Electronic Refrigeration and Precision Mass Spectrometry

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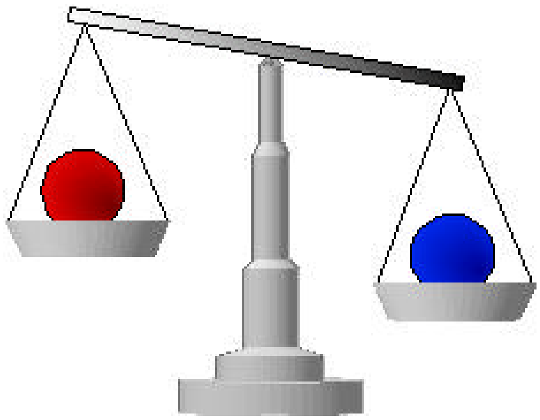
$$$ NSF and NIST $$$

Our Goal: Compare the Masses of Single Ions with Precision > 10^{-10}

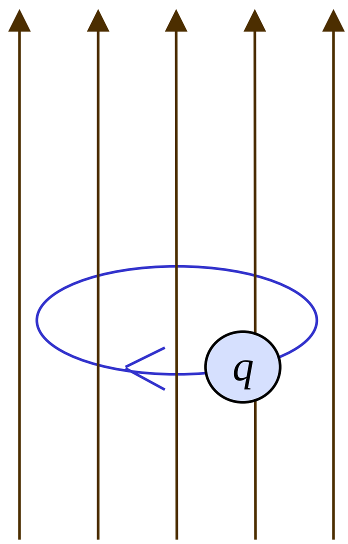


Why?

- Recalibration of γ-ray Spectrum
- Atomically Defined Kilogram Mass Standard
- Accurate Determinations of the Fine Structure Constant α and Molar Planck Constant $N_A h$
- Help Place Limits on the Electron Neutrino Mass
- Precise Tests of $E=mc^2$
- Weigh Chemical Binding Energies

How? Compare Cyclotron Frequencies

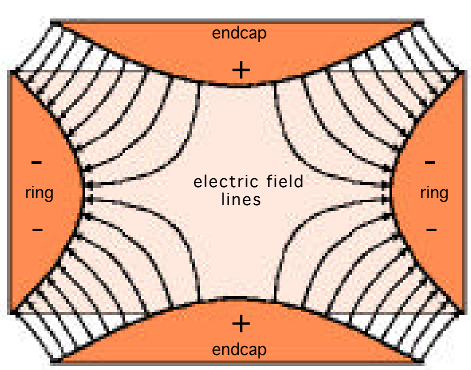
Magnetic Field B



$f_c \sim 5$ MHz

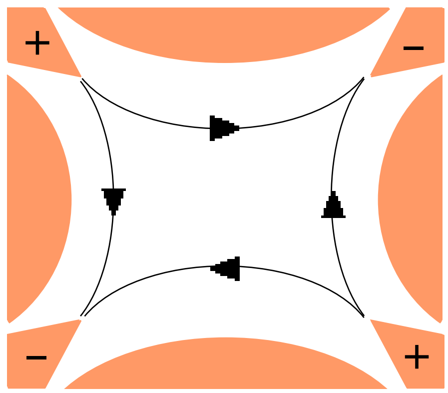
$$\omega_c = \frac{qB}{mc} \longrightarrow \frac{m_1}{m_2} = \frac{q_1\,\omega_2}{q_2\,\omega_1}$$

Add Electrostatic Axial Confinement to form a Penning Trap-- allows long measurement times.

