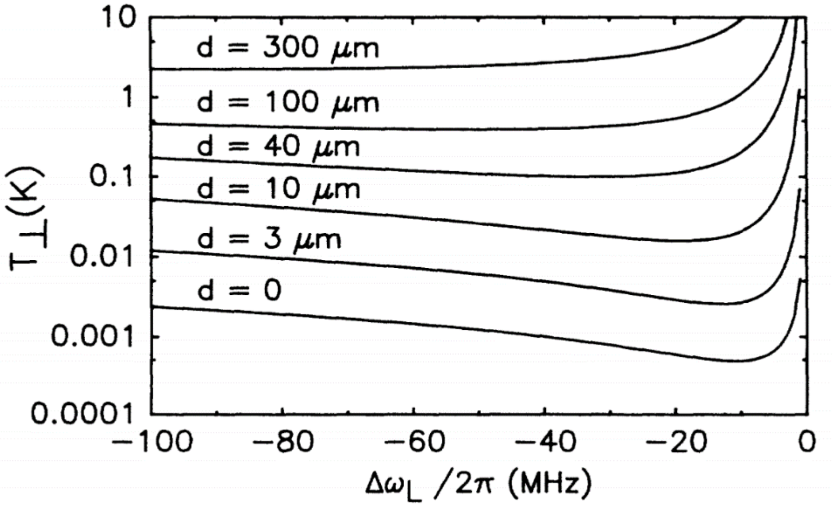


Laser on cooling transition:



Doppler cooling Penning trap: its limit

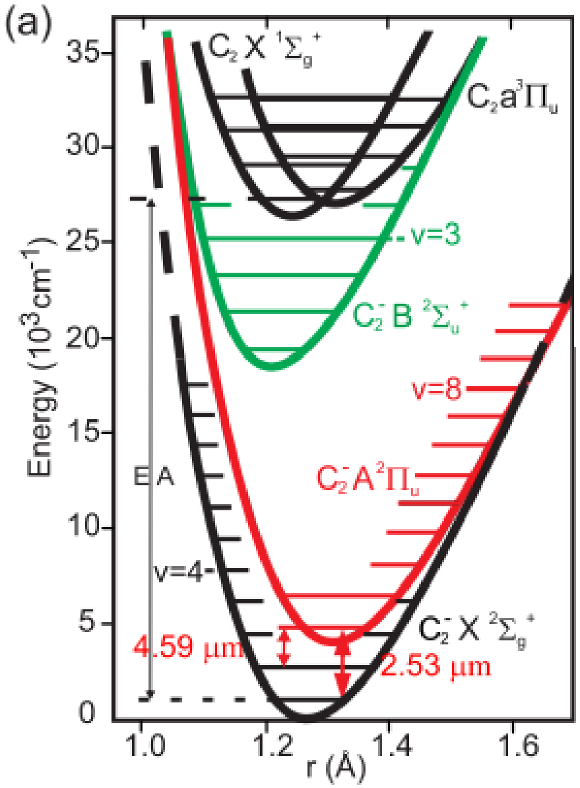
Be$^+$ plasma: Δ=–20 MHz at 313 nm
→ μK reached



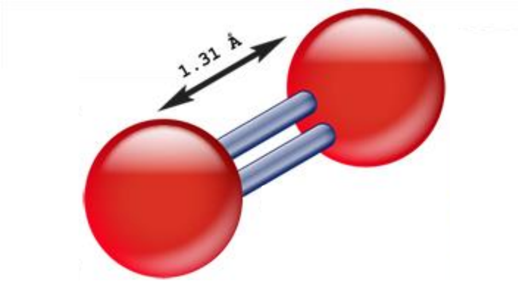
W. Itano et al., *Phys. Rev. A.* **38**, 5698 (1985)

Anion example: Molecule C_2^-

Ro-Vib level structure and molecular potential energy of C_2^-



C_2 Homonuclear molecule



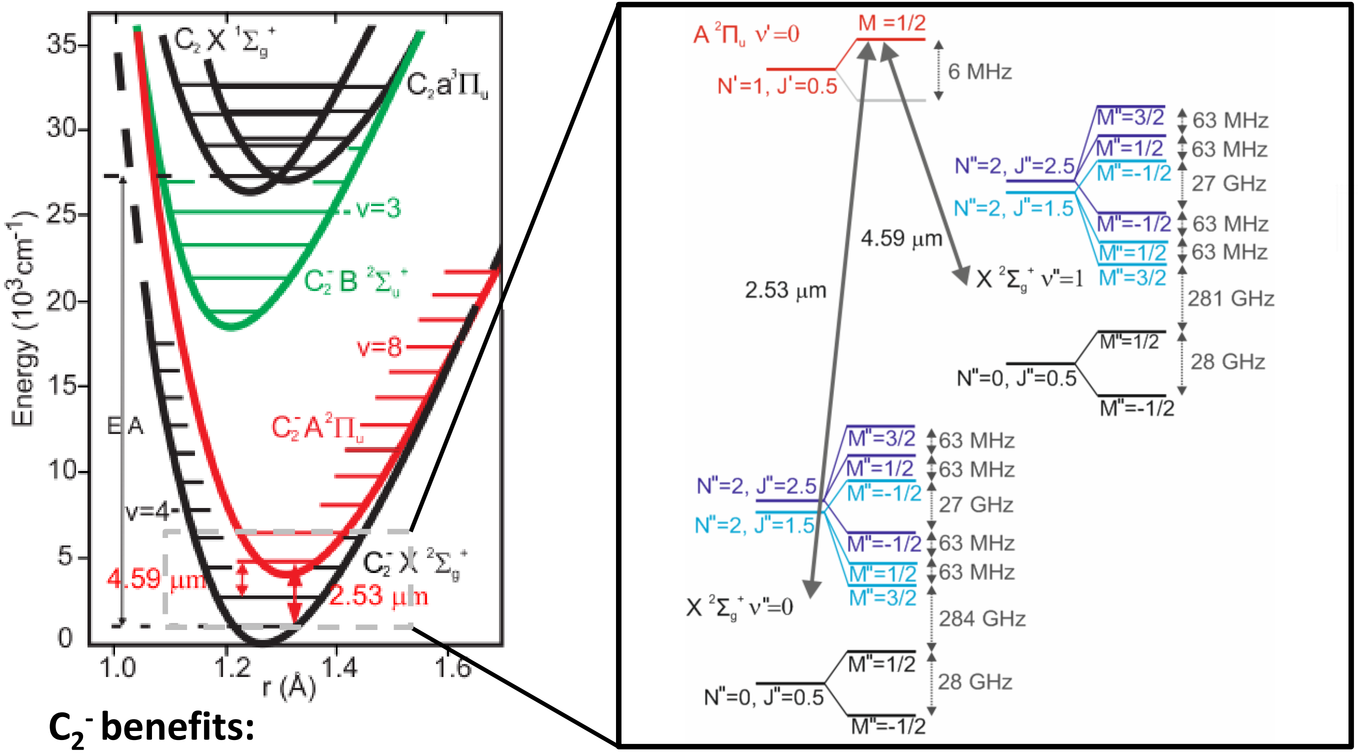
C_2^- benefits:

