Imperial College London

Penning traps – lecture 2

Richard Thompson
Quantum Optics and Laser Science Group
Department of Physics
Imperial College London

Outline of lecture 2

Lecture 1: Penning Trap Basics

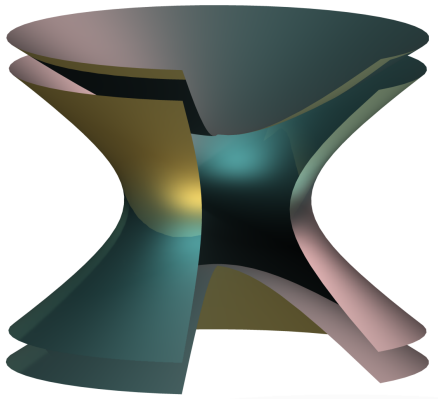
Lecture 2: Review of Experiments

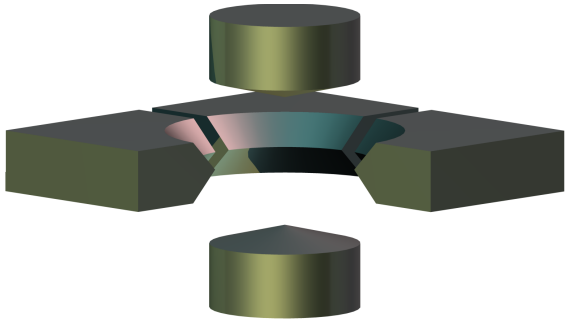
5. Designs of Penning Traps
6. Review of the types of experiments that use Penning traps

Lecture 3: Rotating Frame and Axialisation

5. Design of Penning traps

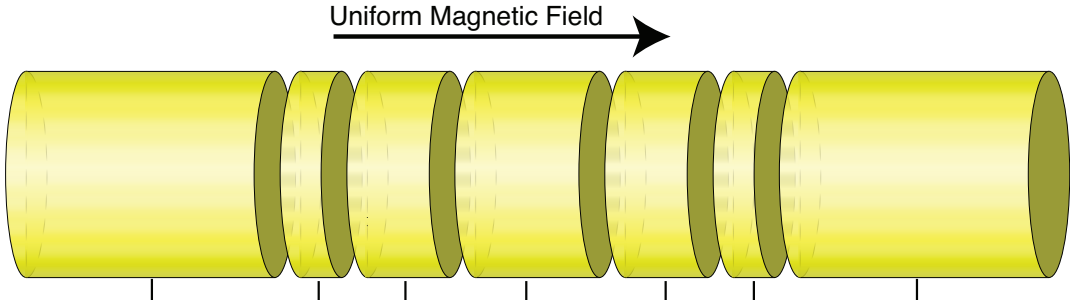
- The ideal trap electrode shape is difficult to manufacture
- Simple modifications make it easier to make:
  - Use a circular cross section surface rather than a hyperbola
  - Use angular cross section
  - These changes can be made in such a way that the effects on the potential are minimised
- A more radical change is to use cylindrical electrodes





Cylindrical electrodes

- Gabrielse showed many years ago that you can use a stack of open cylindrical electrodes to generate a pure quadrupole potential (i.e. to eliminate higher order terms)
  - Generally you need to use more than 3 electrodes
  - You need to choose the length of the electrodes carefully

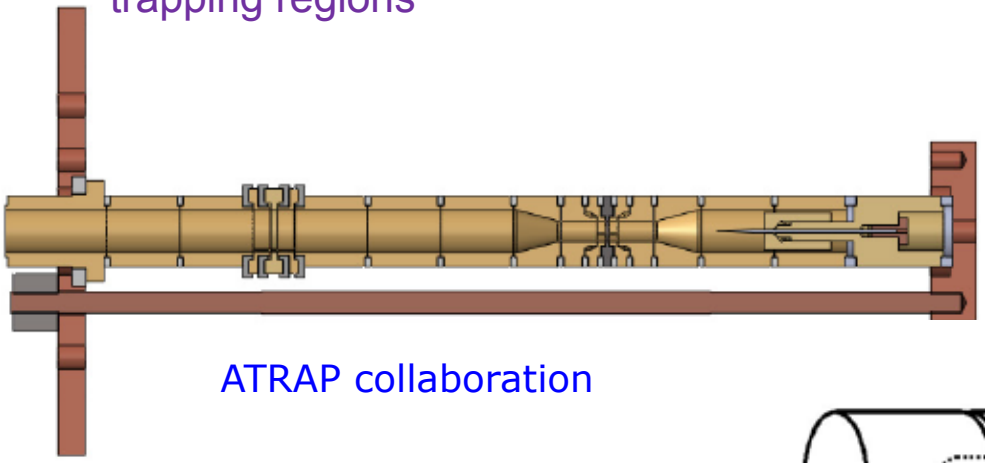


Alpha collaboration

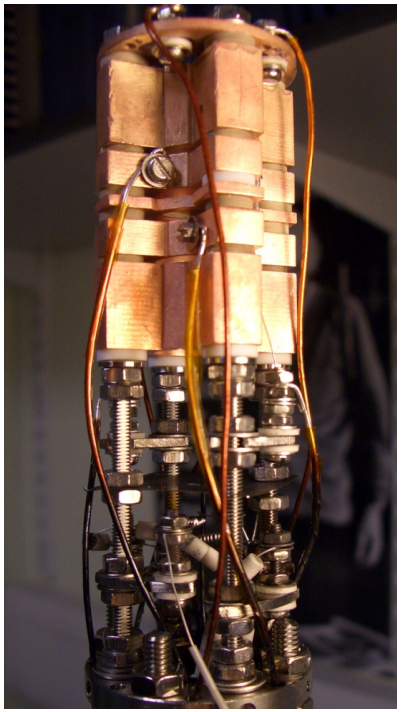
- Many groups use this type of design now
  - Easy access along the field lines
  - Simple to manufacture
  - Potential can be fine-tuned using the additional correction electrodes

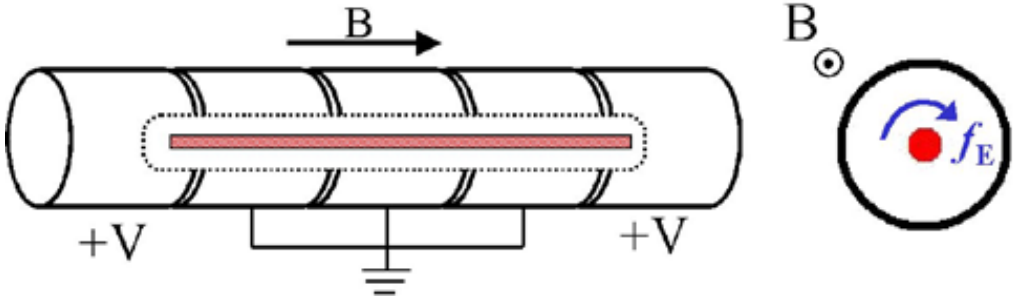
Cylindrical electrode geometries

- Many different geometries are possible with cylindrical Penning traps
- They are well adapted for use with superconducting magnets
  - Particles can be transported between different trapping regions



ATRAP collaboration

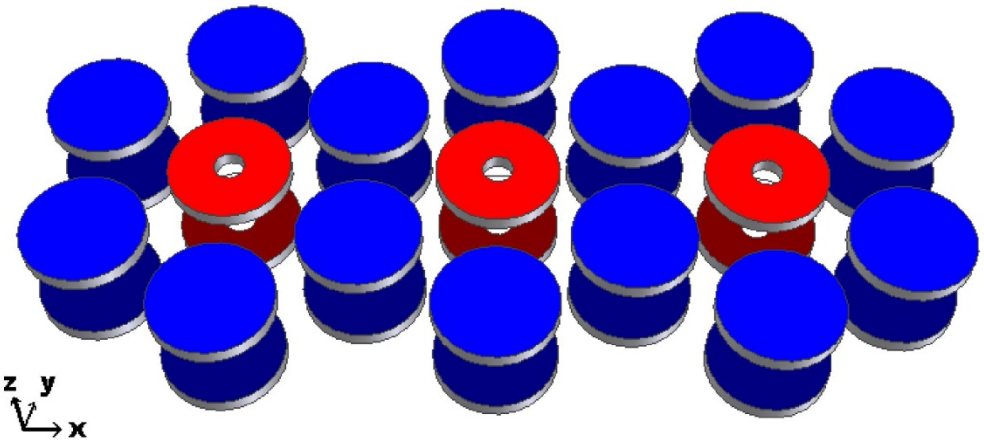


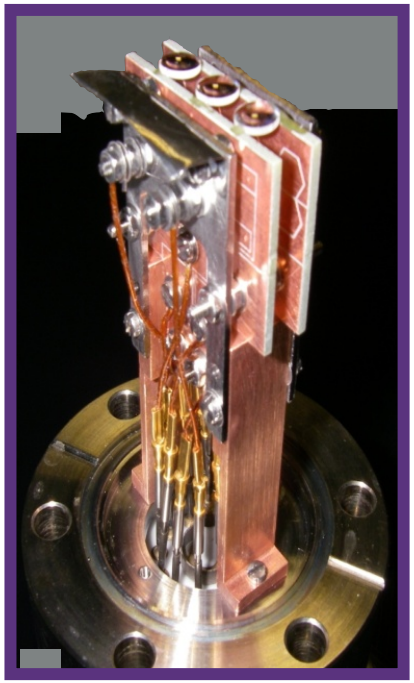


Penning-Malmberg trap (Surko)

Planar electrodes

- This is the opposite extreme: electrodes arranged on a plane (or two planes) perpendicular to **B**
  - Again, the shape and size of the electrodes can be adjusted to optimise the generated potential