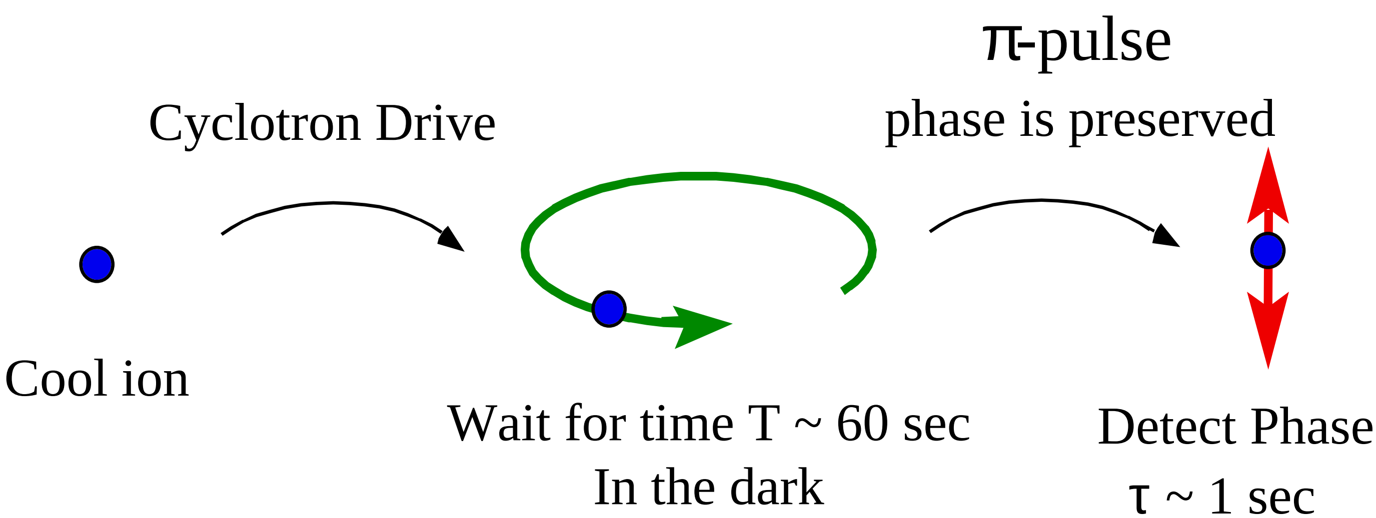


Harmonic Axial Mode $f_z \sim 200$ kHz

Measuring the Cyclotron Frequency of an Ion



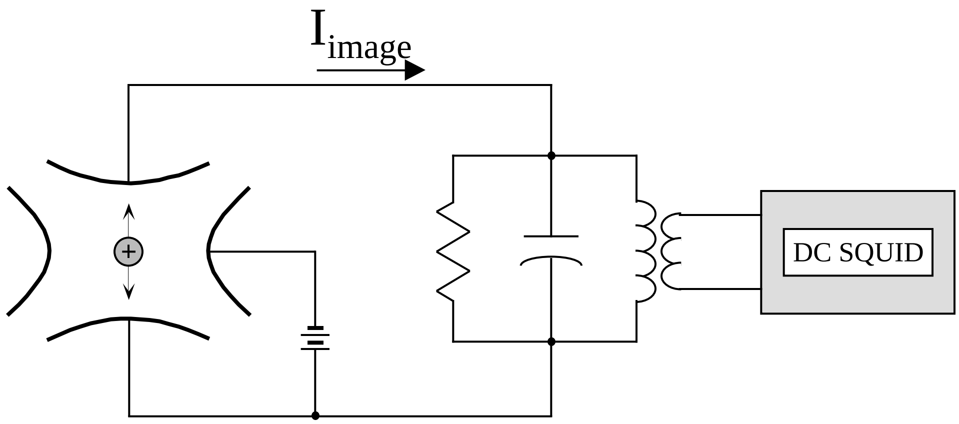
Use RF Mode Coupling Technique to transfer the cyclotron phase information into the axial mode.