- Known level scheme to ν/dν ~100 MHz M. Tulej et al., *J. Raman Spectrosc.* **41,** 853 (2010)
- 2.53 µm and 4.59 µm dipole transition accessible with DFB diode lasers
- Production in supersonic gas expansion

P. Yzombard et al., *Phys. Rev. Lett.* **114** 213001 (2015)

Anion example: Molecule C_2^-

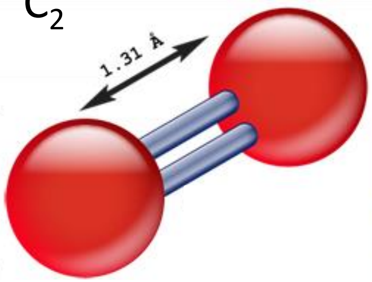
Ro-Vib level structure and molecular potential energy of C_2^- in B=1 T



M. Tulej et al., *J. Raman Spectrosc.* **41,** 853 (2010)

Homonuclear molecule

C_2



C_2^- benefits:

- Known level scheme to ν/dν ~100 MHz
- 2.53 μm and 4.59 μm dipole transition accessible with DFB diode lasers
- Production in supersonic gas expansion

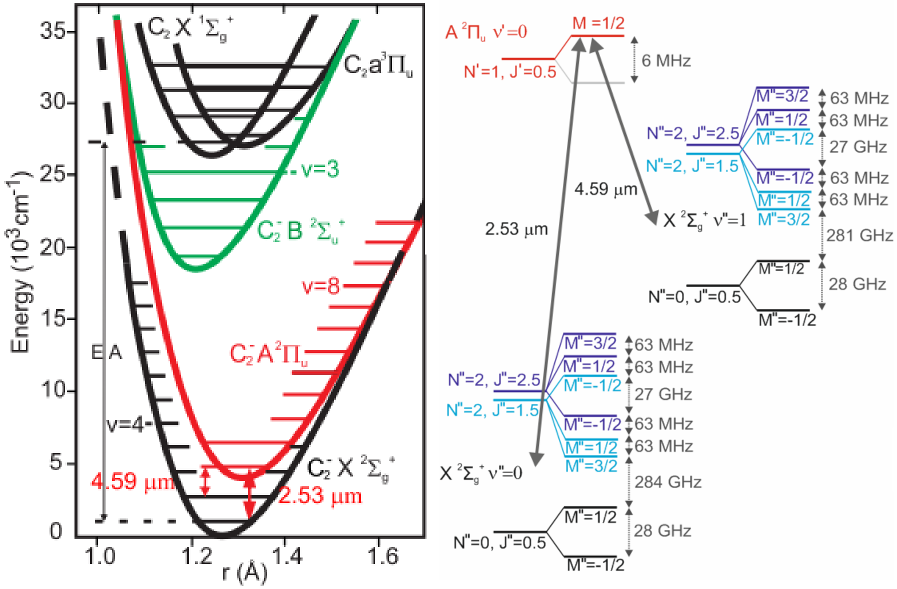
C_2^- challenges:

- 16 transitions for closed laser cycle with Zeeman splitting
- 20 kHz linewidth

P. Yzombard et al., *Phys. Rev. Lett.* **114** 213001 (2015)

Doppler cooling simulation C$_2^-$ / $\bar{p}$

2 x Doppler 2.53 μm laser
6 x Repumper at 2.53 μm, 4.59 μm



→ Crystallization effects at low T
(trap and plasma geometry, B, $\Gamma_{coupling}$)

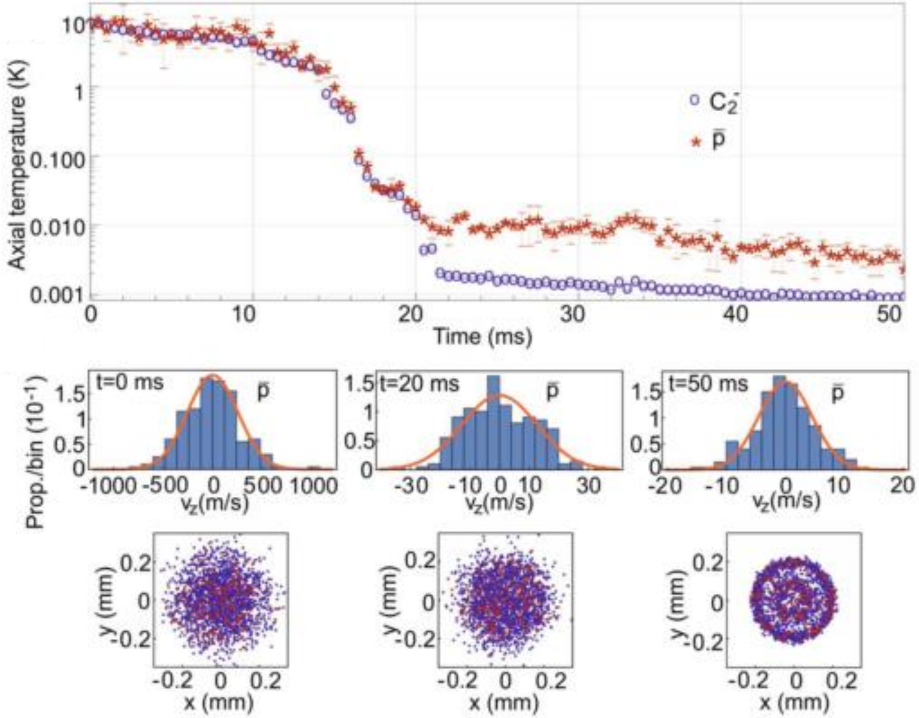
H. Totsuji et al., *AIP Conf. Proc.,* **498,** 77 (1999)
T. Mitchell et al., *Science,* **282,** 1290 (1998)

