Hyperfine Splitting in Highly-Charged Ions

Richard Thompson, Danny Segal
Blackett Laboratory
Imperial College London

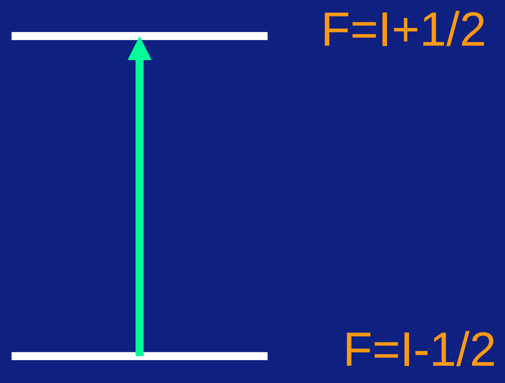
J. Krämer, W. Nörtershäuser,
M. Vogel, D. Winters
GSI

Outline

1. What is the purpose of the experiment?
2. How will the measurement be made?
3. What techniques will be applied?
4. Why is space charge important?
5. Conclusions

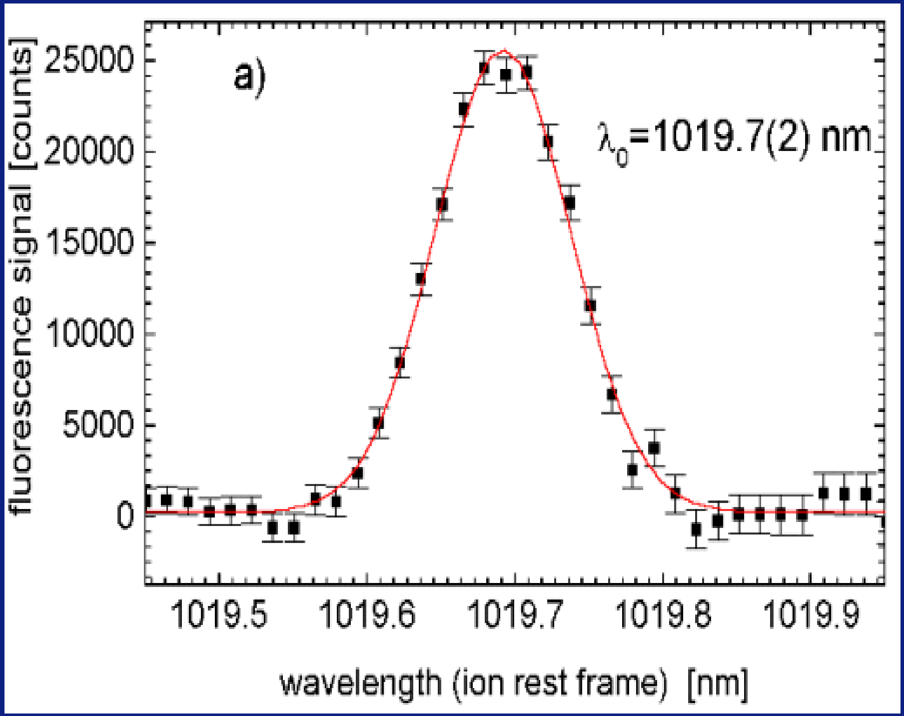
What is the purpose of the experiment?

- To study hyperfine structure in the ground state of hydrogen-like highly charged ions
  - High-order QED effects in strong electromagnetic fields
  - Nuclear polarisation also has an effect
  - Measurement in H-like and Li-like ions separates QED
- Ground state HFS splitting proportional to Z^3
  - Hydrogen: 1400 MHz (21 cm)
  - H-like lead: 300 THz (1.02 µm)



How will the measurement be made?

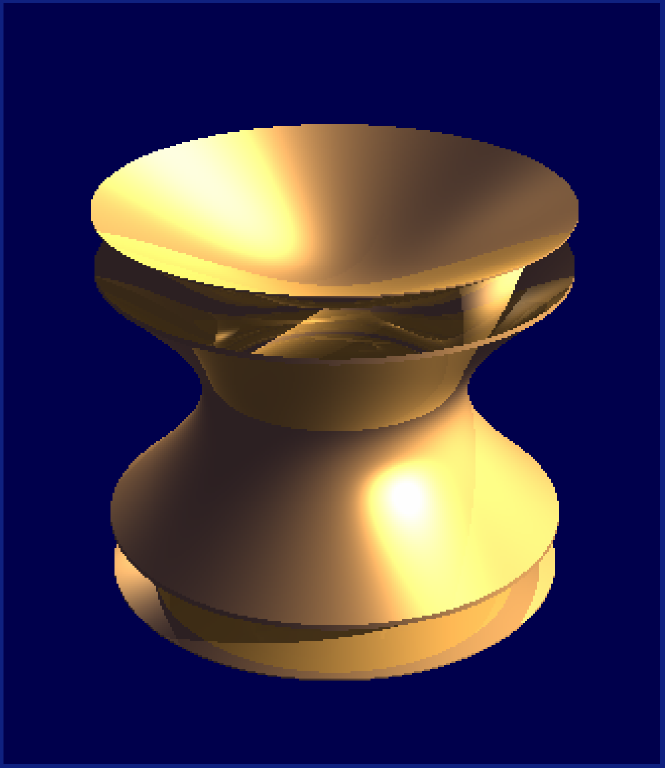
- For $Z > 70$ the ground state HFS splitting can be reached with lasers directly
- Laser spectroscopy is a good technique to use
  - Highly sensitive
  - High precision
  - Non-invasive
  - Non-destructive