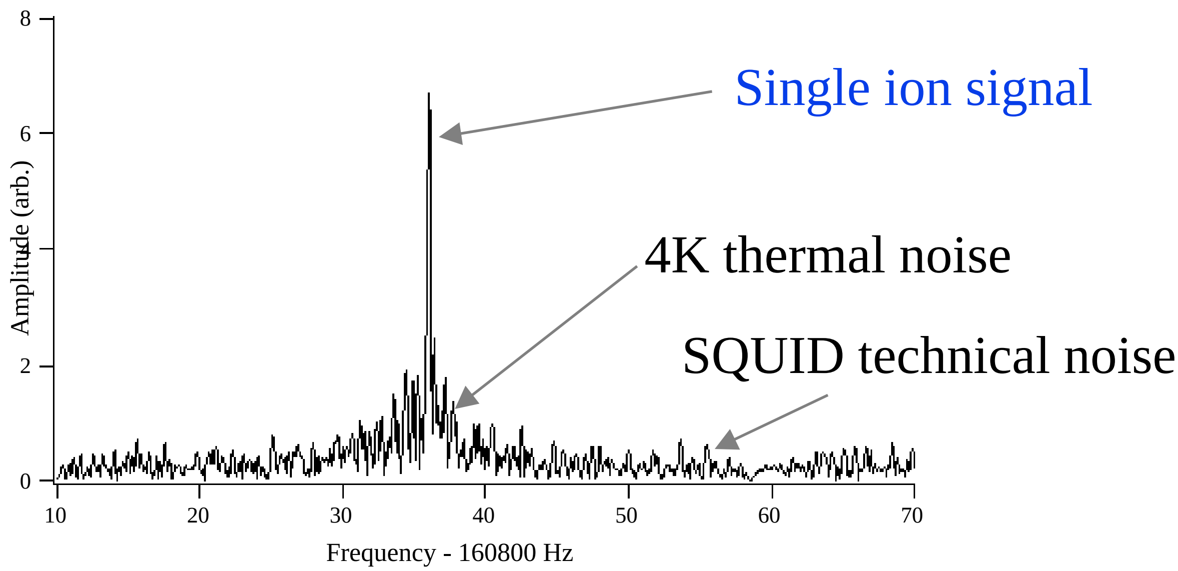
Need a Phase Sensitive Axial Detector

Axial Detector

1 ion oscillating along z axis → 10^{-15} amps induced in the endcaps !

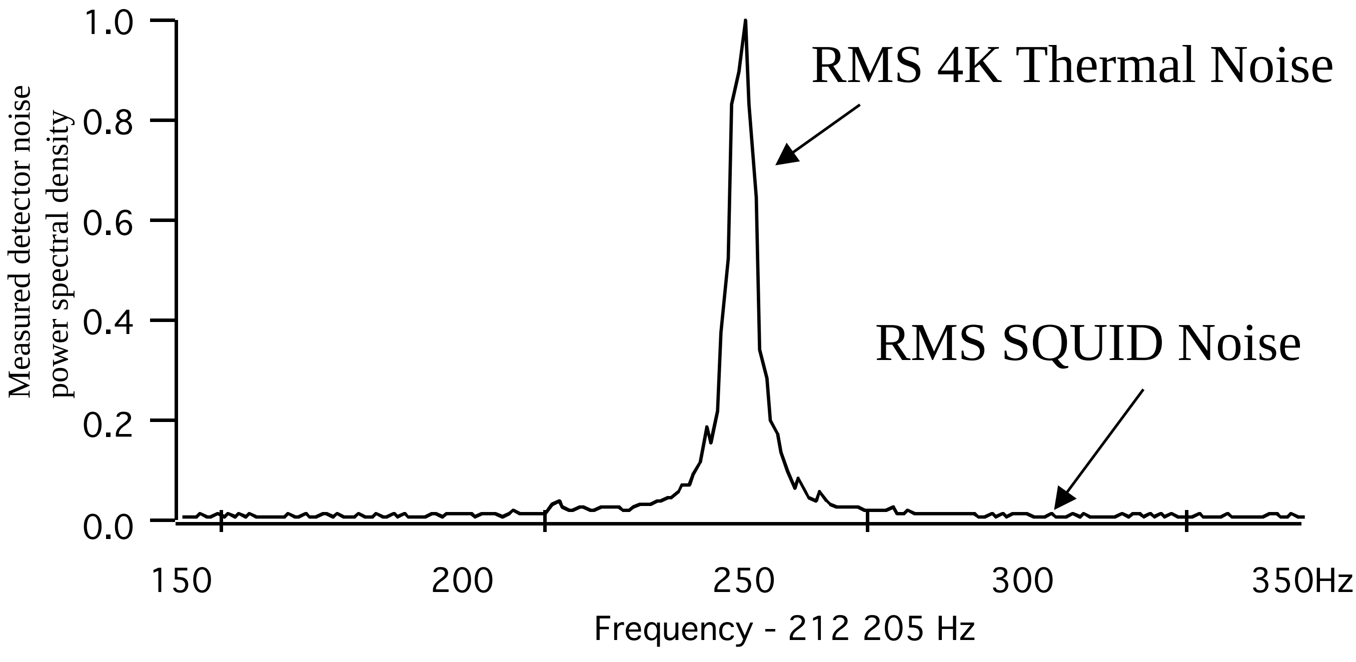


- Superconducting resonant transformer Q=40000, f_o= 210kHz
- dc SQUID operated as current detector
- Ion dissipates energy in transformer with τ ~ 1 sec