→ ~10 mK temperature within minutes

simulation

$n_{C_2^-/\bar{p}}$ =10^7 cm^{-3} , B=1 T, initialized at 11 K

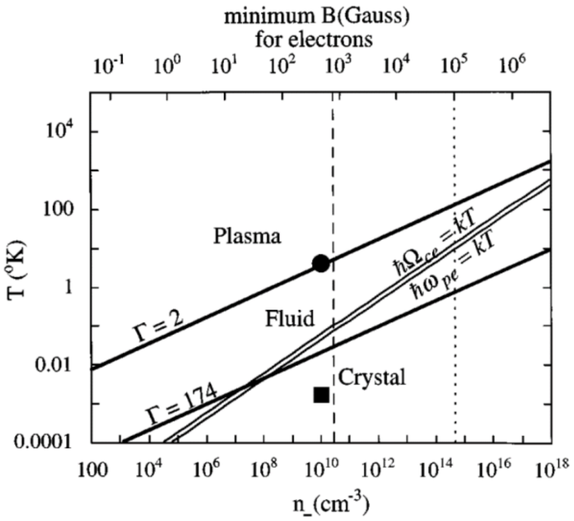
GPU calculation of 1000 C$_2^-$/100 $\bar{p}$ particle-particle interactions Coulomb factor increased by 10^4



Detuning adjusted in 4 steps from Δν=-39 MHz to Δν -3.4 MHz.
Laser linewidth δν=-1 MHz

Doppler cooling simulation $C_2^- / \bar{p}$

Phase diagram B - T - n:



Malmberg and O'Neil (1977)

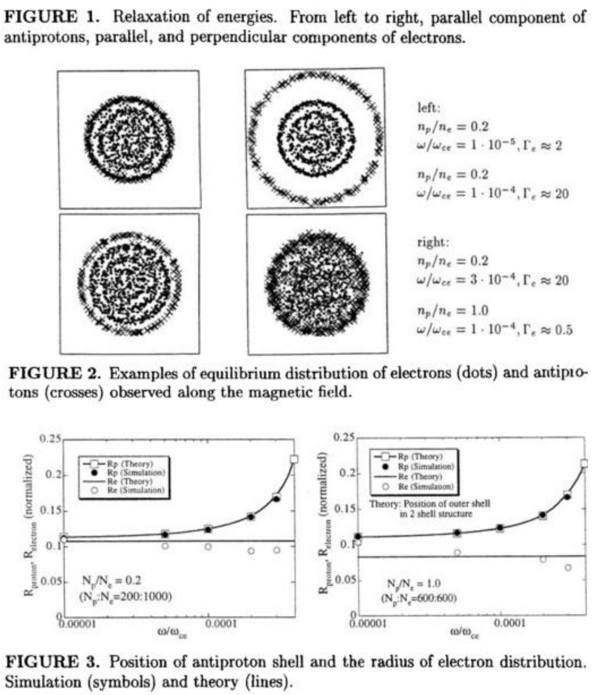


FIGURE 1. Relaxation of energies. From left to right, parallel component of antiprotons, parallel, and perpendicular components of electrons.

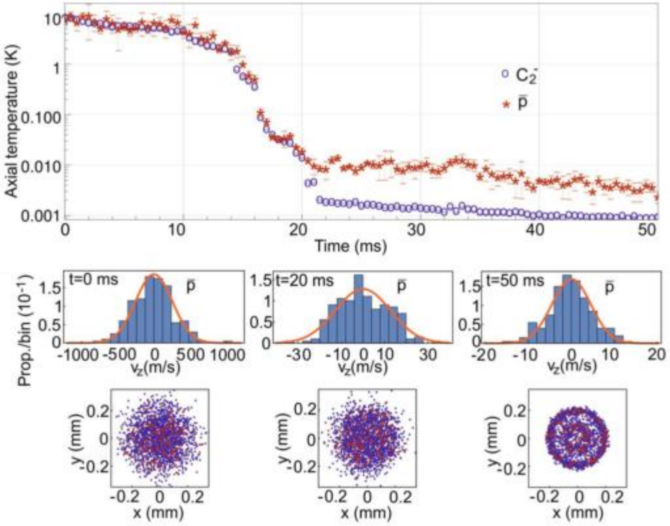
left:
$n_p/n_e = 0.2$
$\omega/\omega_{ce} = 1 \cdot 10^{-5}, \Gamma_e \approx 2$
$n_p/n_e = 0.2$
$\omega/\omega_{ce} = 1 \cdot 10^{-4}, \Gamma_e \approx 20$

right:
$n_p/n_e = 0.2$
$\omega/\omega_{ce} = 3 \cdot 10^{-4}, \Gamma_e \approx 20$
$n_p/n_e = 1.0$
$\omega/\omega_{ce} = 1 \cdot 10^{-4}, \Gamma_e \approx 0.5$

FIGURE 2. Examples of equilibrium distribution of electrons (dots) and antiprotons (crosses) observed along the magnetic field.