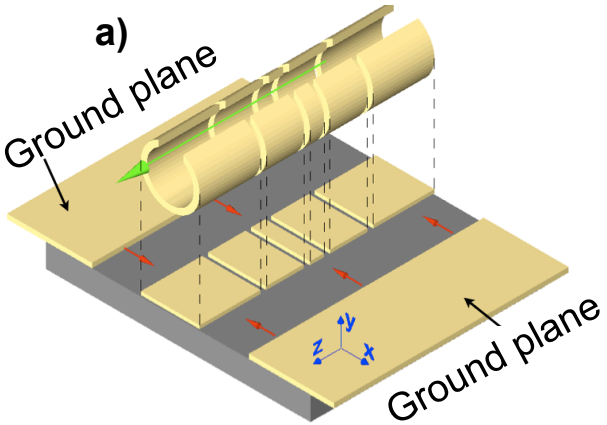


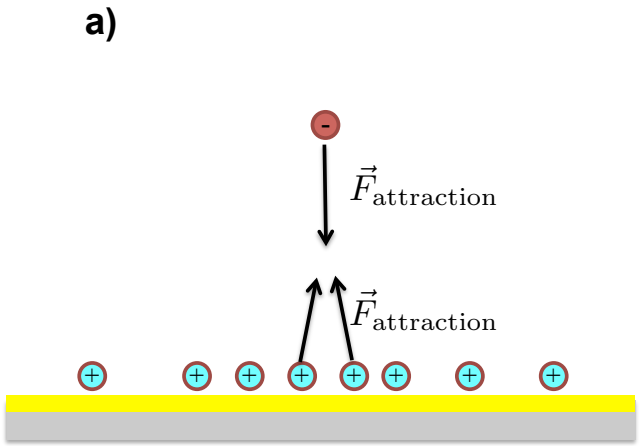


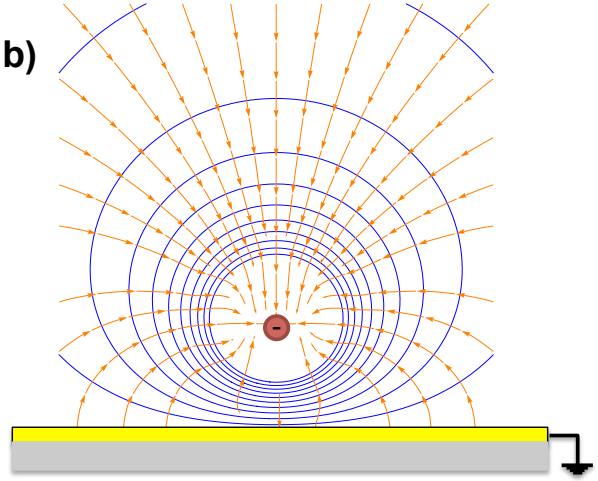
Imperial College
"pad trap"

Co-planar waveguide (CPW) trap

- In this device planar electrodes are used to make a trap for electrons whose axis is parallel to the surface
- The magnetic field is generated using conductors on the surface
- To be used for experiments in circuit QED







Verdu group, Sussex

6. Review of experiments with Penning traps

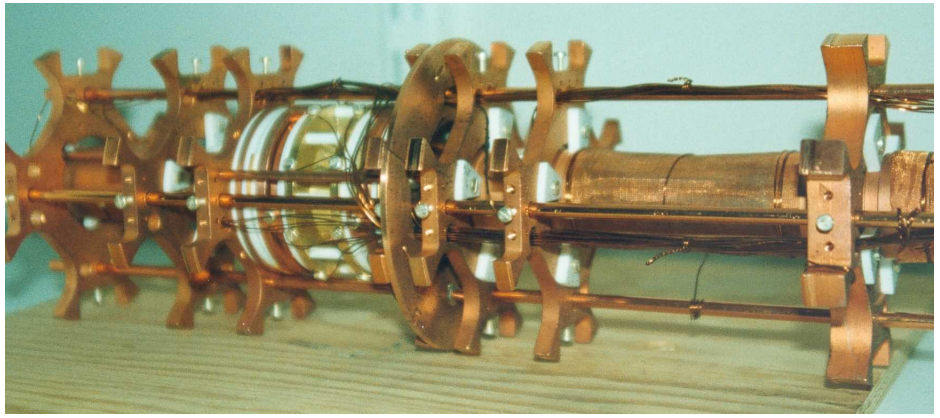
- "Classical"
  - Mass spectrometry
  - Electron $g-2$
  - Non-neutral plasmas
  - Antihydrogen production
- "Quantum"
  - Quantum jumps
  - Quantum Information
- Laser cooling
  - Doppler cooling
  - Sideband cooling
  - Sympathetic cooling
  - Spectroscopy
  - Ion Coulomb crystals
- Frequency standards
  - High resolution spectroscopy
  - Microwave frequency standards

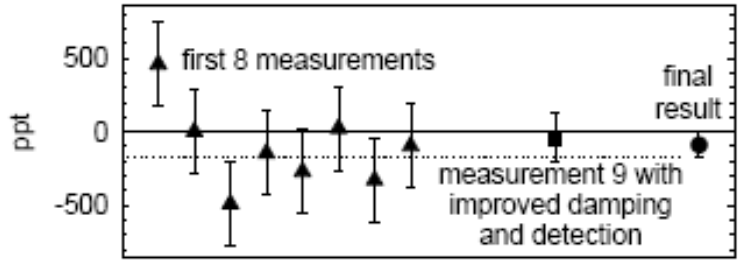
Mass spectrometry

- Since $\omega_c = qB/m$ we can in principle find m from frequency measurements:

$$\omega_c = \omega_c' + \omega_m \quad \text{or} \quad \omega_c^2 = \omega_c'^2 + \omega_z^2 + \omega_m^2$$

- Used for high precision measurements of nuclear masses
  - SMILETRAP (Stockholm)
  - ISOLTRAP (CERN)
  - Typically 10^{-9} accuracy
    - » Even for unstable nuclei
- Proton/antiproton mass
  - Gabrielse group – 10^{-11}

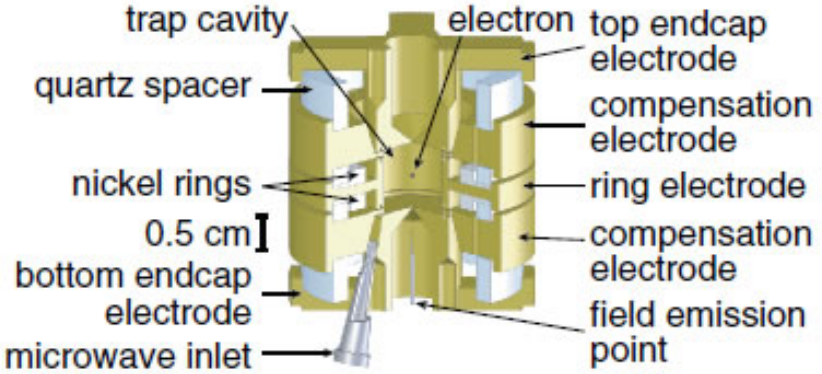




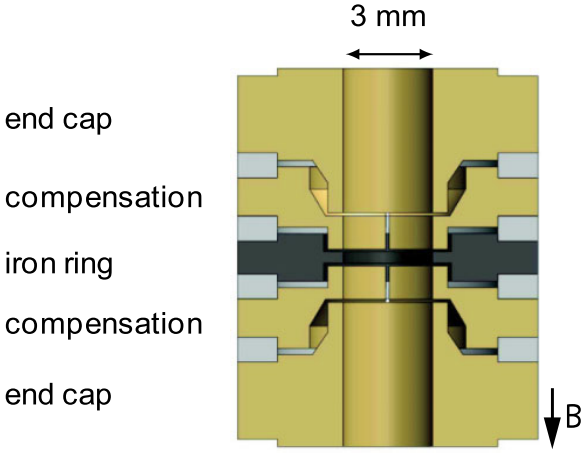
You can even "weigh" the 1S ground state Lamb shift in a heavy hydrogen-like ion this way

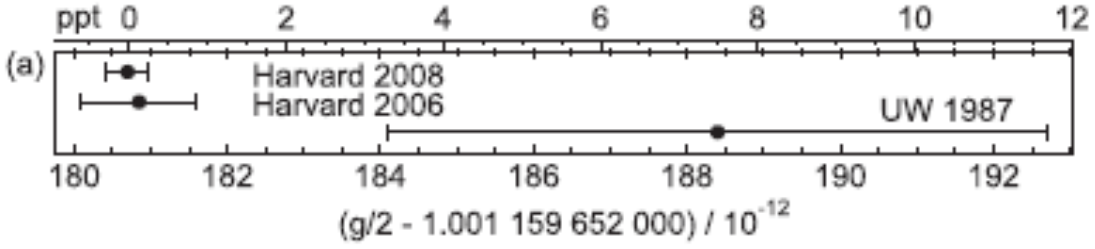
$g-2$ measurements – free electrons

- One electron in a Penning trap (Gabrielse 2008)
- Compare the cyclotron and spin-flip frequencies
  - $(g-2)/2$ determined to 0.3 ppb
  - Highest accuracy for a fundamental constant
- Result can be used to test QED or to determine α