Measuring Thermal Noise of Transformer

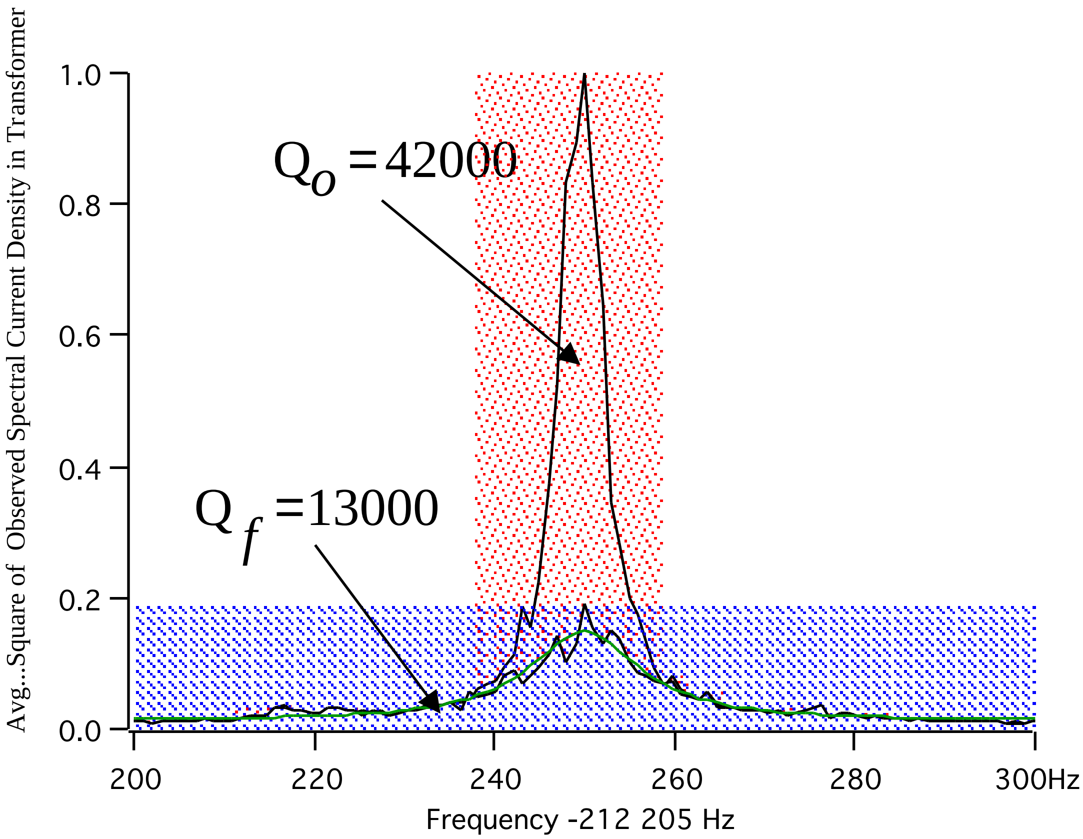
- New dc SQUID 10x quieter than previous rf SQUID
- Increased coupling between transformer and SQUID



Result: Can now "measure" the 4K thermal noise currents in the transformer with a peak S/N ~100

Electronic Refrigeration

Use feedback to reduce the thermal currents in the transformer.



$$\frac{T_o}{T_f} = \frac{\left\langle \frac{1}{2} L I_o^2 \right\rangle}{\left\langle \frac{1}{2} L I_f^2 \right\rangle} = \frac{Area_o}{Area_f} \approx \frac{Q_o}{Q_f} \approx 3$$