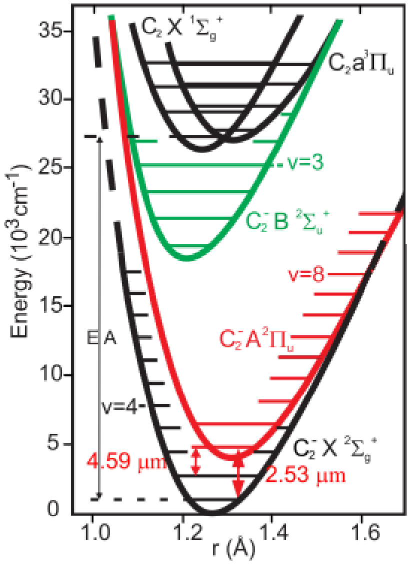
FIGURE 3. Position of antiproton shell and the radius of electron distribution. Simulation (symbols) and theory (lines).

H. Totsuji et al., *AIP Conf. Proc.* **498,** 77 (1999)



Doppler cooling simulation C_2^- / $\bar{p}$

2 x Doppler 2.5 μm laser
6 x Repumper at 2.5 μm, 4.5 μm



→ Crystallization effects at low T
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→ ~10 mK temperature within minutes

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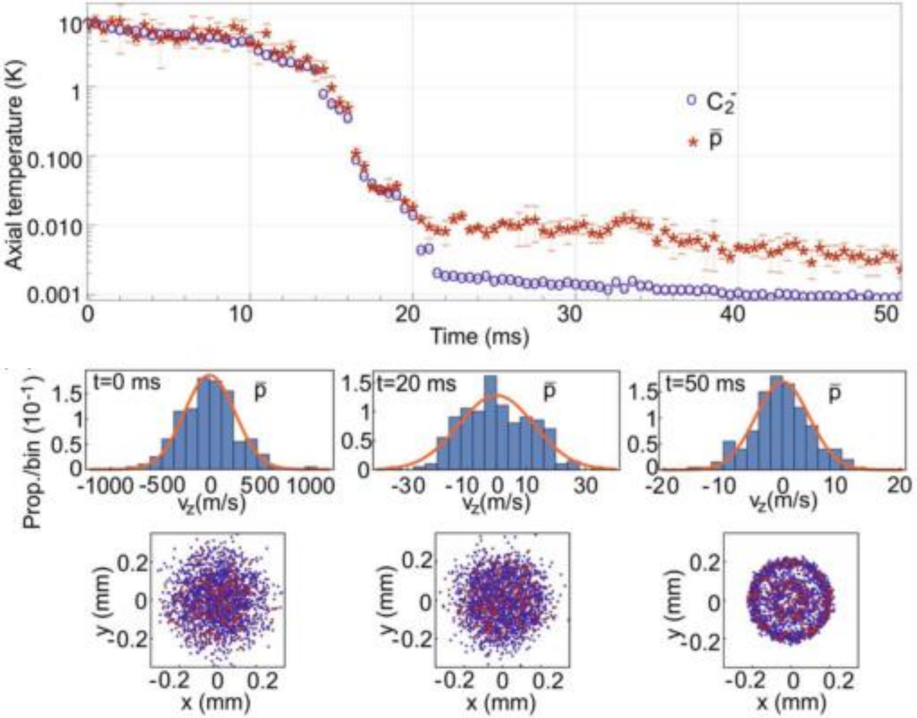
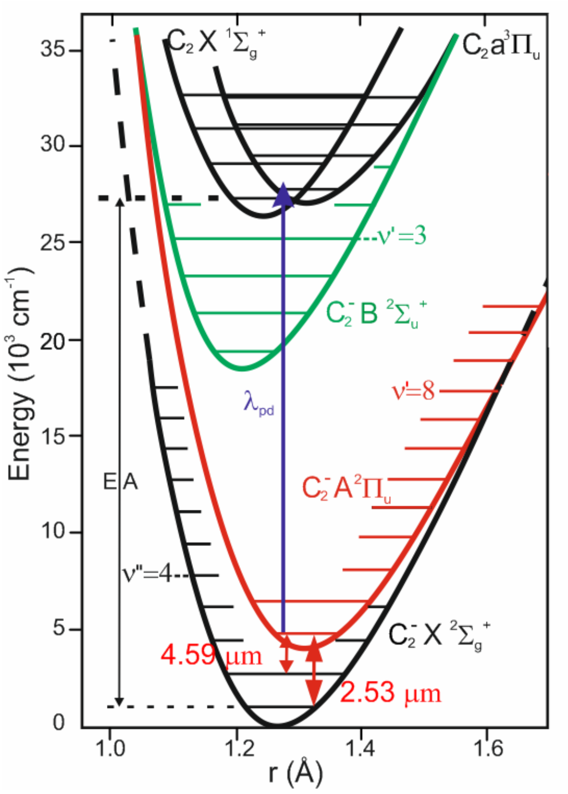


Detuning adjusted in 4 steps from Δν=-39 MHz to Δν -3.4 MHz.
Laser linewidth δν=-1 MHz

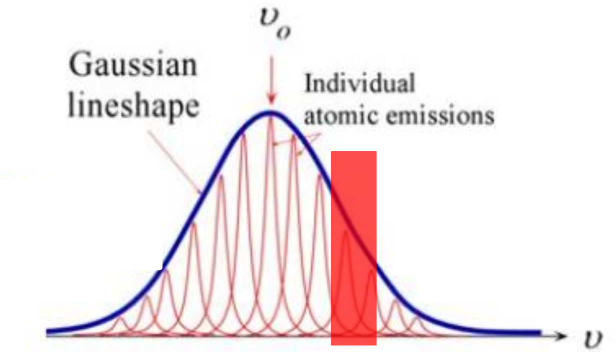
→ Possible, but challenging in Penning tap
(scatter ~10^6 photons with 8 lasers plus sidebands to <MHz stabilized)

Photodetachment cooling C_2^-

Ro-Vib level structure and molecular potential energy of C_2^-



$$\Delta v = v_0 \sqrt{\frac{2\, k_B\, T\, \ln(2)}{m\, c^2}}$$



2.53 μm laser addresses ν+Δν

Photodetachment cooling

- 2.53 μm laser addresses high velocity fraction of molecules
- UV laser 399 nm photodetaches this fraction