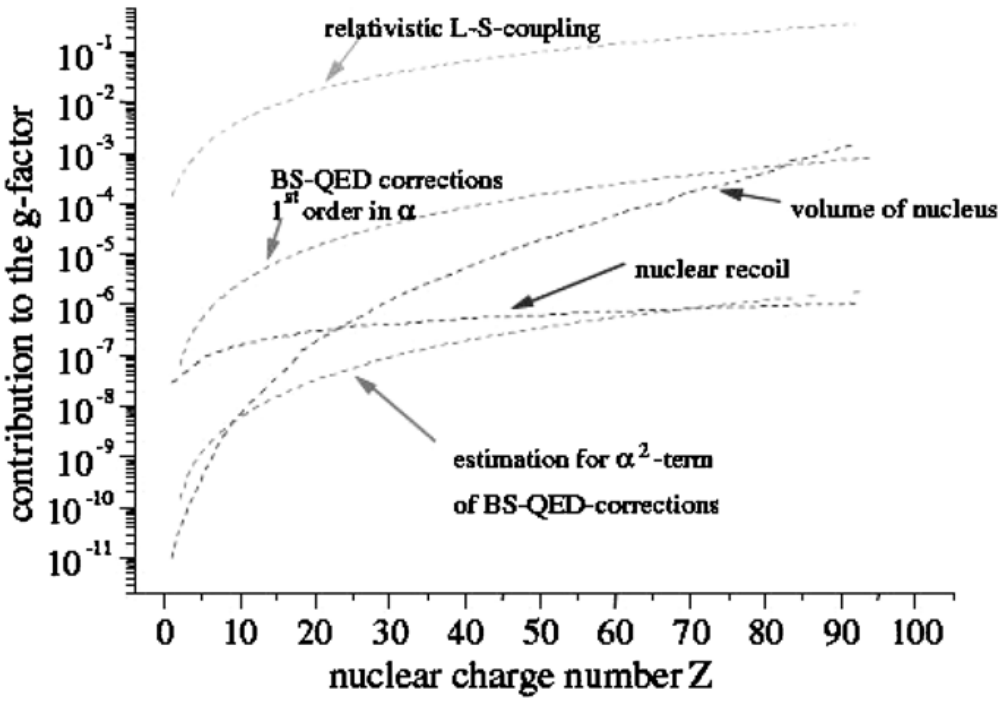
Also protons and antiprotons (ATRAP and BASE) [Ulmer]





g–2 measurements – bound electrons

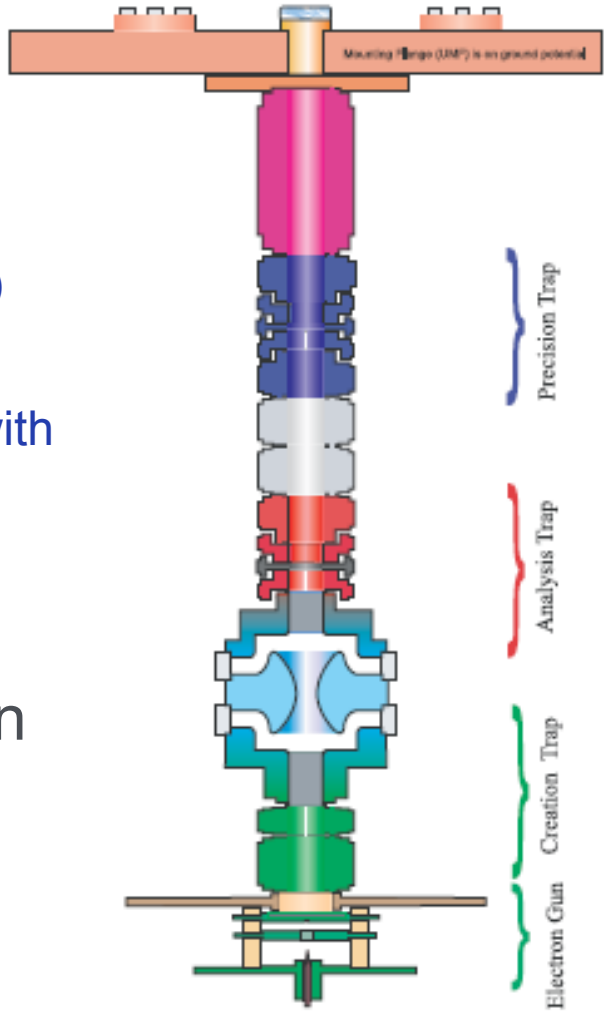
- In a hydrogen-like ion the free electron *g*-factor is modified by the presence of the nucleus
  - This is a QED effect dependent on *Z* and calculable
- Mainz group has studied a range of systems
  - C^{5+}, O^{7+}
  - 10^{-9} accuracy in *g*
  - < 0.25% test of QED terms
  - Or use to determine m_e
  - New plans for Si^{13+}, Ca^{19+}

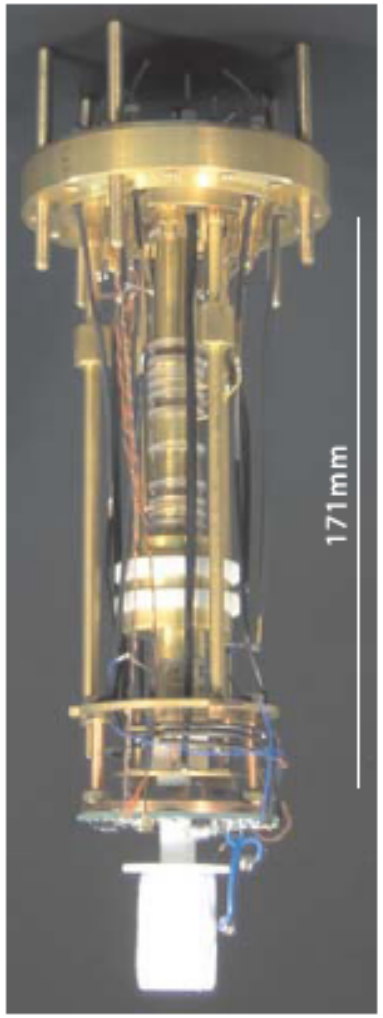


See lectures from Wolfgang Quint

Apparatus for *g*-factor experiment

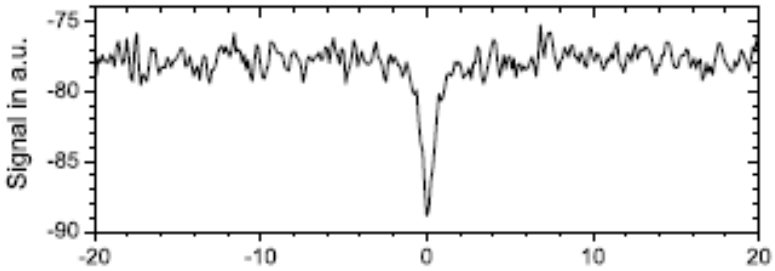
- Triple trap structure:
  - Creation trap
    - » Strip electrons to create Highly-Charged Ions (HCI)
  - Analysis trap
    - » Determine spin direction with inhomogeneous *B*-field
  - Precision trap
    - » Driving of the resonances
- Expect ~ ppb accuracy in HCI with *Z* up to 20 (Blaum et al 2009)



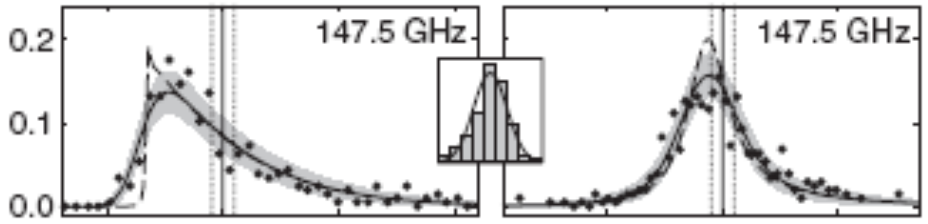


Why use Penning traps for these experiments?

- *B*-field of superconducting magnet is extremely stable
  - Long storage time allows repeated measurements
- Cryogenic electronics sensitive enough to detect motion of a single electron or ion
  - Use of single ion ensures no interactions between ions
- Frequency measurements inherently very accurate
  - Especially in the 10^7 to 10^{10} Hz region considered here
  - Most measurements reduced to *ratios* of frequencies