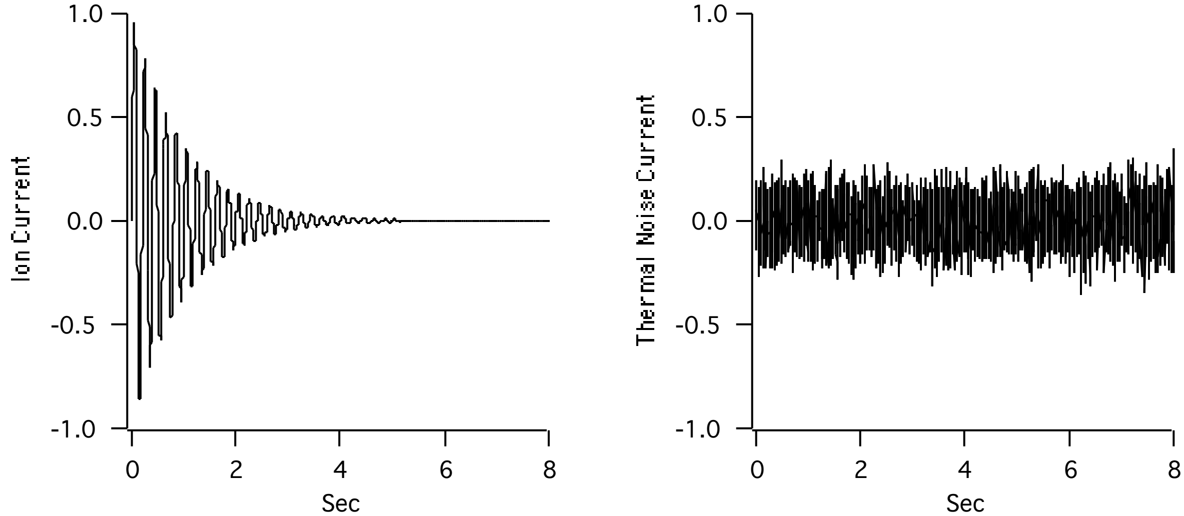
The transformer temperature is reduced from 4K to 1.3 K

Improved Ion Detector?

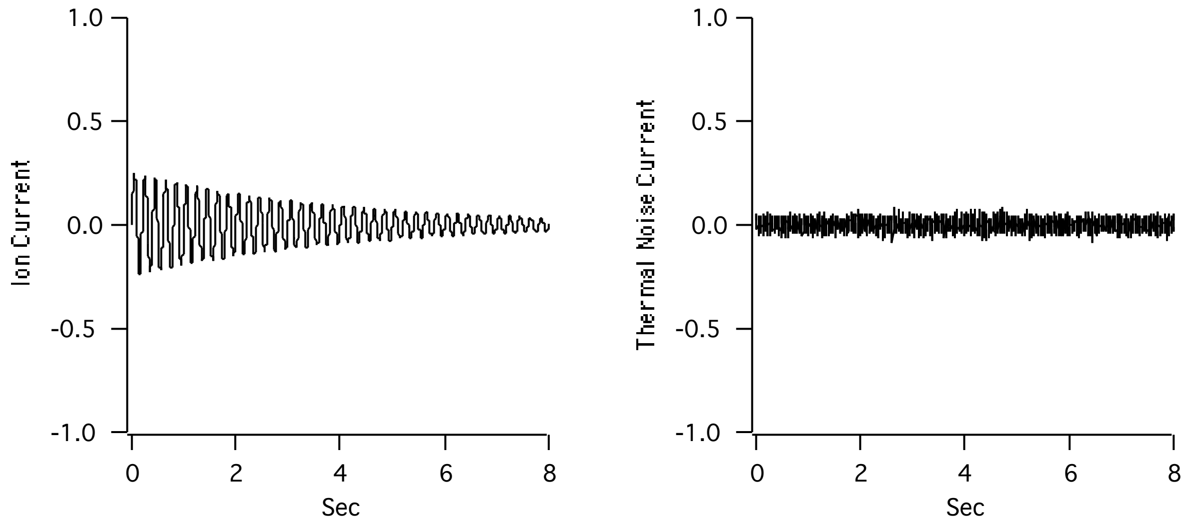
Feedback reduces both the ion current and thermal noise currents flowing in the transformer.