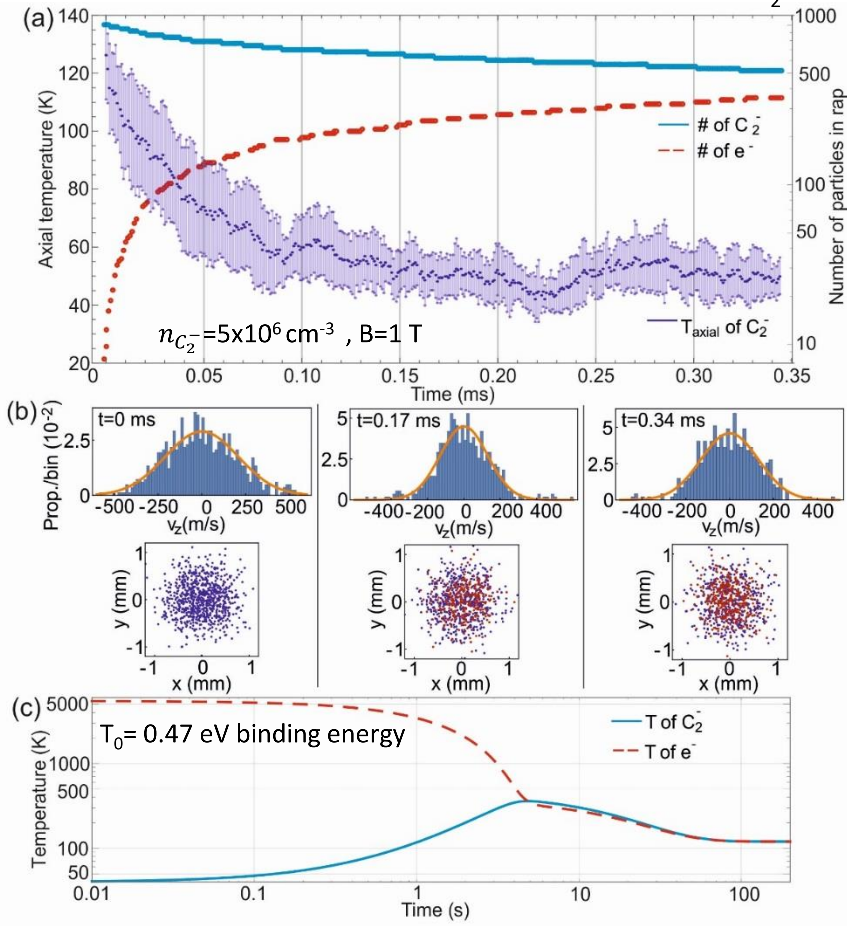
P. Yzombard et al., *Phys. Rev. Lett.* **114** 213001 (2015)

Photodetachment cooling C_2^-

simulation

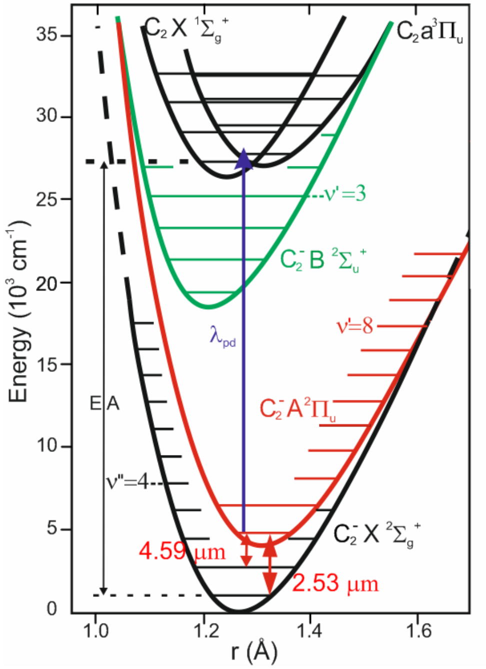
1 x 2.5 μm laser, 1 x photodetachment laser 399 nm (100 mW enhanced in F~1000 cavity)

GPU based Coulomb interaction calculation of 1000 C_2^-:



$n_{C_2^-}$=5x10^6 cm^{-3} , B=1 T

T_0= 0.47 eV binding energy



Photodetachement rate:

$$\Gamma = \frac{I}{h\,\nu}\sigma \sim 65\ kHz$$

Photodetachement cross section:

$$\sigma/cm^2 \sim 1\times 10^{-17}$$

S. Gerber et al., *New J. Phys.* **20**, 023024 (2018)

Photodetachment cooling C_2^-

simulation

1 x 2.5 μm laser, 1 x photodetachment laser 399 nm (100 mW enhanced in F~1000 cavity)

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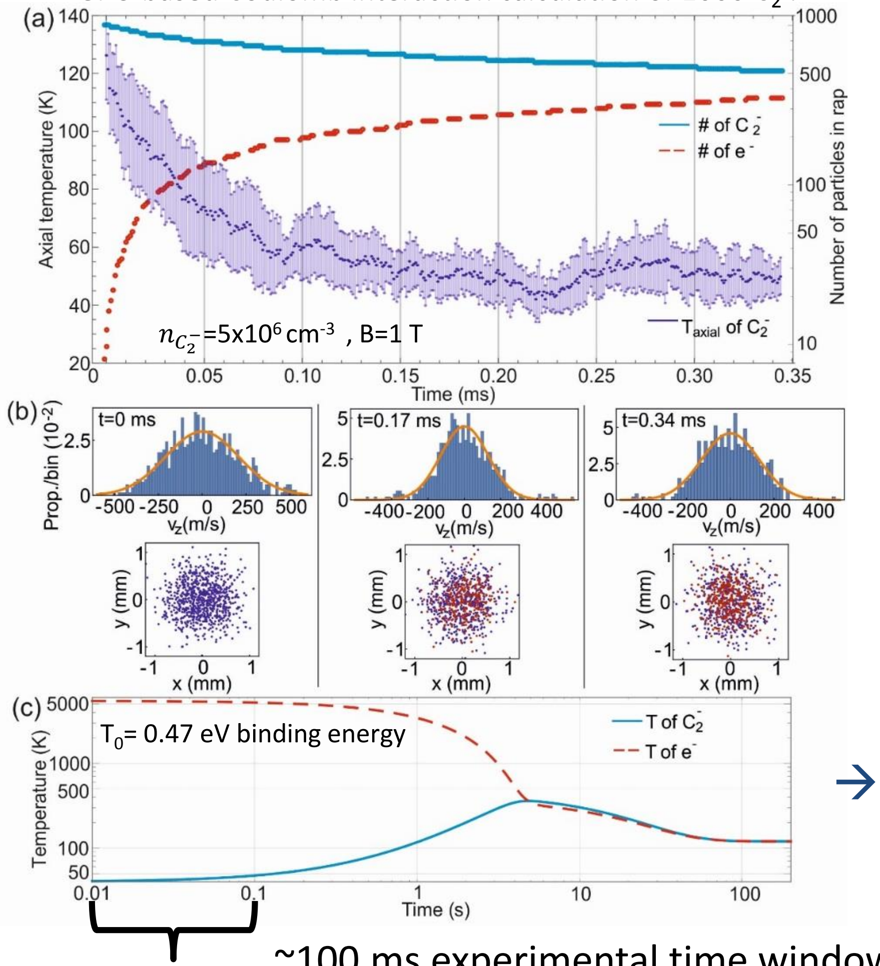