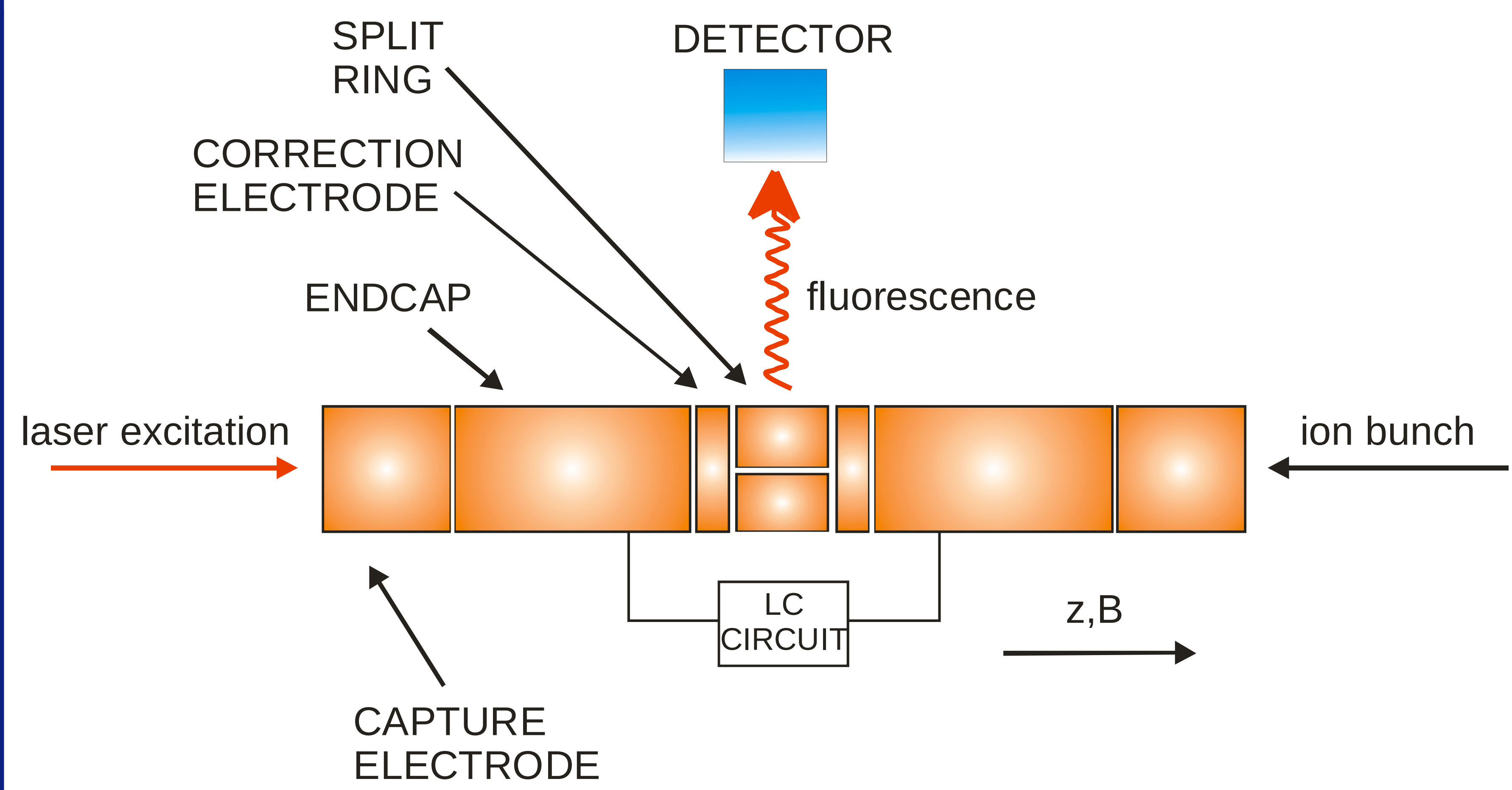
Earlier GSI measurement
in beam of hydrogen-like lead

What techniques will be applied?

- We will store HCI from HITRAP in a cryogenic Penning trap
  - Long ion lifetime in trap
  - Very clean environment
  - No Doppler shift as in ion beam experiments
  - Good for laser spectroscopy
- For good signal/noise we need
  - Low Doppler width: **Cold ions**
  - Large ion number: **High Density**
- ***See Danyal Winters' and Manuel Vogel's talks for trap details***