Ion and Noise Currents in Transformer vs Time

Without Feedback



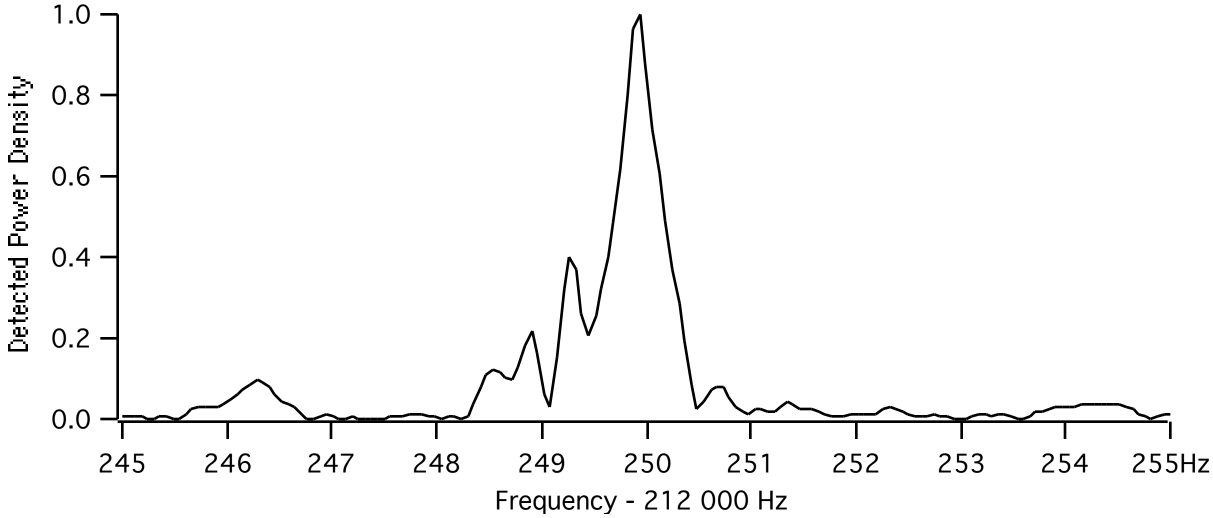
With Feedback



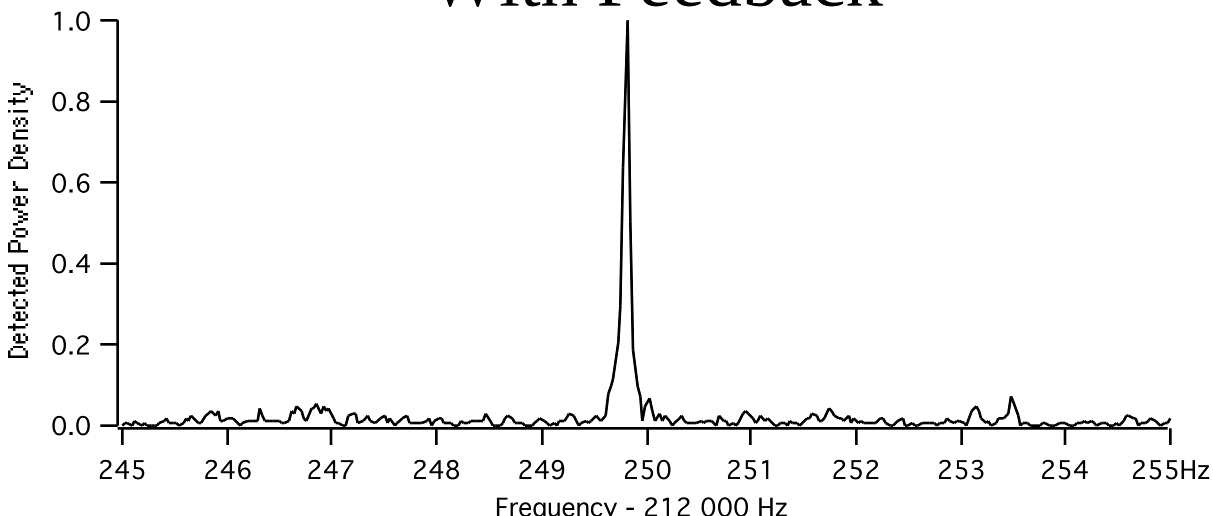
Ion current flowing in the transformer is the source of ion damping so the ion signal lasts longer with feedback.

Improved Ion Detector!