~100 ms experimental time window at lower temperature

- Factor ~2.5 temperature reduction after 0.3 ms; e^- released with binding energy 0.47 eV as: $C_2^- + h\nu \rightarrow C_2 + e^-$

- e^- equilibrate with C_2^- in ~5 s then thermalizing with 120 K environment after 100 s in 1 T.

→ **Simple method, but only for small time window**

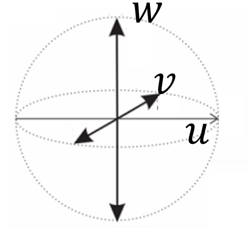
S. Gerber et al., *New J. Phys.* **20**, 023024 (2018)

Dipole force Sisyphus cooling in Penning trap

- 1 x 2.5 μm ~1.5 GHz detuned dipole laser
- Spontaneous decay lifetime
  τ_{spon}=50 μs > axial trap motion
- T_{min} given by potential depth U_{dipole} to ~ mK

Force of light-matter interaction for a 2 level-system:

Bloch sphere



$$|\psi\rangle\langle\psi| = \begin{pmatrix} \rho 11 & \rho 12 \\ \rho 21 & \rho 22 \end{pmatrix}$$

$u = \rho 12 + \rho 21$ in-phase

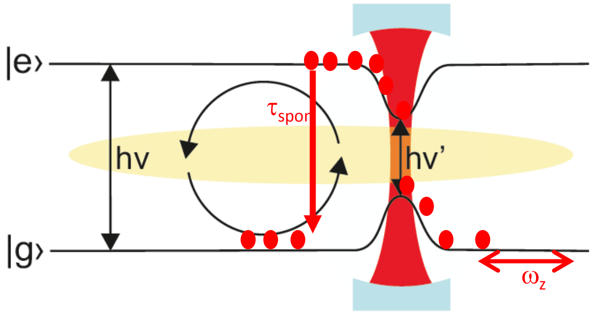
$v = -i(\rho 12 - \rho 21)$ quadrature

$\mathrm{w} = \rho 11 - \rho 22$, $|\mathrm{R}|^2 = u^2 + v^2 + \mathrm{w}^2 = 1$

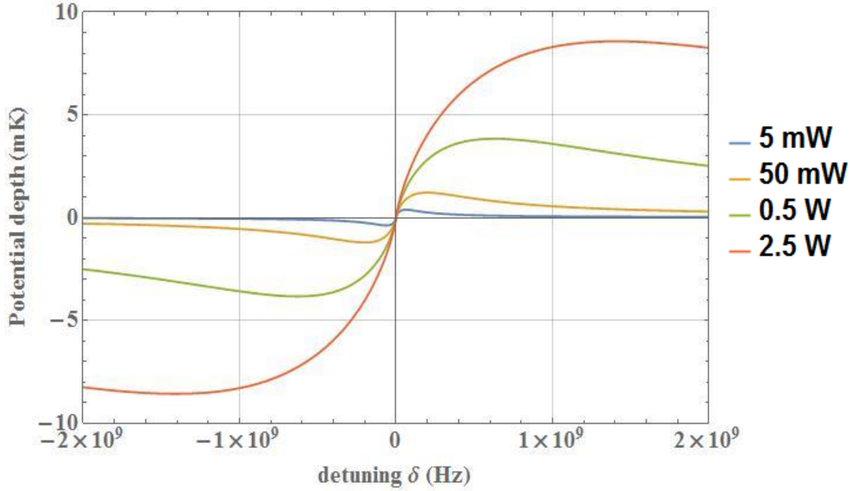
$$F = \frac{-q\,\chi_{12}}{2}\left[u\frac{\partial E}{\partial z} + vEk\right]$$

$$F = F_{dipole} + F_{scatter}$$

$F_{dipole} = \nabla U_{dipole}$, $\mathrm{U}_{dipole} = \hbar\delta\ \ln\left[1 + \frac{2\Omega^2}{4\delta^2 + \Gamma^2}\right]$