Schematic of the Experiment

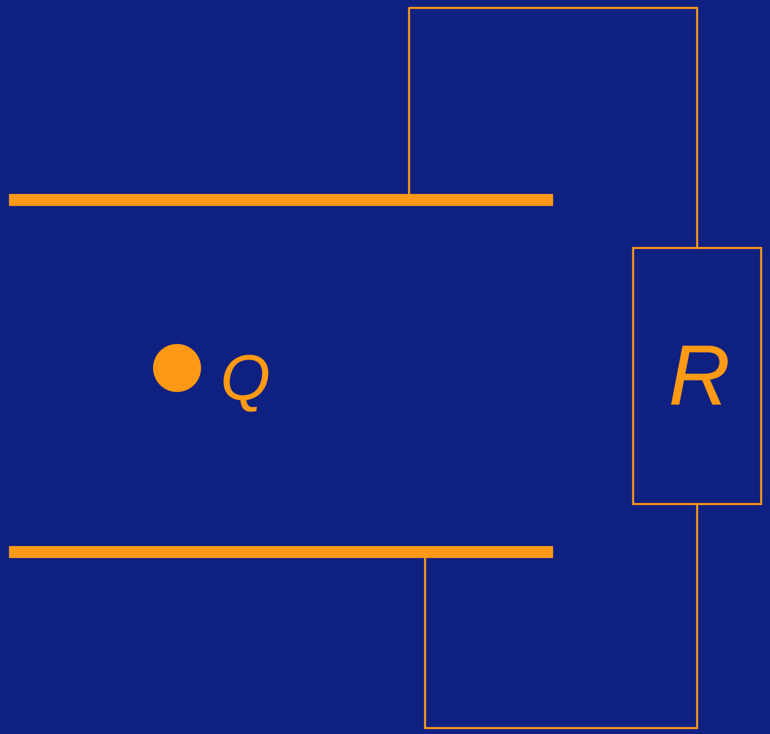


Need for cold ions

- Doppler width at 300 K is 250 MHz
  - Limits resolution
  - Reduces maximum signal
- Doppler width at 4 K is 30 MHz
  - At 4K lifetime of ions is also much longer
- Needs cryogenic vacuum system and resistive cooling of ion cloud
  - Then expect signals of several thousand counts per second

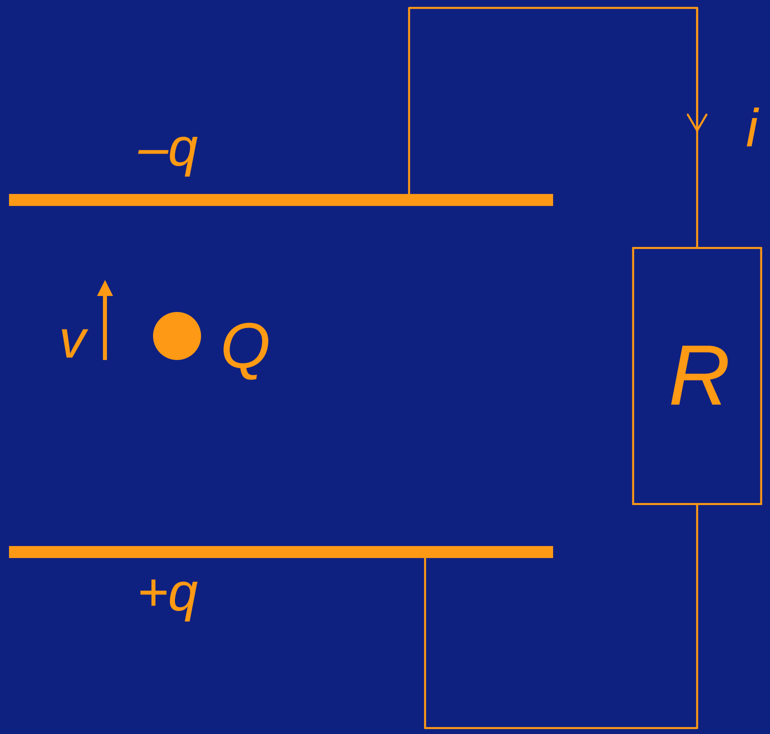
Resistive cooling

- A single ion induces an image charge in the two endcaps of the trap



Resistive cooling

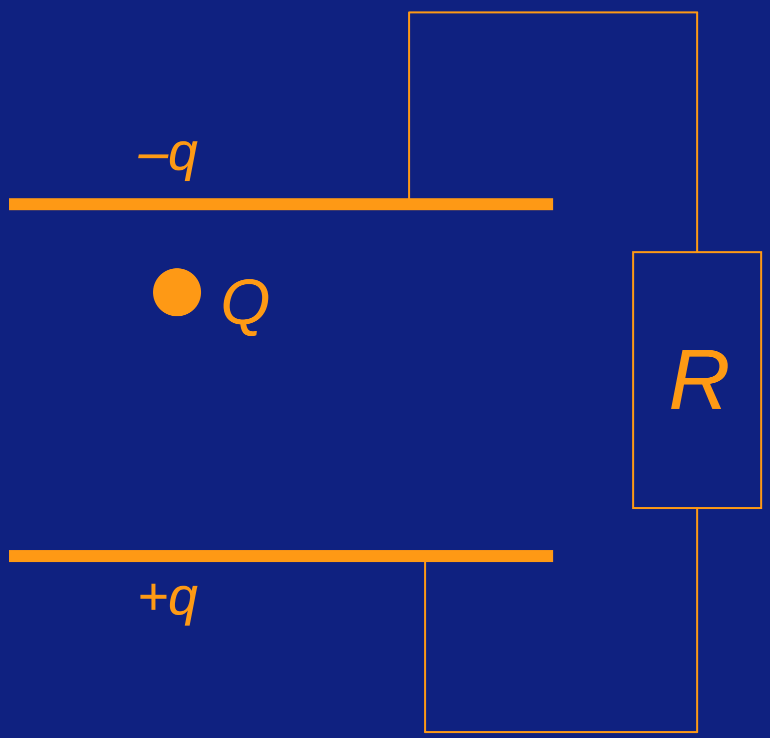
- A single ion induces an image charge in the two endcaps of the trap
- Motion of the ion gives
  - – Current in external circuit
    - Dissipates energy
  - – Potential across endcaps
    - Provides damping force on ion