Without Feedback



With Feedback

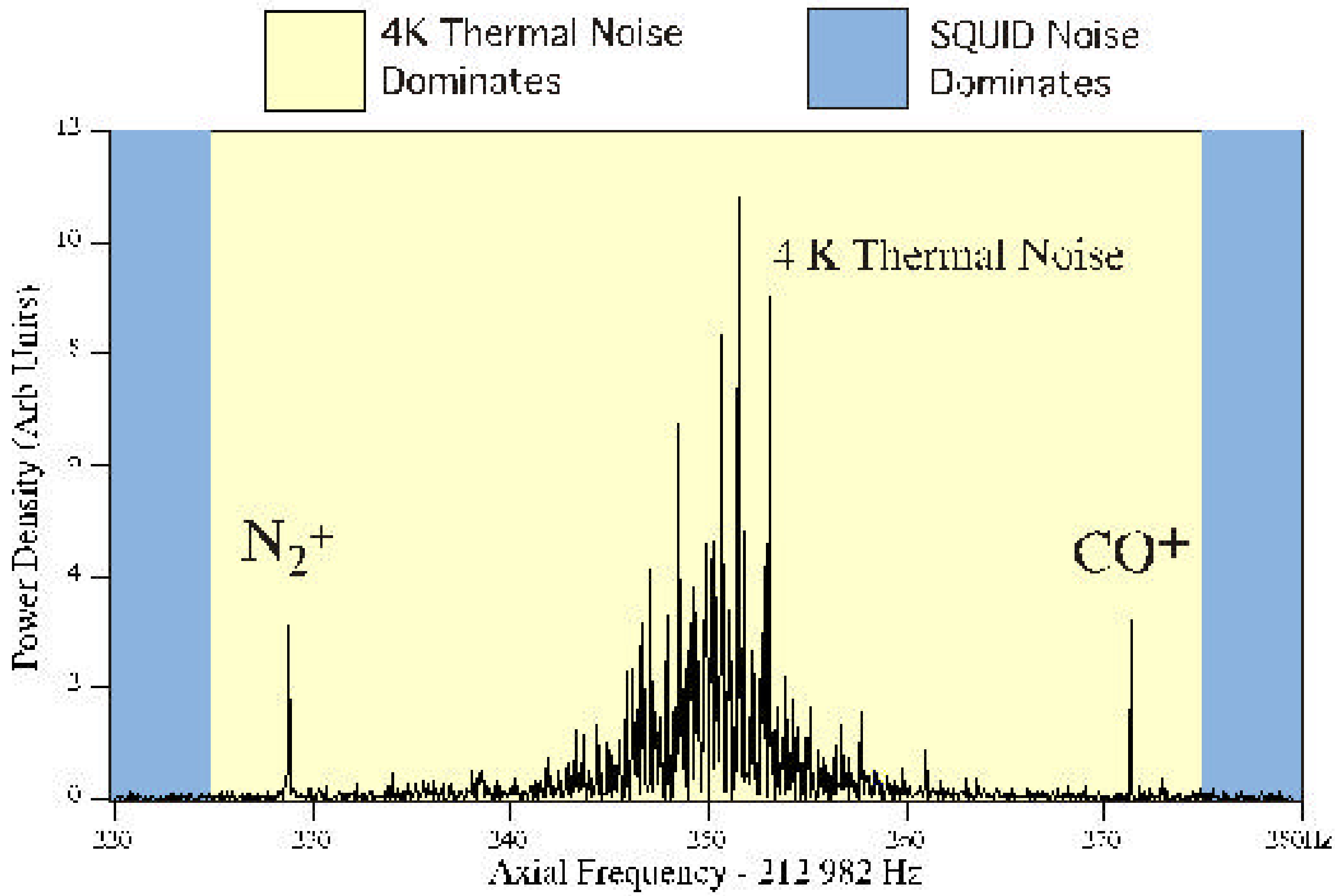


Conclusion:

4 x less axial frequency noise

2 x less Phase and Amplitude Noise
yields 2 x shorter cyclotron
measurement time T

Seeing Double



Typical Axial Signals from ions after 240 sec of Cyclotron Phase Accumulation

- Simultaneously observe the axial motion of 2 ions
- Simultaneous cyclotron frequency measurements
- Achieve common mode rejection of magnetic field noise which limits our precision to 10^{-10}

Future: 10^{-11} mass comparisons??