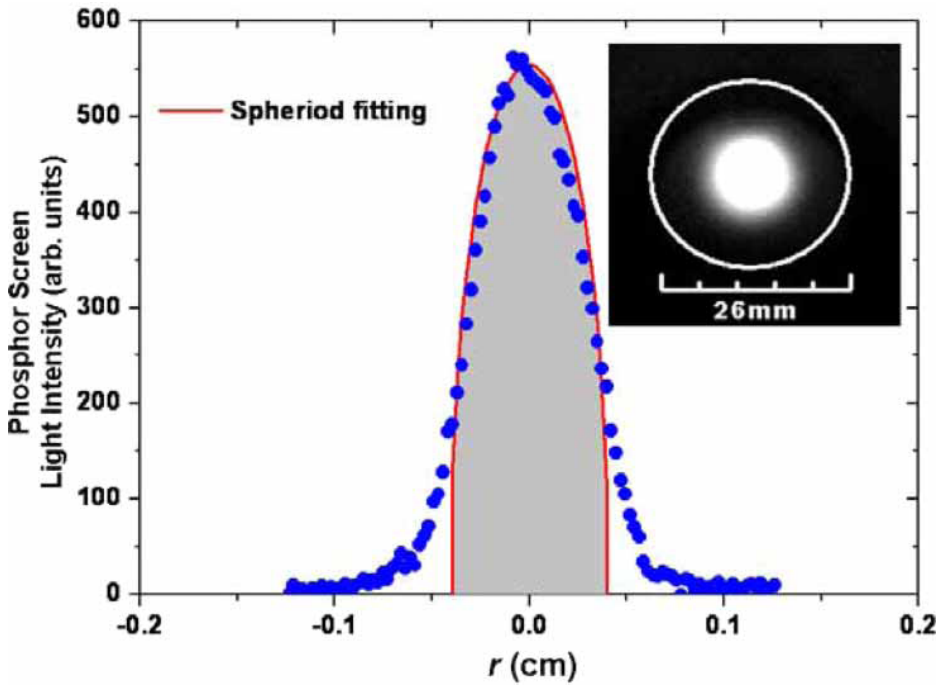
Single ion



Single electron

Non-neutral plasmas

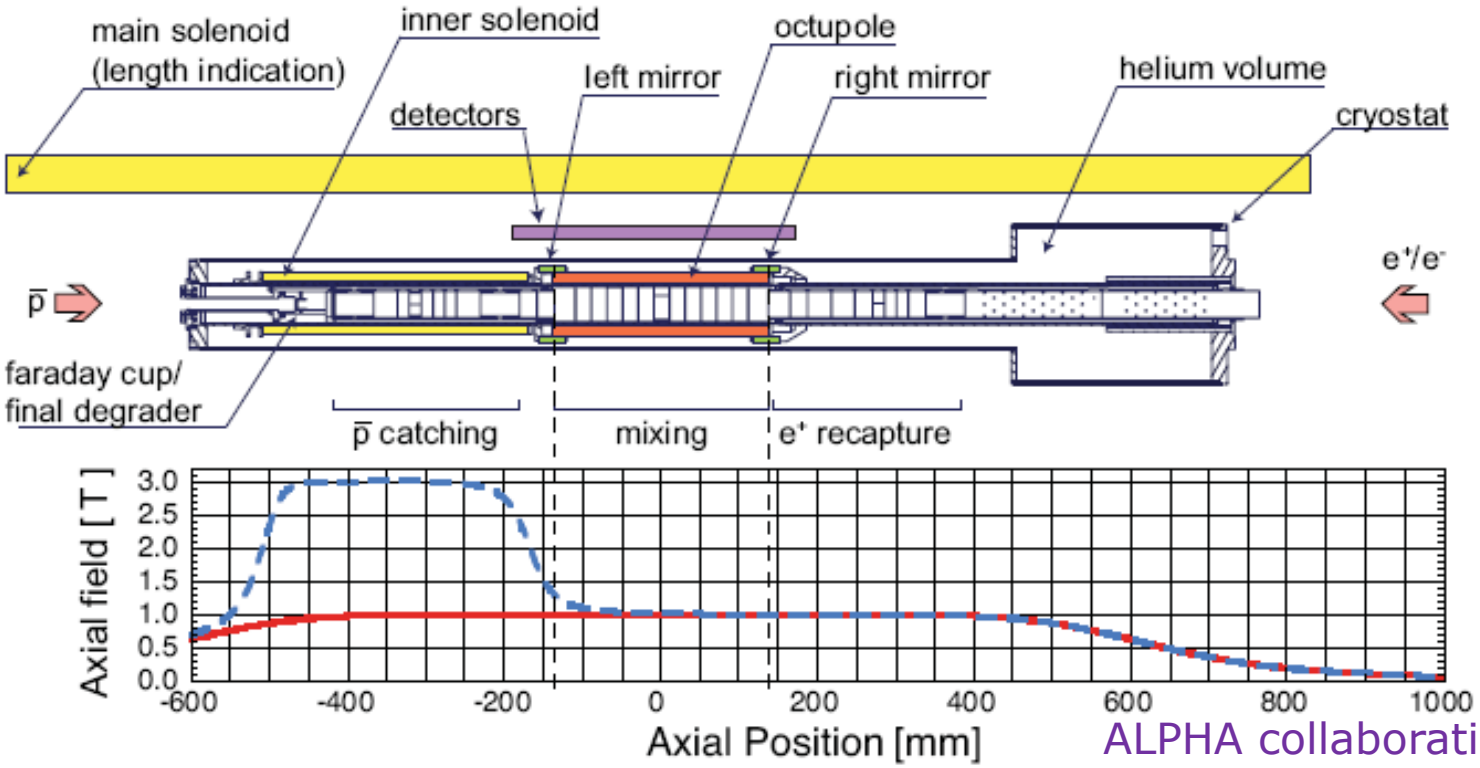
- With large numbers of ions an individual particle treatment of motion becomes inappropriate
  - Need to describe as plasma
  - Needs Debye length << cloud size
  - $\lambda_D^2 = \varepsilon_0 k_B T / ne^2 << r$
  - Then cloud has sharp edge
- Ions behave as if in uniform density of opposite charge
  - "single component plasma"
  - Rotates at a uniform rate ω_R
  - ω_R depends on the plasma density *n*



- A whole range of experiments with large, dense clouds in traps
  - Electrons / positrons (e.g. Mohamed 2008) [see other lectures here]
  - Ions (e.g. Be^+ at NIST: Bollinger et al 2003)

Antihydrogen production

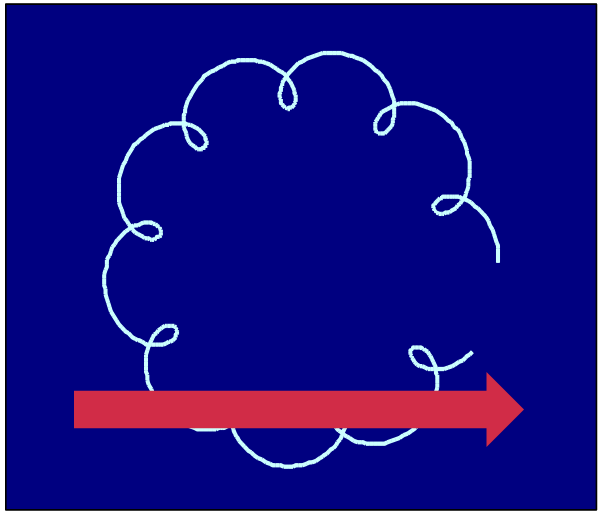
- Creation of antihydrogen requires accumulation of p^- and e^+
  - Slow production rate and low cross-section
- Penning traps well suited to this
  - ALPHA and ATRAP collaborations at CERN

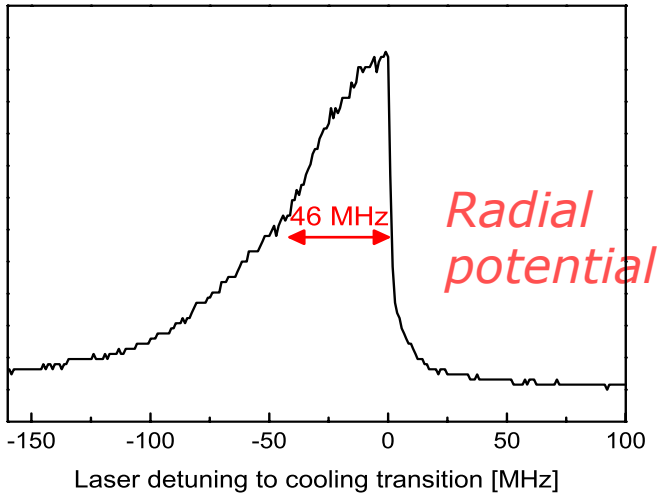


ALPHA collaboration

Laser cooling in the Penning trap

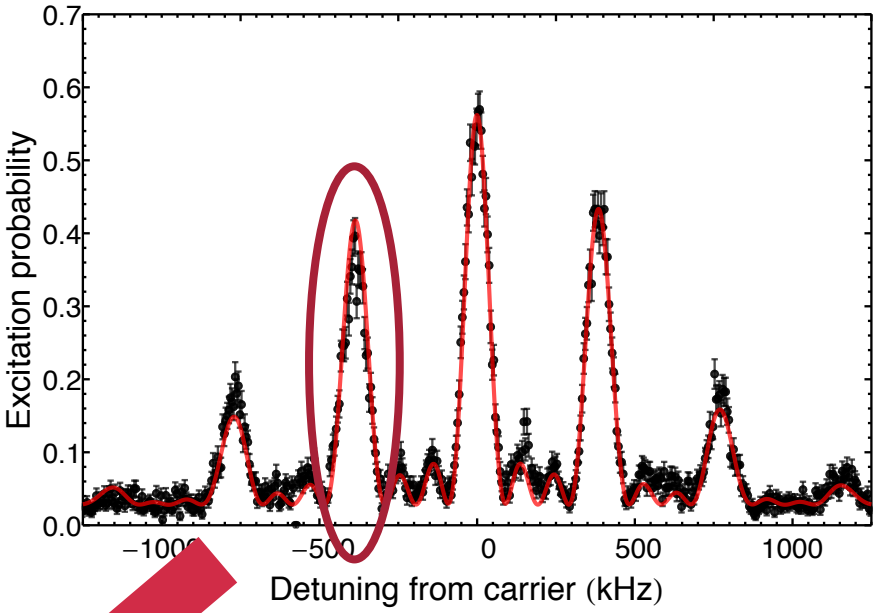
- In the Penning trap the ions are in an orbit around the trap centre
  - Magnetron motion has negative total energy
  - To cool both cyclotron and magnetron motions the laser must be offset from trap centre
    - To the side where the ions go *away* from the laser
  - Magnetron motion is always cooled less effectively than cyclotron
- Tight localisation is difficult
- But cooling still works well

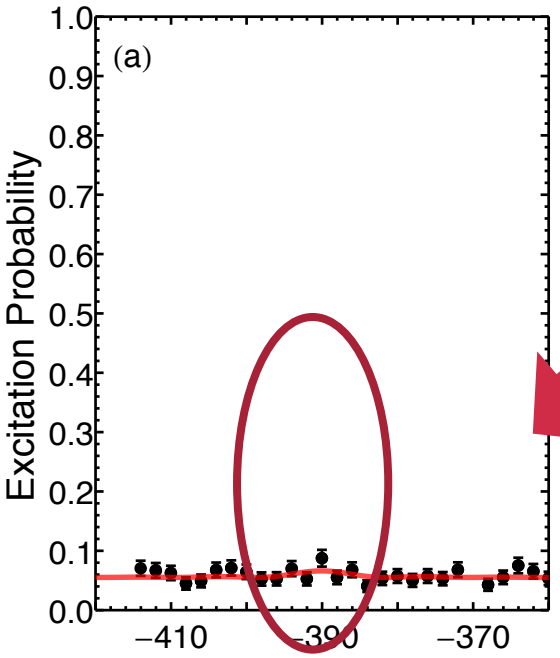




Sideband spectra in the Penning trap

- Doppler cooling takes the axial temperature to ~1mK
  - Measured here on a forbidden transition
  - Optical sidebands from motion in the axial potential well

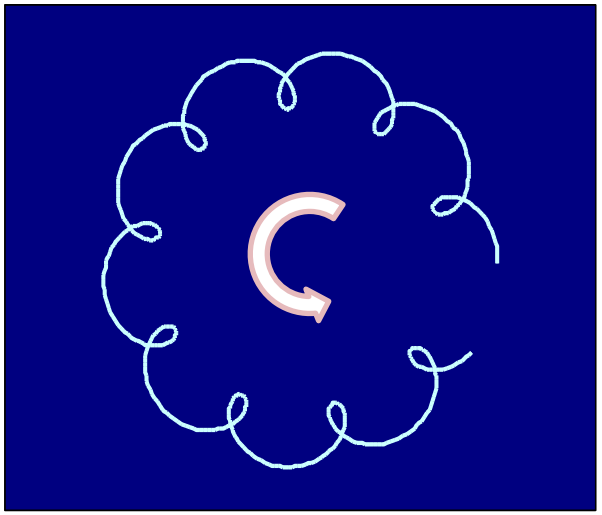




- Optical sideband cooling takes the ion into the ground state of its motion
  - Ground state occupation 99%