Circuit is normally made to be resonant at axial oscillation frequency of ions

Resistive cooling

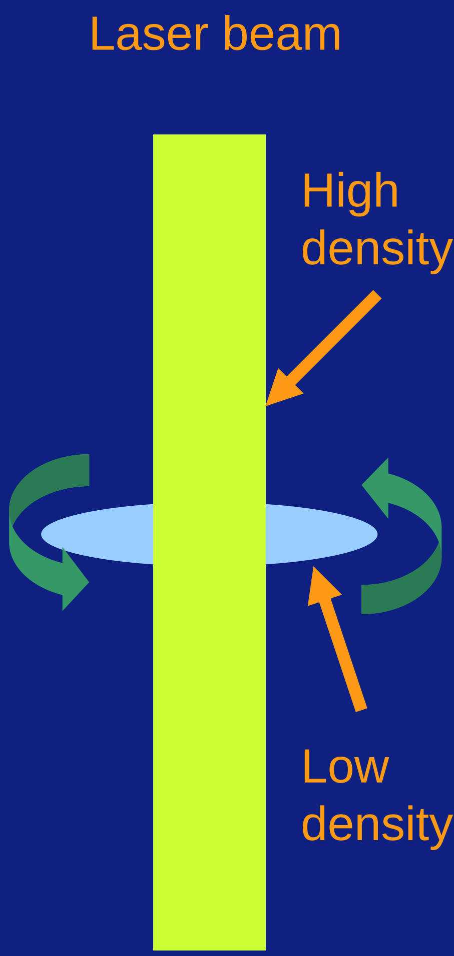
- A single ion induces an image charge in the two endcaps of the trap
- Motion of the ion gives
  - Current in external circuit
    - Dissipates energy
  - Potential across endcaps
    - Provides damping force on ion
- In equilibrium ion has same temperature as the resistor



q depends linearly on the ion displacement from trap centre

Need for high density

- About 10^5 ions available per pulse
  - Need maximum overlap with laser beam
  - High density to bring all ions within beam diameter
- Needs use of rotating wall technique:
  - Stops ion cloud spreading out in radial direction
  - Increases density by spinning cloud to higher rotation frequencies
- Space charge effects come into play at high densities

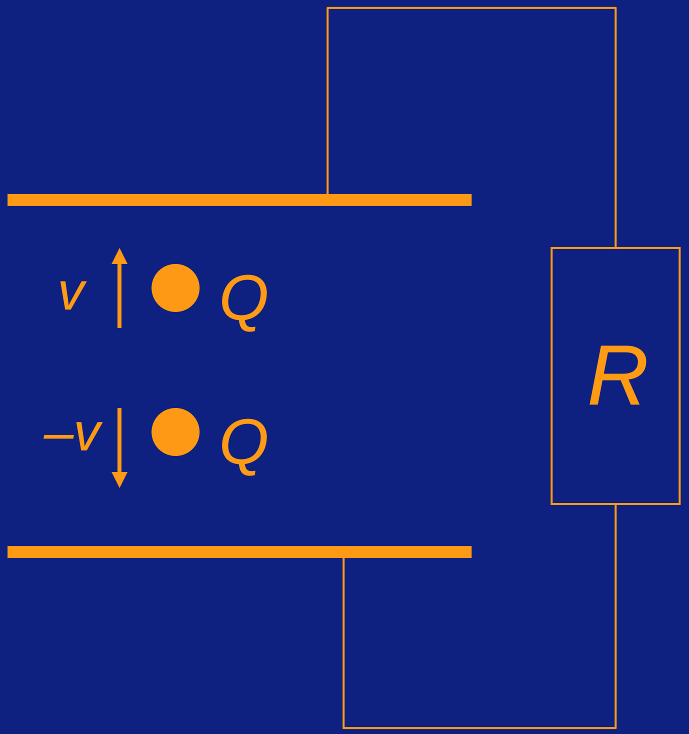


Why is space charge important?