Dipole potential depth vs laser detuning, waist = 0.2 mm

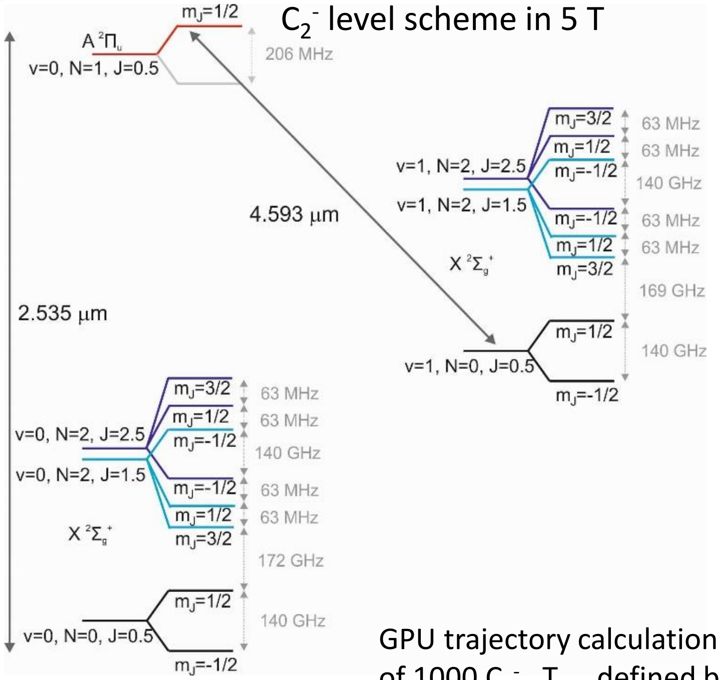


Sisyphus scheme: J. Dalibard and C. Cohen-Tannoudji, *J. Opt. Soc. Am. B*, **2**, 11 (1985)
Sisyphus cooling in magnetic traps: S. Wu, W. Phillips, J. V. Porto et al., *Phys. Rev. Lett*. **106**, 213001 (2011)

Dipole force Sisyphus cooling in Penning trap

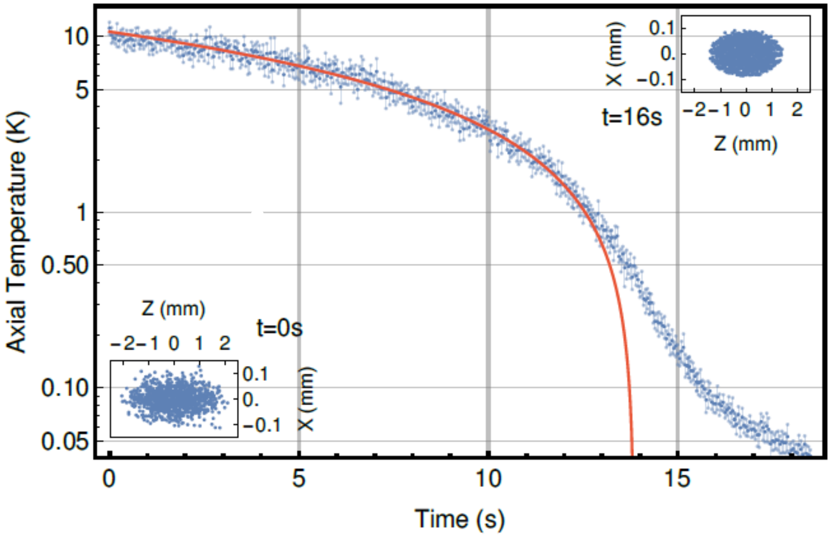
simulation

- 1 x 2.5 μm ~1.5 GHz detuned dipole laser (U_{dipole}=7 mK)
- Spontaneous decay τ_{spon}=50 μs > axial trap motion
- 1 x pump at 2.5 μm, 4 x repumper at 2.5 μm and 4.5 μm



C_2^- level scheme in 5 T

$n_{C_2^-}$=10^7 cm^{-3} , B=5 T, Dipole=2.5 W, Pump=10 mW, w=0.2 mm, F=1000



GPU trajectory calculation including Monte Carlo for optical transitions of 1000 C_2^- . T_{min} defined by potential depth U_{dipole} to ~1 mK

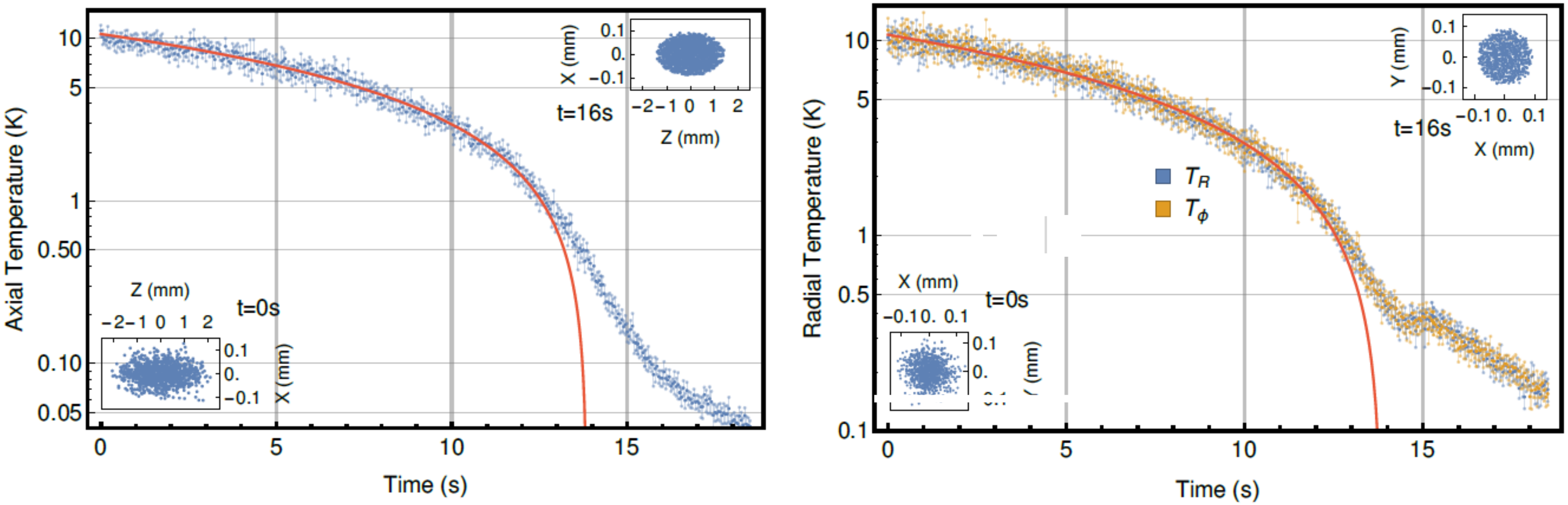
J. Fesel et al., *Phys. Rev. A* **96**, 031401 (2017)