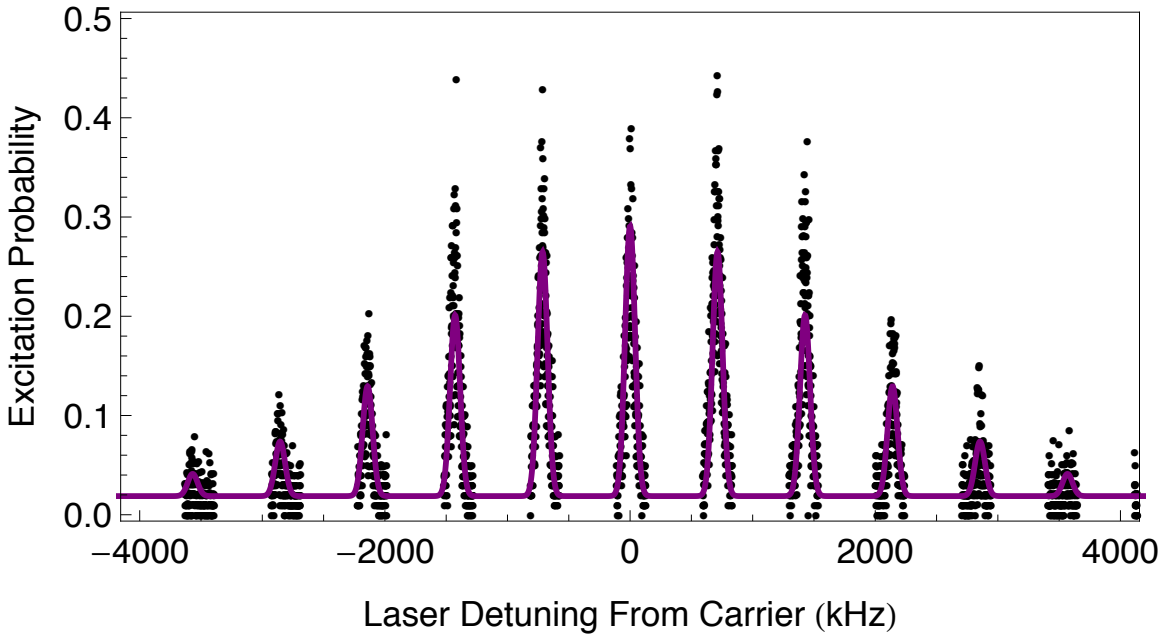
Radial spectrum in the Penning trap

- The radial spectrum is expected to be more complicated:
  - We should see sidebands due to both the cyclotron and the magnetron motions
  - Therefore expect many sidebands
  - If the motions are at a similar temperature the sidebands will overlap strongly



Radial spectrum at low potential

- The (fast) cyclotron motion gives rise to sidebands
- The ~4 MHz FWHM corresponds to a cyclotron temperature of ~7 mK
- Each cyclotron sideband has structure due to the magnetron motion
  - but individual sidebands are not resolved here

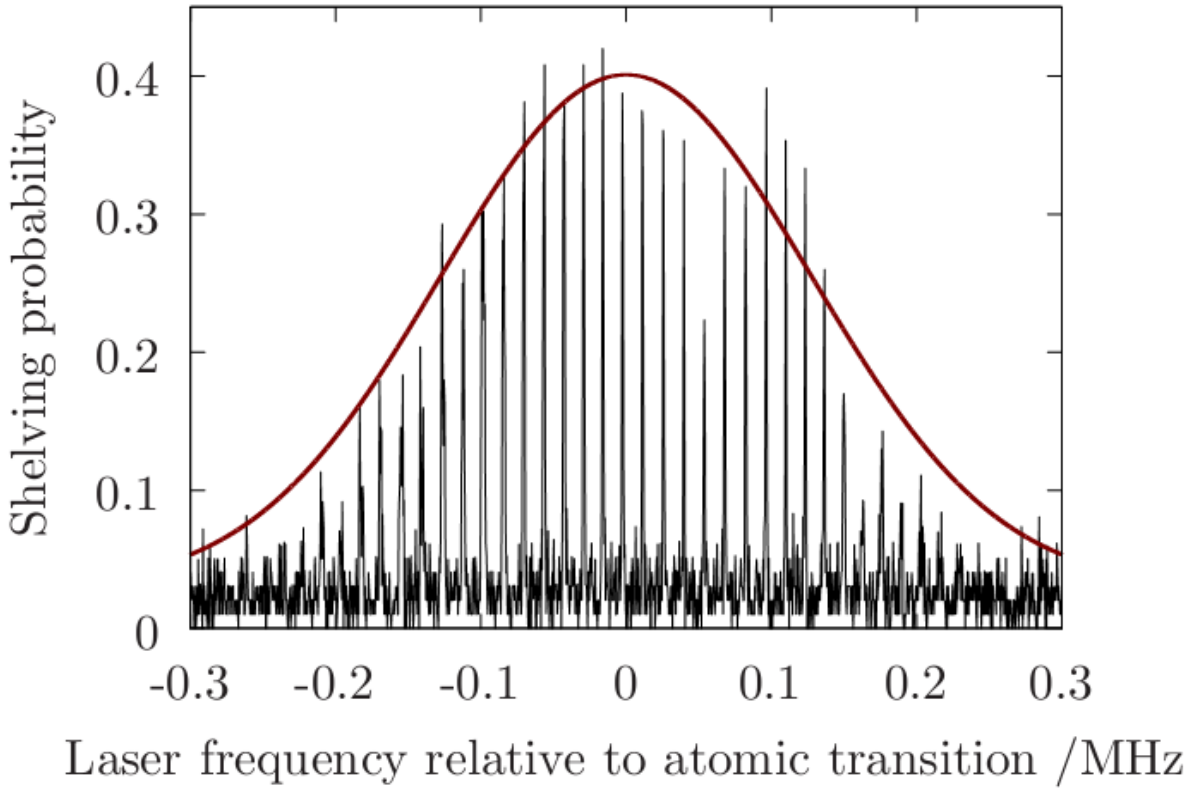


The narrow width of the magnetron structure demonstrates that its "temperature" is very low

See Mavadia et al
*Phys. Rev. A **89**, 032502*

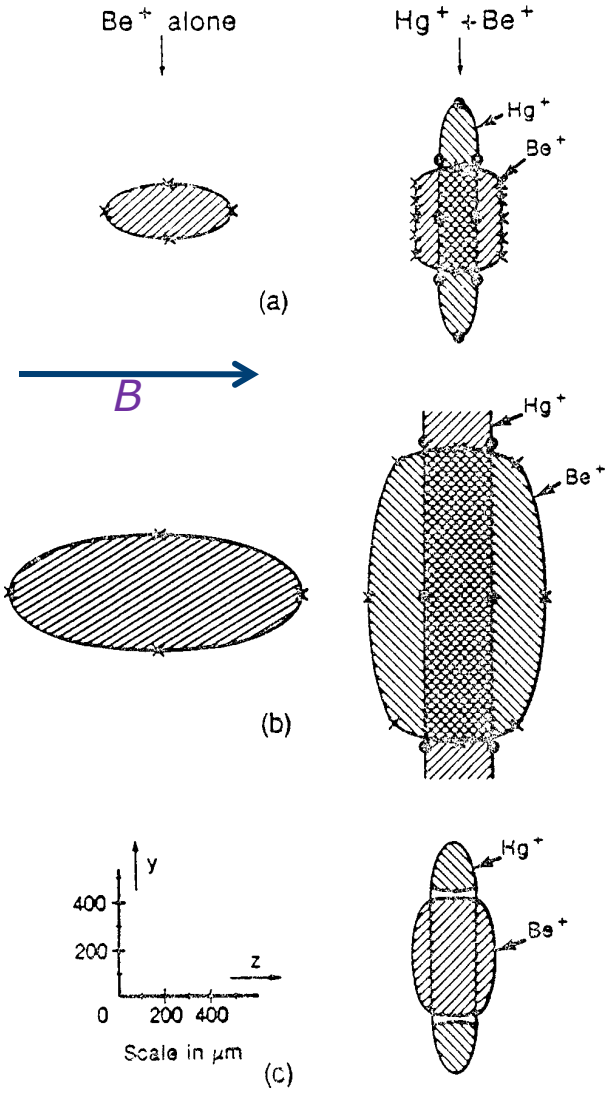
Magnetron Sidebands on a single Cyclotron Sideband

- This spectrum is taken at higher resolution
- The FWHM of ~0.3 MHz indicates a temperature of ~ 40 μK
  - Well below the standard Doppler limit
- This is well understood and is a consequence of the nature of the magnetron motion and the way it is cooled



Sympathetic cooling

- Cooling of one species by another laser cooled species in the same trap
- Sympathetic cooling was first investigated in Penning traps at NIST
  - Hg^+ ions cooled by interaction with laser-cooled Be^+ ions
  - Centrifugal separation occurs
    - » Heavy ion (Hg^+) on the outside
    - » Later experiments show they rotate together
  - Allows ions to be kept cold without being directly laser cooled
  - Allows a wider range of species to be used
    - » Including molecular ions



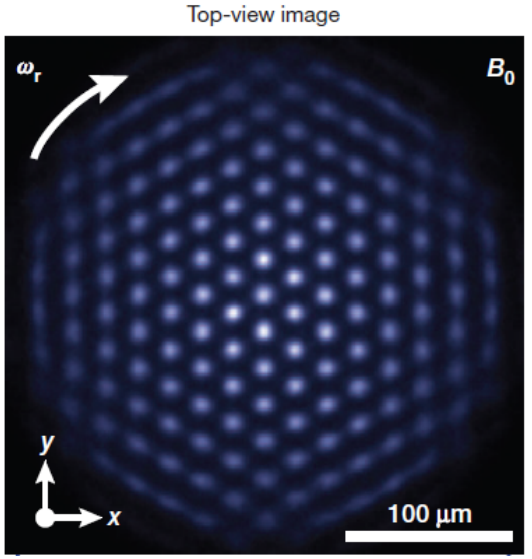
Ion crystals in Penning traps

$$\Gamma = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{a_{WS}k_BT}$$

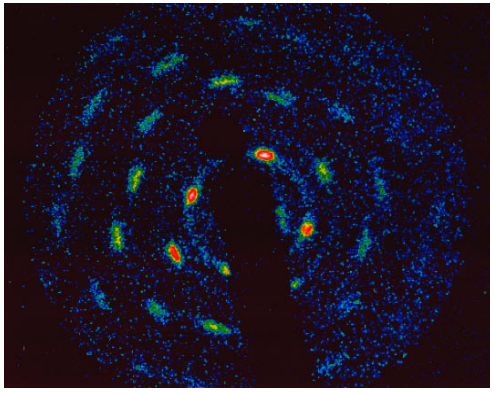
Plasma parameter Γ determines whether crystallisation takes place