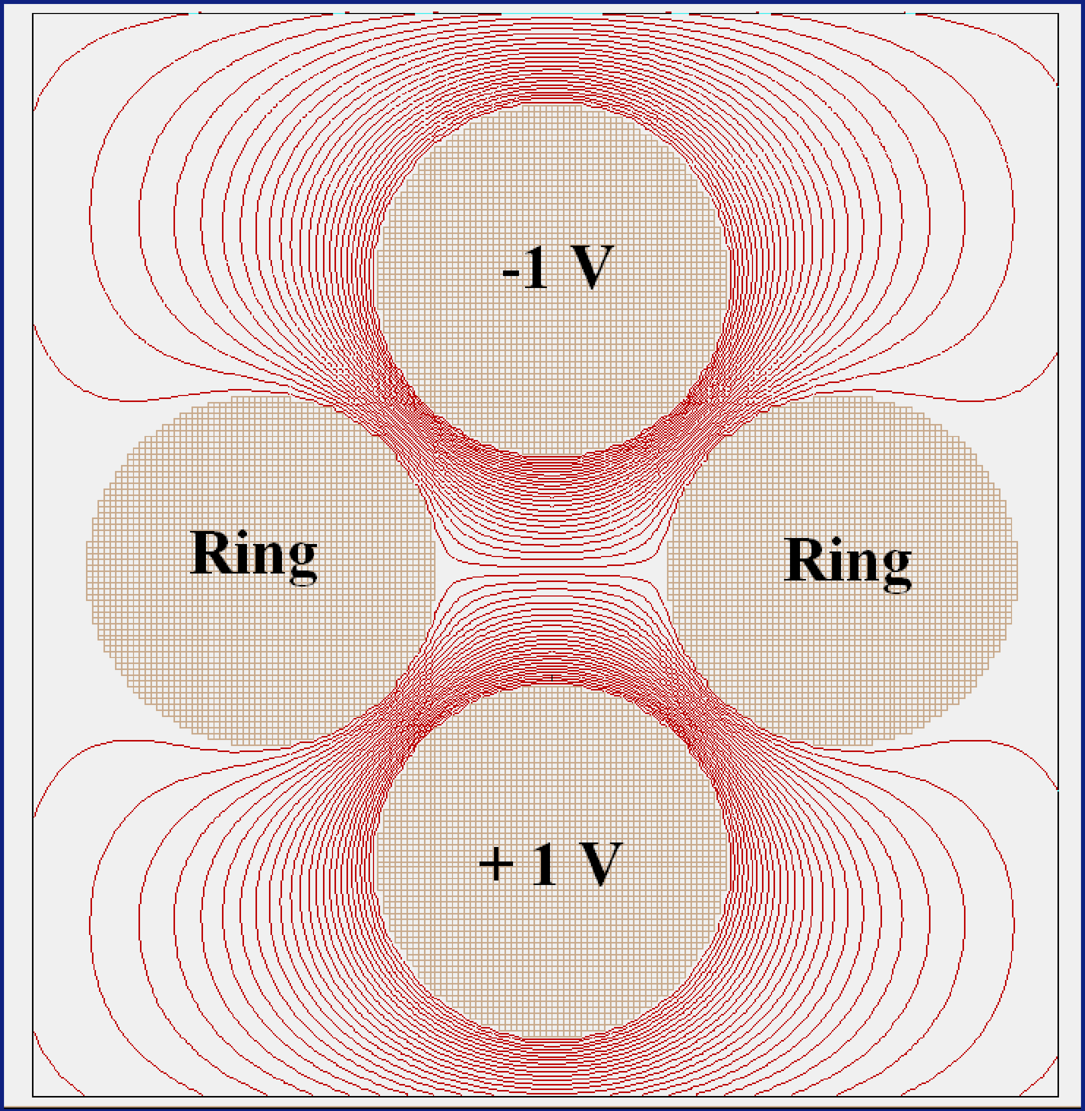
- Resistive cooling is effective for a single ion
  - And for the centre of mass mode of a cloud
- But space charge leads to flattening of potential curve at trap centre
  - Gives shifts of ion oscillation frequencies
  - Resonant external circuit only provides cooling over a narrow range of frequencies
  - At high densities cooling no longer effective

Why is space charge important?

- Also internal motions in a pure cloud do not induce a current in the electrodes
  - Therefore there is no cooling of internal modes
  - Need a mechanism for internal modes to couple to external circuit
    - Collisions with residual gas
    - Impurities in the cloud
    - Nonlinearities due to finite size of electrodes