Dipole force Sisyphus cooling in Penning trap

simulation

- 1 x 2.5 μm ~1.5 GHz detuned dipole laser (U_{dipole}=7 mK)
- Spontaneous decay τ_{spon}=50 μs > axial trap motion
- 1 x pump at 2.5 μm, 4 x repumper at 2.5 μm and 4.5 μm

$n_{C_2^-}=10^7\,\mathrm{cm}^{-3}$, B=5 T, Dipole=2.5 W, Pump=10 mW, w=0.2 mm, F=1000



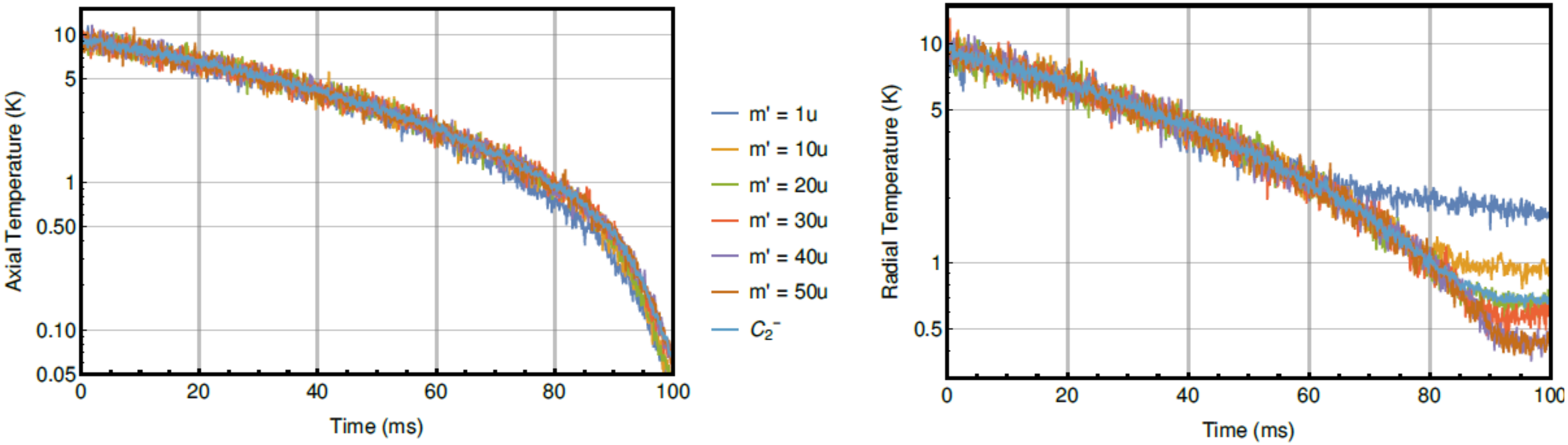
GPU trajectory calculation including Monte Carlo for optical transitions of 1000 C_2^- . T_{min} defined by potential depth U_{dipole} to ~1 mK

J. Fesel et al., *Phys. Rev. A* **96**, 031401 (2017)

Sympatheic cooling with C_2^-

simulation

$n_{C_2^-}=10^7\ \mathrm{cm}^{-3}$, B=5 T, Dipole=2.5 W, Pump=10 mW, w=0.2 mm, F=1000



GPU trajectory calculation including Monte Carlo for optical transitions of 1000 C_2^- / 100 m'. T_{min} defined by potential depth U_{dipole} to ~1 mK

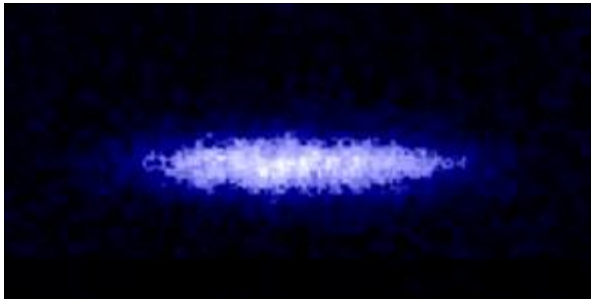
→**mK $\bar{\mathrm{p}}$ feasible (scatter ~10^4 photons, 6x lasers drift stabilized to cell/wavemeter)**

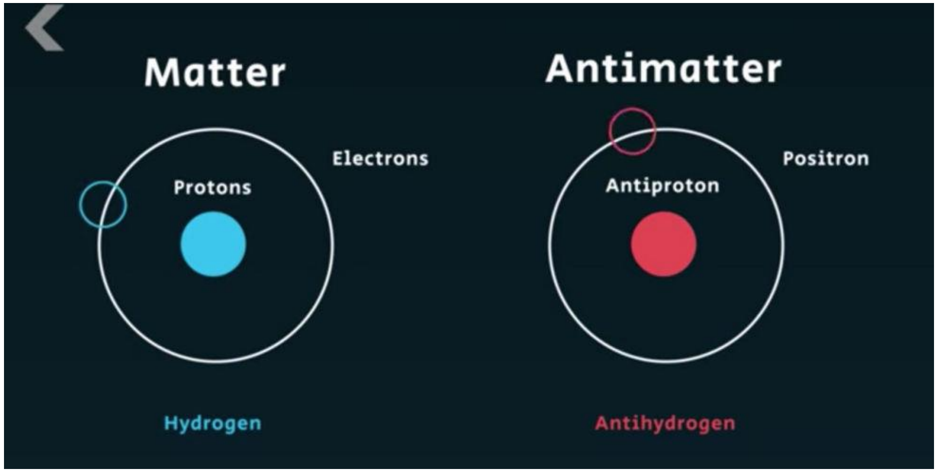
→**sub-K $\bar{\mathrm{H}}$ production becomes feasible with current** Ps **technology** (e^+ are 1822x lighter)

Goal for $\bar{\mathbf{H}}$: $T_{\bar{p}}$~10 mK limited by 100 K Ps momentum transfer to 100 mK $\bar{\mathrm{H}}$

J. Fesel et al., *Phys. Rev. A* **96**, 031401 (2017)

Stay tunes for ultracold antiproton and antihydrogen physics





Thank you very much for your attention!