- For $\Gamma > 170$ expect crystal
- Predicted bcc lattice if infinite
- Other structures for smaller clouds
  - e.g. Planar hexagonal crystal
  - Ion string at low axial potential
  - Or investigate with Bragg scattering

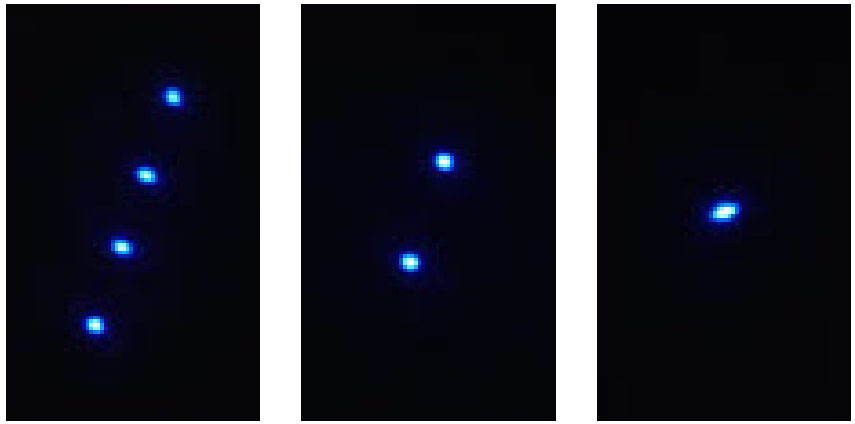
NIST group



NIST group



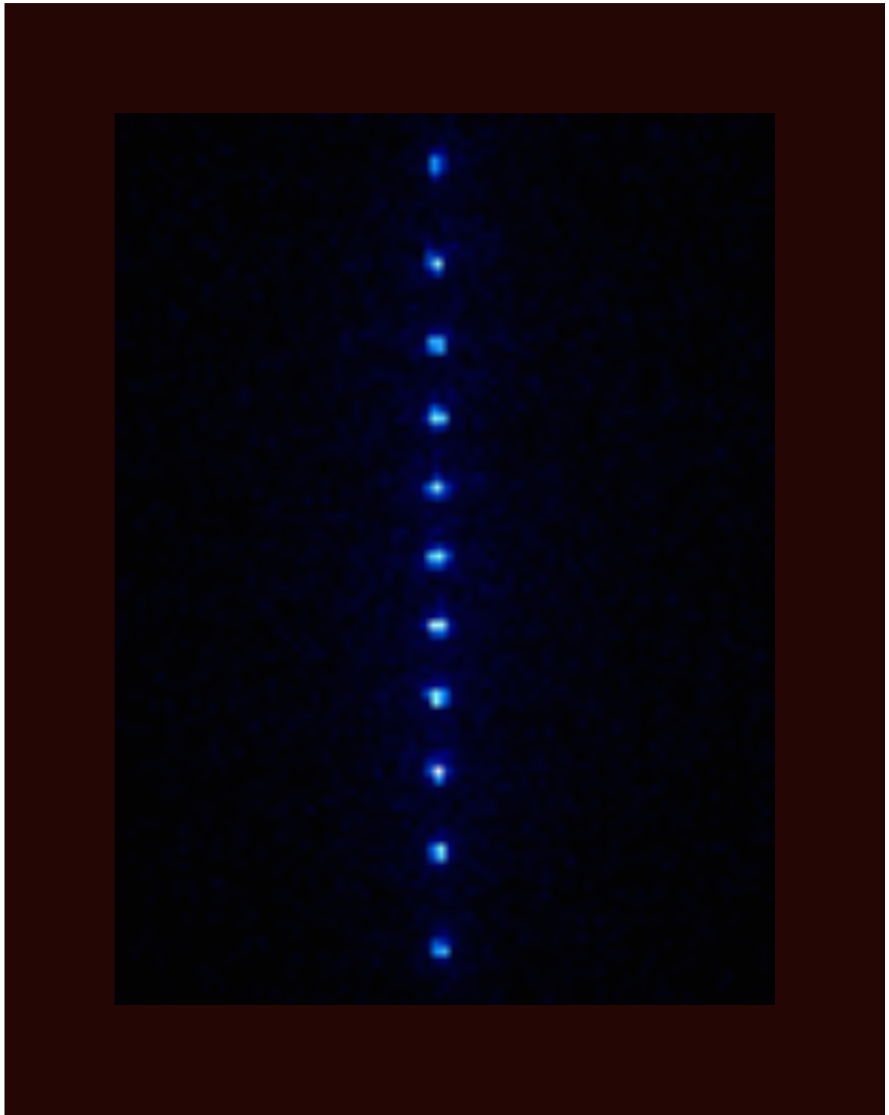
Imperial College group



Controlling the shape of the Crystal

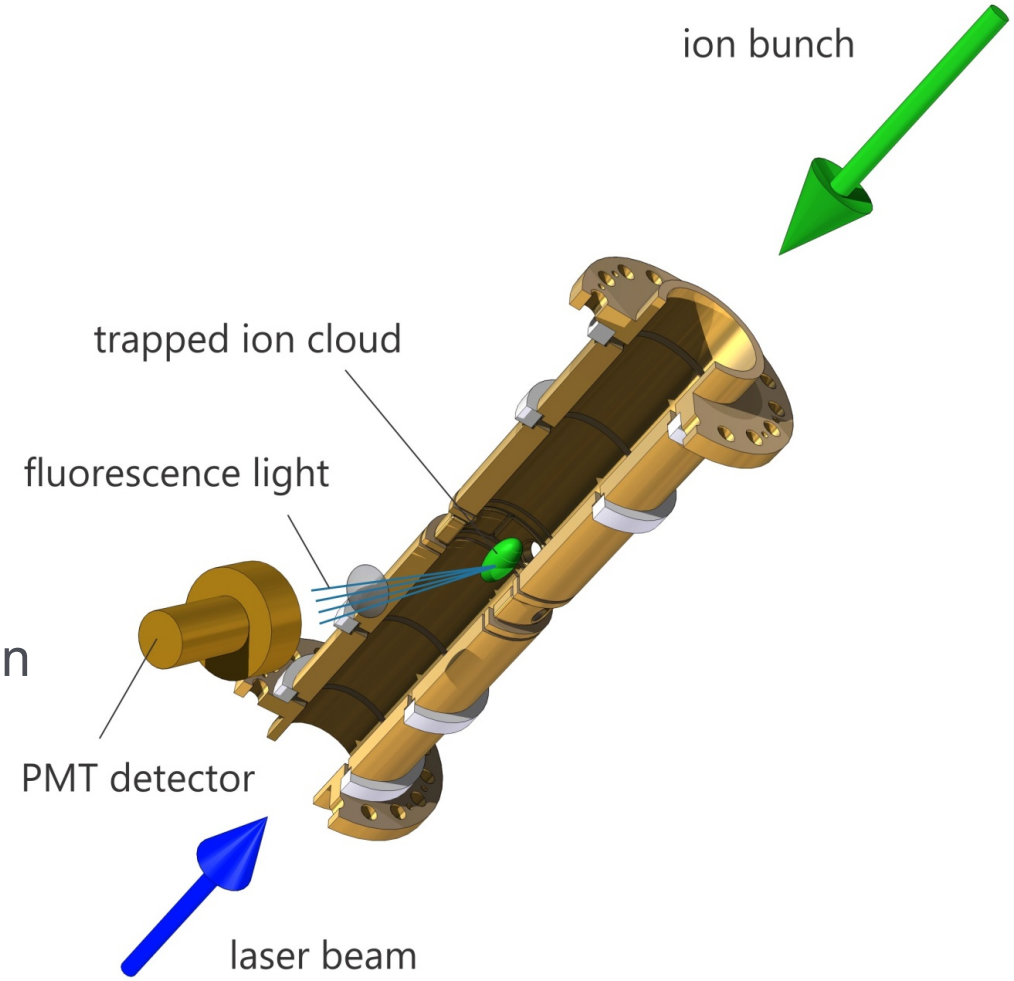
This shows a string of 11 ions changing their configuration as the trap potential is changed

The image is taken from the side and the *z*-axis is vertical



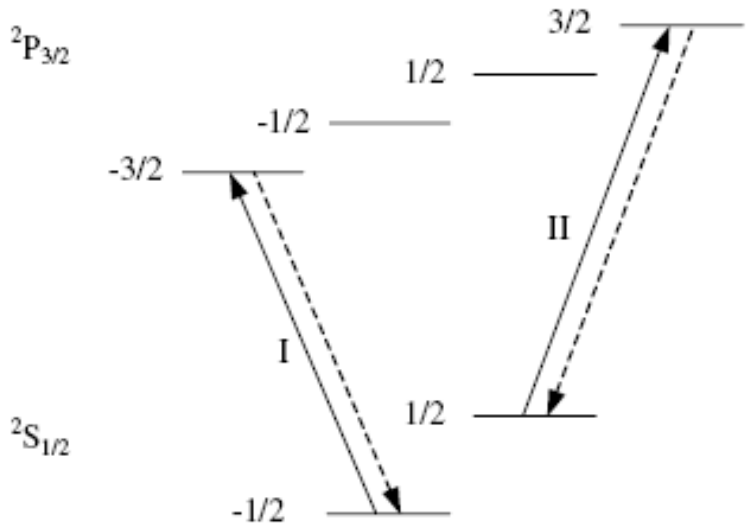
Spectroscopy of HCI

- SPECTRAP will be used at GSI (Darmstadt) to carry out spectroscopy of Highly Charged Ions (HCI)
  - e.g. hydrogen-like Bi
- Ions will be loaded from the HITRAP beam line at low energy
- Sympathetic cooling will be used with laser-cooled Mg^+
- Spectroscopy will be carried out on the ground state hyperfine transition in the visible
  - This is a test of high field QED