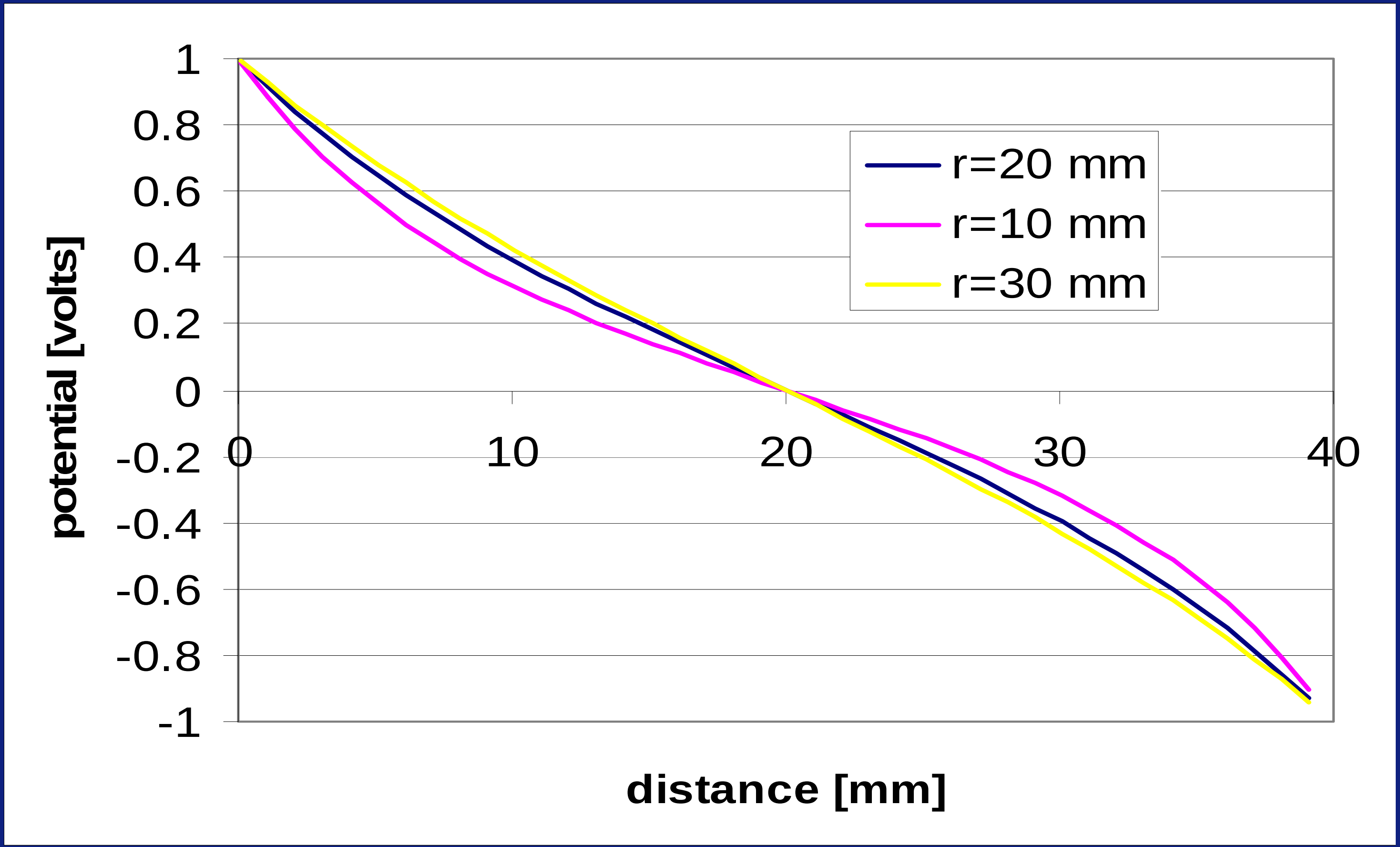


Resistive cooling with finite sized electrodes



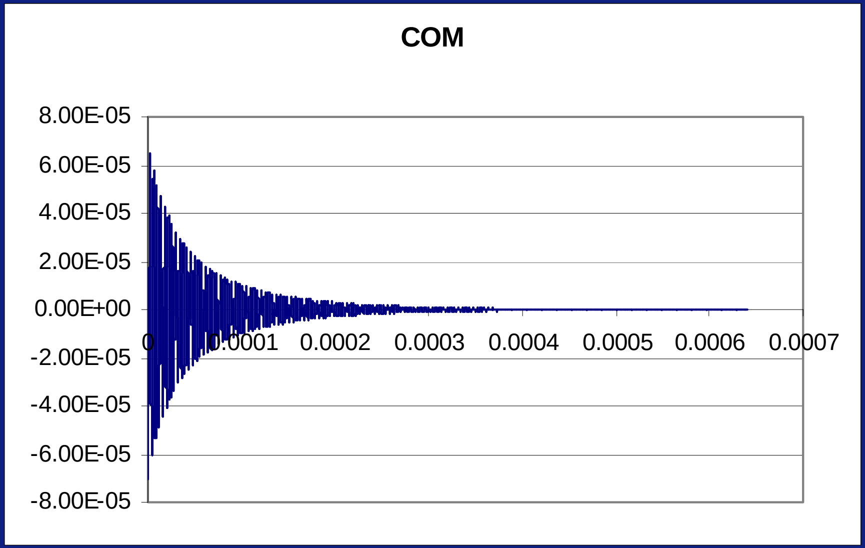
- Potential is steeper near electrodes than at trap centre
  - Hence image charge induced by moving charge has cubic term
  - Now sensitive to internal motions
  - But effect very small

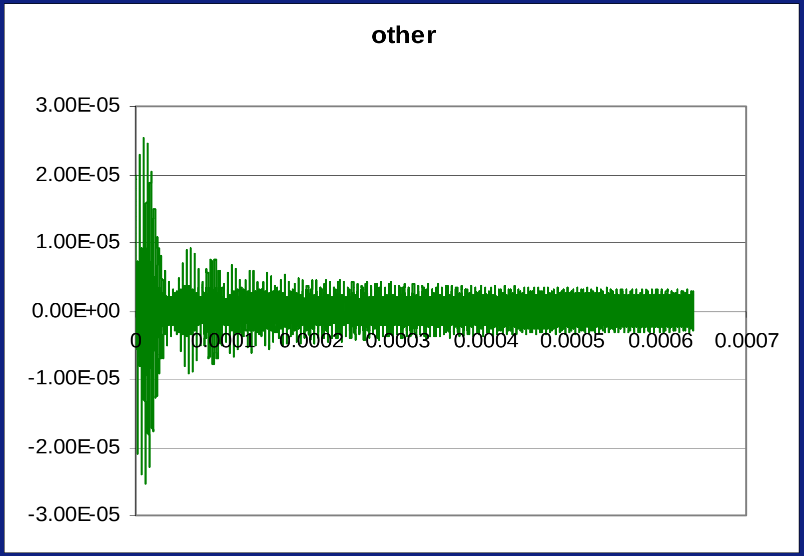
Resistive cooling with finite sized electrodes