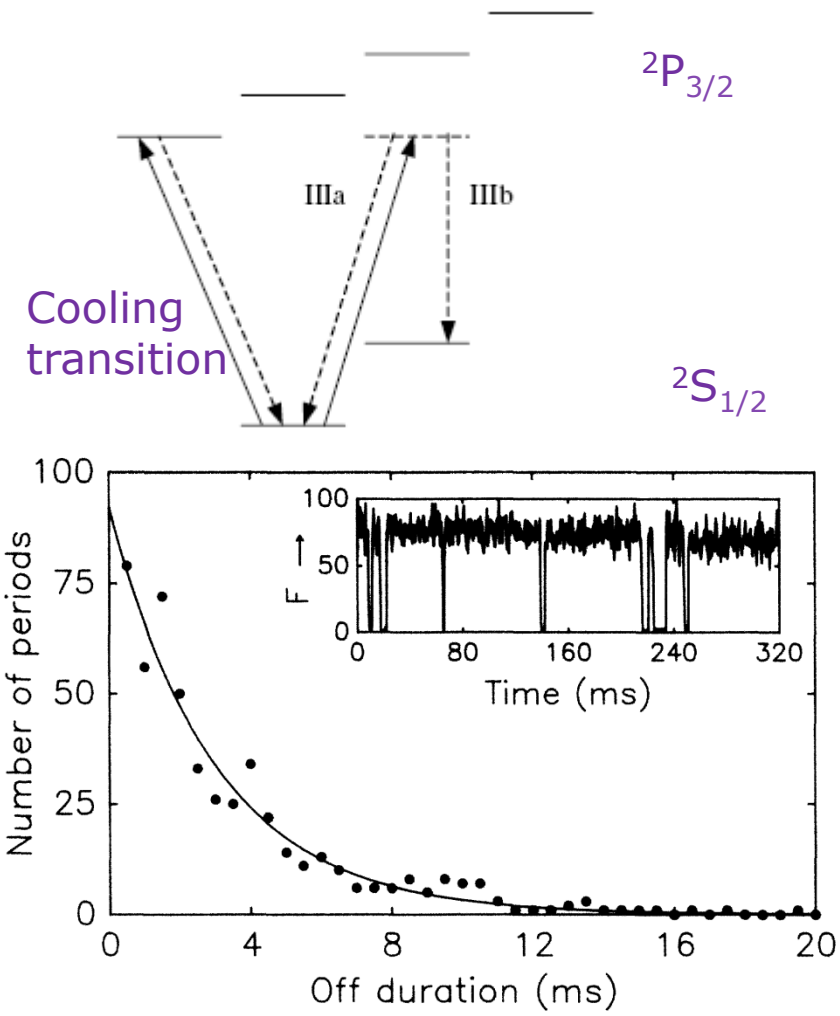
Effect of Zeeman splitting on laser cooling

- In an ion like Mg^+ or Be^+:
  - The transition $^2S_{1/2}$ to $^2P_{3/2}$ displays optical pumping
  - With σ-polarised light we have two possible closed systems
  - Laser cooling possible with a single laser despite the Zeeman effect



Quantum jumps in Mg^+

- Quantum jumps occur when an ion jumps in and out of a metastable level
- One of the earliest investigations was with an ion in a Penning trap (Hulet et al 1988)
  - Zeeman effect gives large level splitting
  - In $^{24}Mg^+$ QJ are driven off-resonantly by cooling laser
  - QJ take place between m_s=±1/2 states
  - Gives a fixed ratio of bright:dark periods of 16:1



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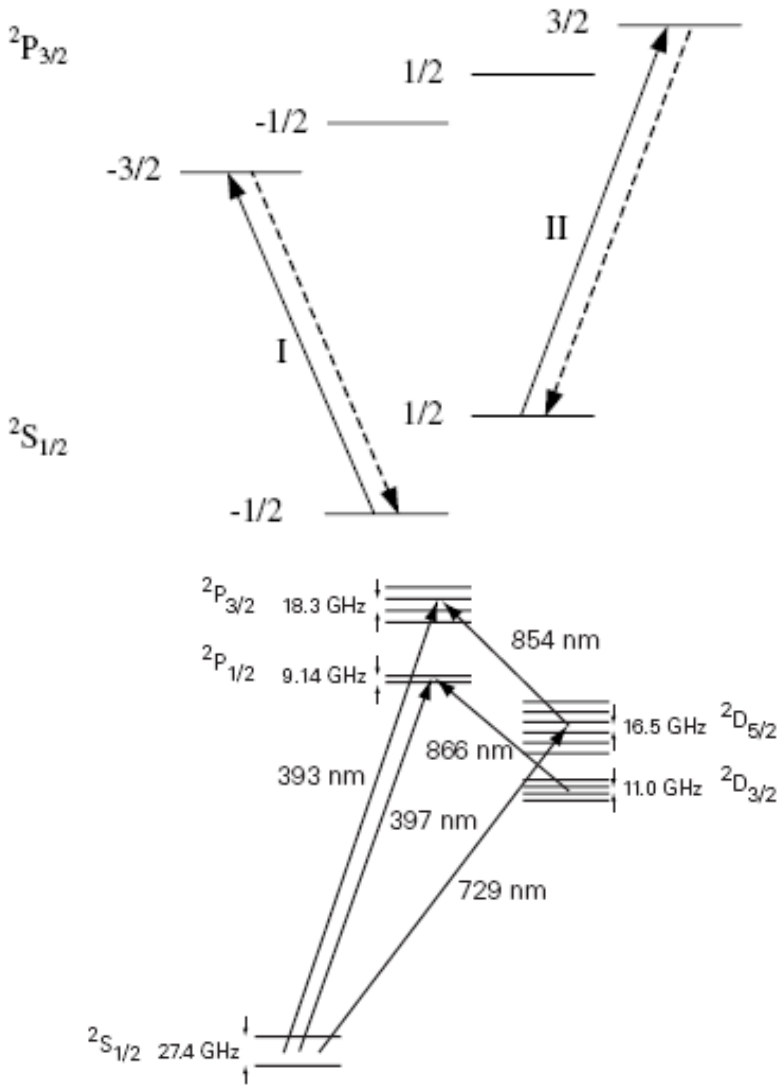
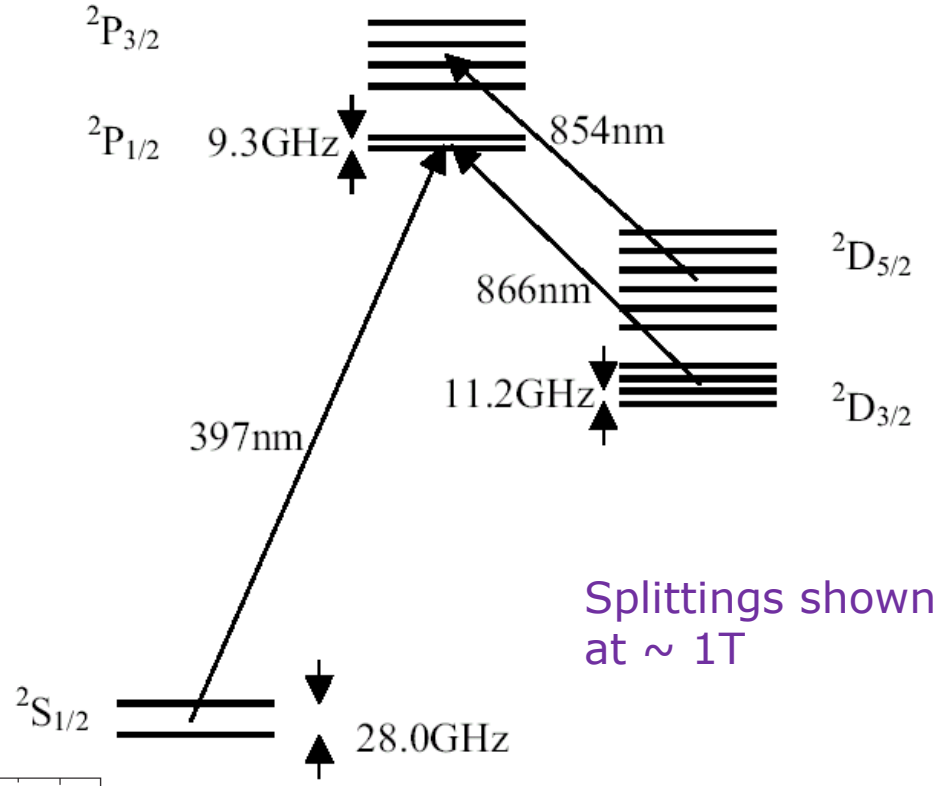
  - The transition $^2S_{1/2}$ to $^2P_{3/2}$ displays optical pumping
  - With σ-polarised light we have two possible closed systems
  - Laser cooling possible with a single laser despite Zeeman effect
- This no longer applies in Ca^+
  - Decay from ^2P to metastable ^2D states
  - At least 6 laser frequencies now needed

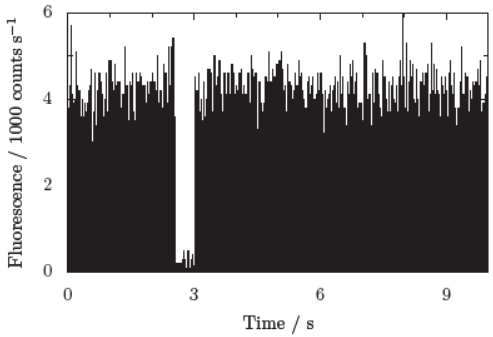


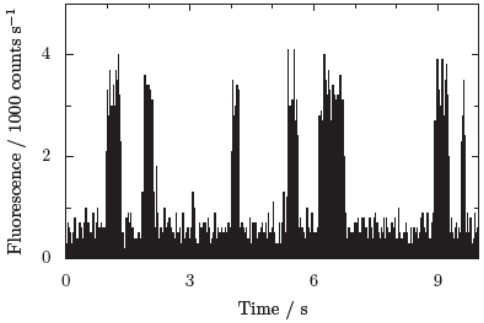
Quantum jumps in Ca^+

- No closed system possible using optical pumping
- Six lasers for laser cooling
  - Decay to $^2D_{3/2}$ from $^2P_{1/2}$
  - Two at 397nm, four at 866nm
- We see quantum jumps to $^2D_{5/2}$
- Even with careful filtering of laser light we see some QJ to $^2D_{5/2}$
  - More frequent at high *B*
  - Prevent use of $^2D_{5/2}$ as qubit?