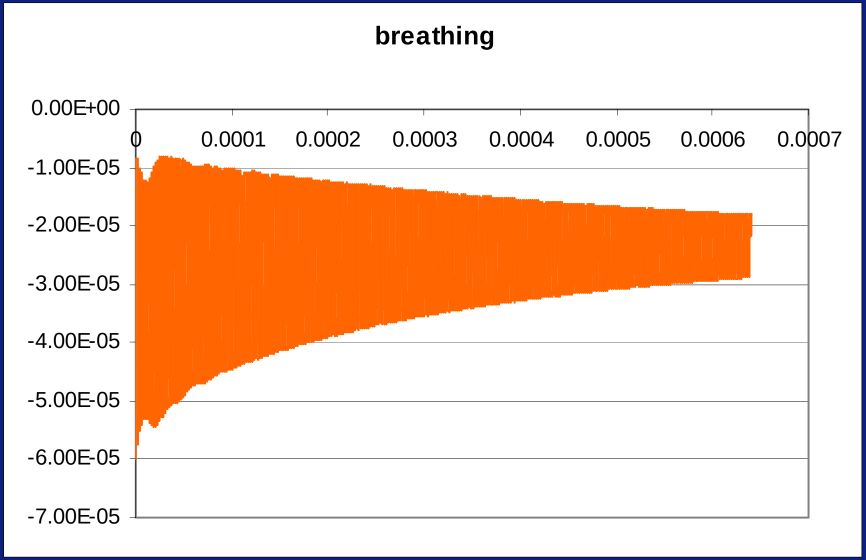


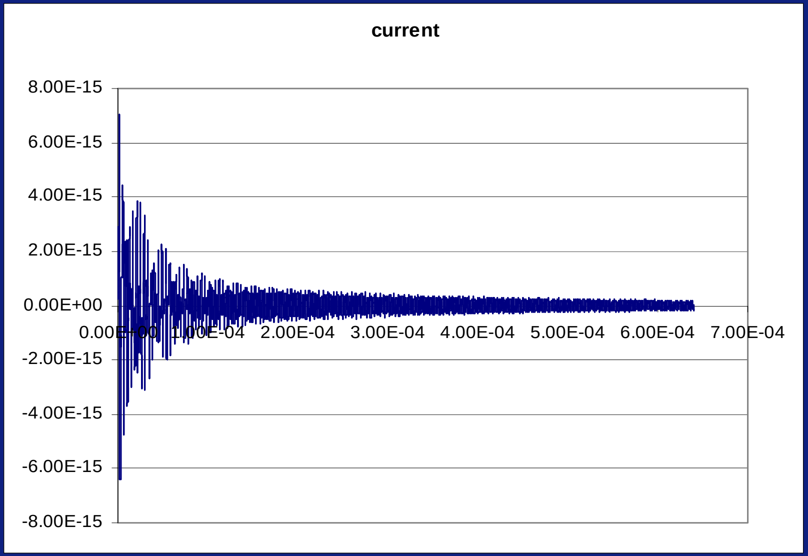
- Cubic term is bigger for small electrodes
  - But effect at trap centre is always small

Effect of nonlinear terms in the potential (3 ions, 1-D trap)





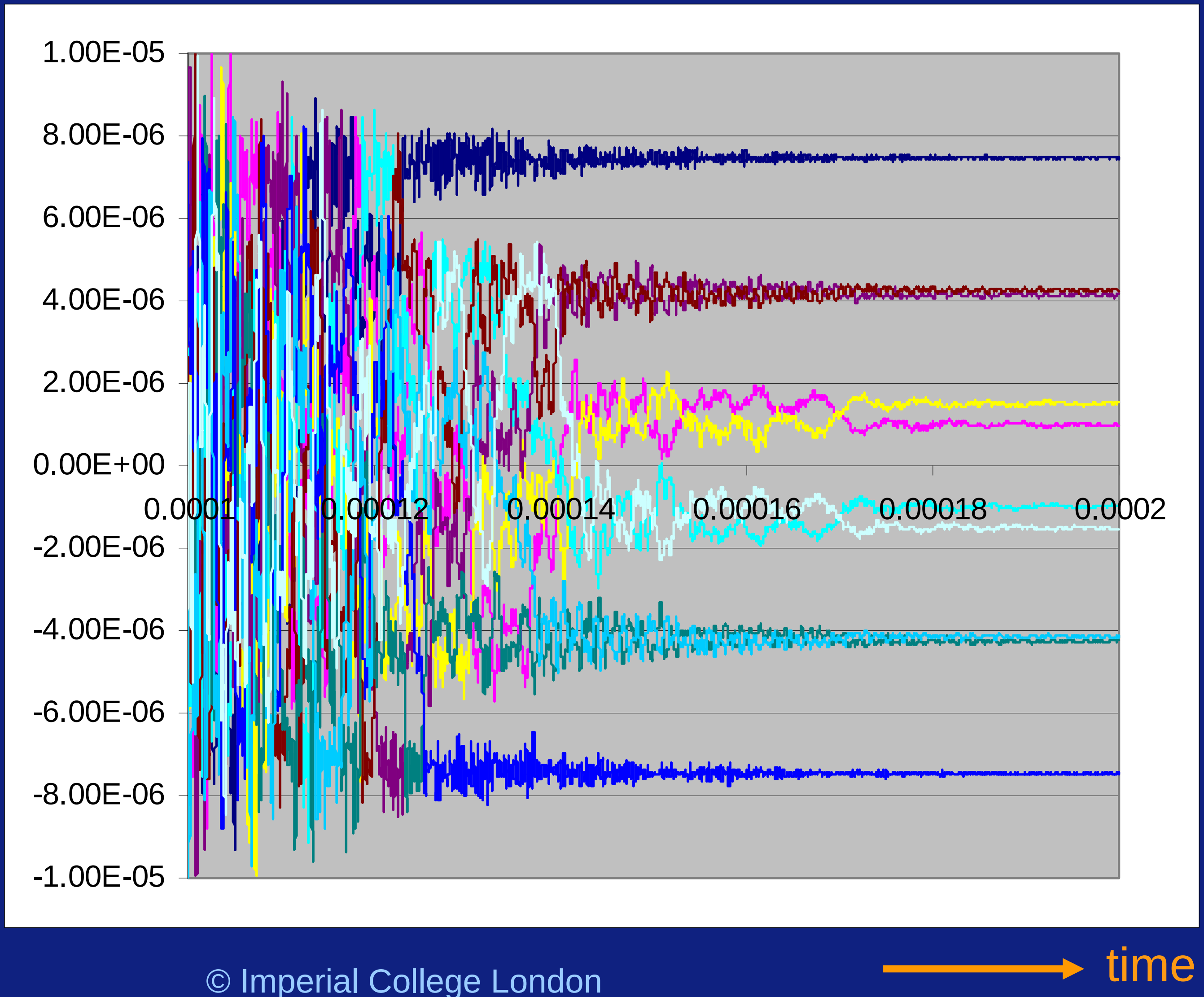




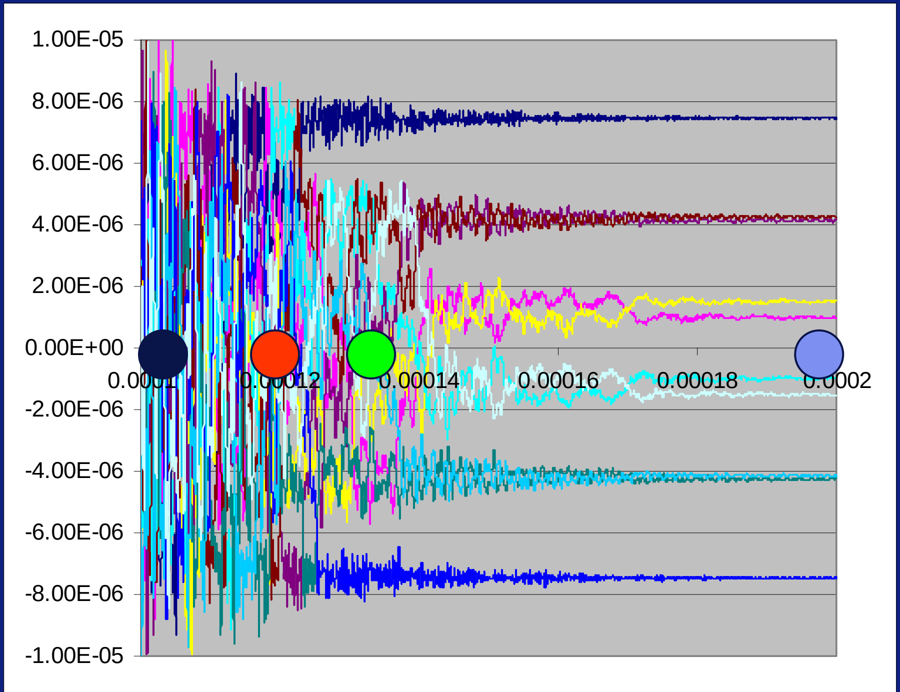
Effect of nonlinear terms in the potential (3 ions, 1-D trap)

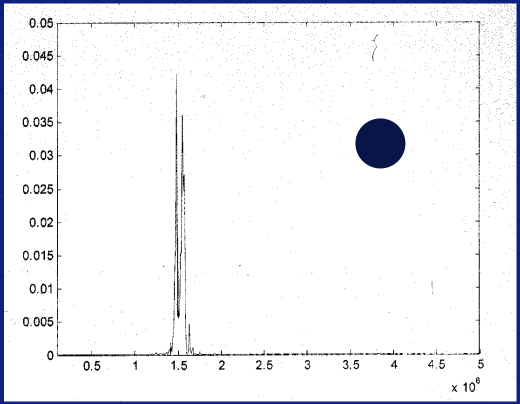
- Centre of mass mode cools quickly from linear term
  - Exponential decay
- Breathing mode needs quadratic term
  - e.g. from misalignment of trap
  - Cools slower and with power law decay
- Third mode needs cubic term
- Amplitude of current in circuit does not reflect true amplitude of motion

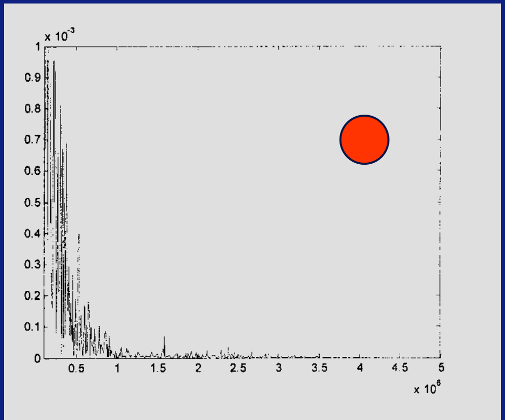
Cooling of cloud in 3-D (uniform damping)

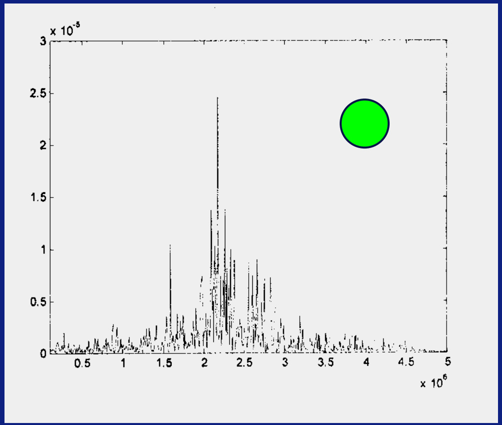


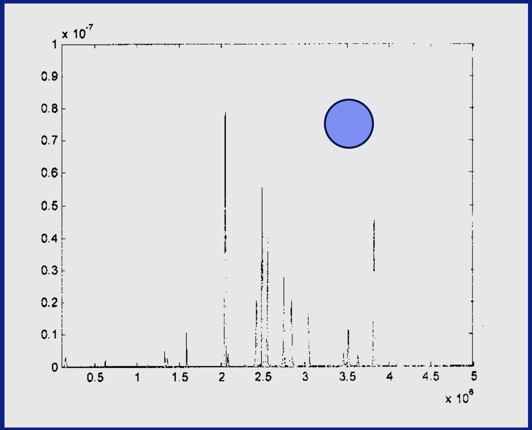
Frequency spectra of motion











Conclusions

- Spectroscopy of HFS splitting in HCI can yield new information on QED effects in strong fields
- Experiment needs cold ions and high densities
- Space charge effects must be considered carefully for effective cooling of all degrees of freedom of cloud