Splittings shown at ~ 1T

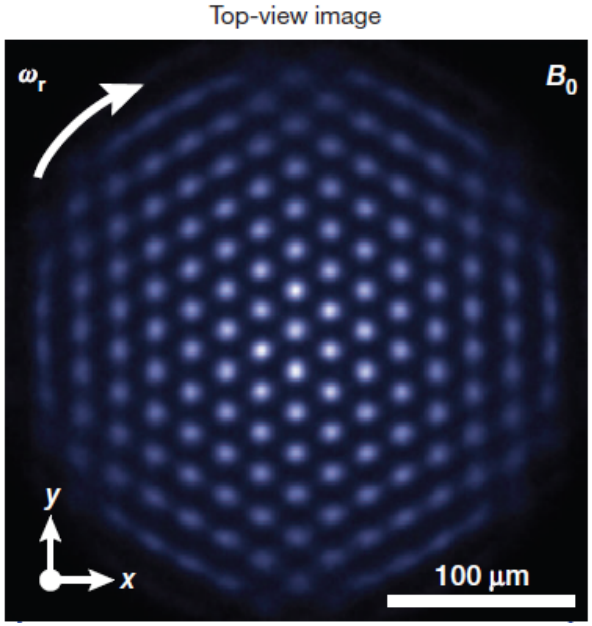


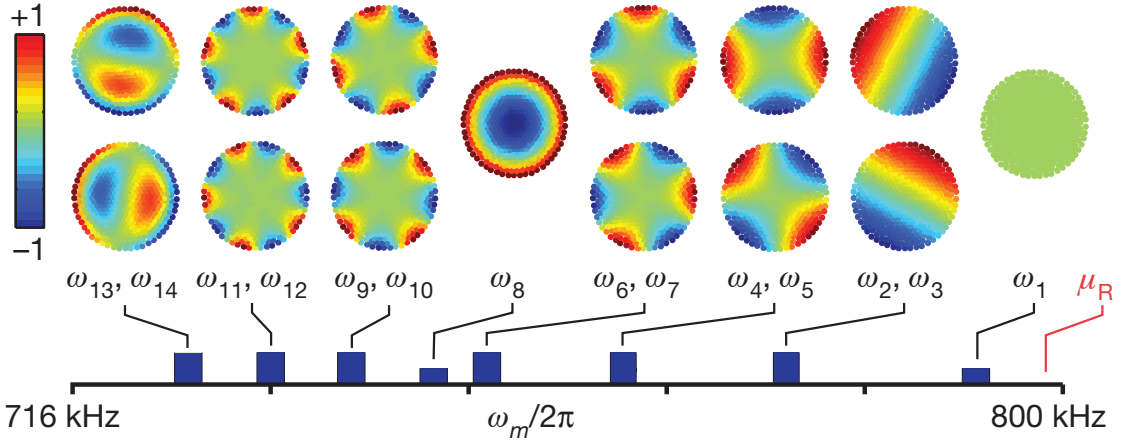


The magnetic field is mixing states of the same *J* but different M_J

Spectroscopy of "drumhead" modes

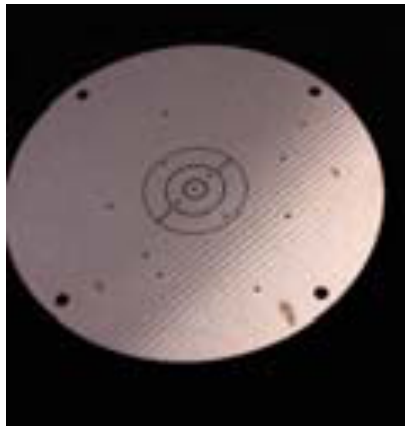
- Bollinger's group at NIST has used quantum information techniques to study the modes of vibration of a planar crystal
- They have also used this system to do a quantum simulation of spin-spin interactions between many particles



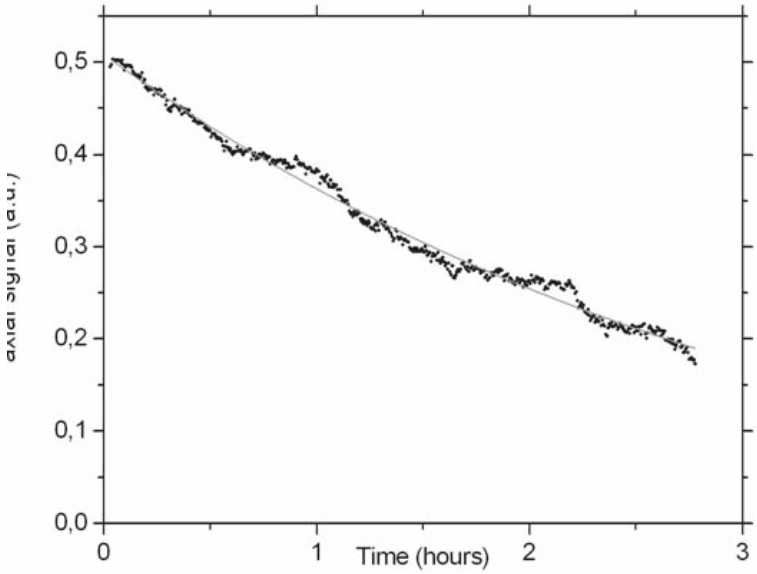


Quantum Information with electrons

- Proposal to use electrons in a Penning trap for QIP
  - Initial experiments trapping electrons in a planar trap at 100mK
  - Electronic detection with cryogenic resonant circuit
  - Measured lifetime of hours
- Very hard to detect a single electron in this trap due to anharmonicities
- Proposal is then to couple electrons in separate traps with wires

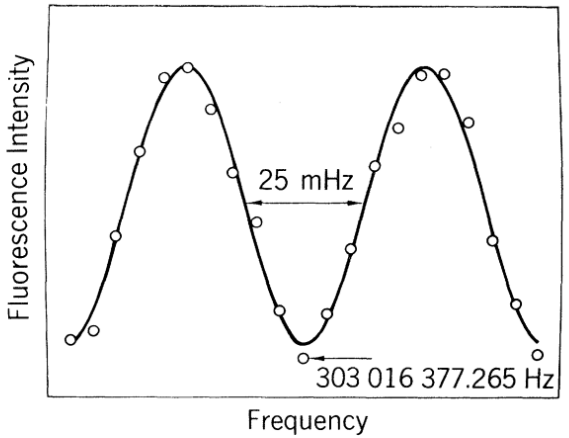


Bushev et al 2008



High resolution spectroscopy

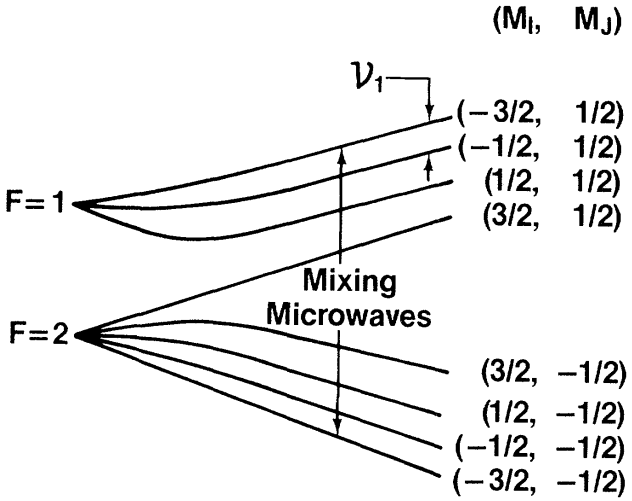
- Penning traps offer many of the same advantages for RF spectroscopy as Paul traps
  - Isolated system
  - Stable environment
  - Laser cooling
  - Long interaction time
- Additional advantages
  - Selection of field-free point
    - » By choice of *B* field strength
  - Many ions participating
    - » Good signal to noise ratio



Bollinger et al 1985

- Disadvantages:
  - Difficult to achieve Lamb-Dicke regime
  - Rotation of ion cloud
  - Limited optical access
  - Effectively limited to RF/ microwave frequencies

Be+ microwave frequency standard



- Transition is field-free at 0.82T (303 MHz)
- Low frequency means long interrogation times needed (~10s)
  - Q of order 10^{10}
  - Final uncertainty ~2 10^{-13}

Not competitive with optical frequency standards

TABLE I. Estimated systematic errors. The size of the effect is the fraction of the transition frequency ν_1.

Systematic effect	Size of effect
Second-order Doppler	$-38(9)\times10^{-14}$
Magnetic field fluctuations	$-1.3(^{+1.3}_{-2.5})\times10^{-14}$
Rotation of Earth	$-1.8(0.2)\times10^{-14}$
Microwave leakage	$\leqslant 1\times10^{-14}$
Background slopes	$\leqslant 5\times10^{-15}$
Servo offsets	$\leqslant 5\times10^{-15}$
Blackbody radiation shift	$-3(3)\times10^{-16}$
Coherence between cycles	$<1\times10^{-15}$
Background gas collisions	$<1\times10^{-15}$
Stark shifts	$<1\times10^{-15}$
First-order Doppler	$<1\times10^{-15}$
ac Zeeman shifts	$<1\times10^{-15}$
Total systematic offset	$-41.1(9.4)\times10^{-14}$

Bollinger et al 1985

Summary of Lecture 2

Where else do you see a single device being used for so many different types of experiment?

- Fundamental constants
- Spectroscopy
- Frequency standards
- Plasma physics
- Fundamental symmetries
- Nuclear physics
- Quantum information
- QED tests
- Magnetic moments