A Cryogenic Linear Paul Trap For Quantum Simulation

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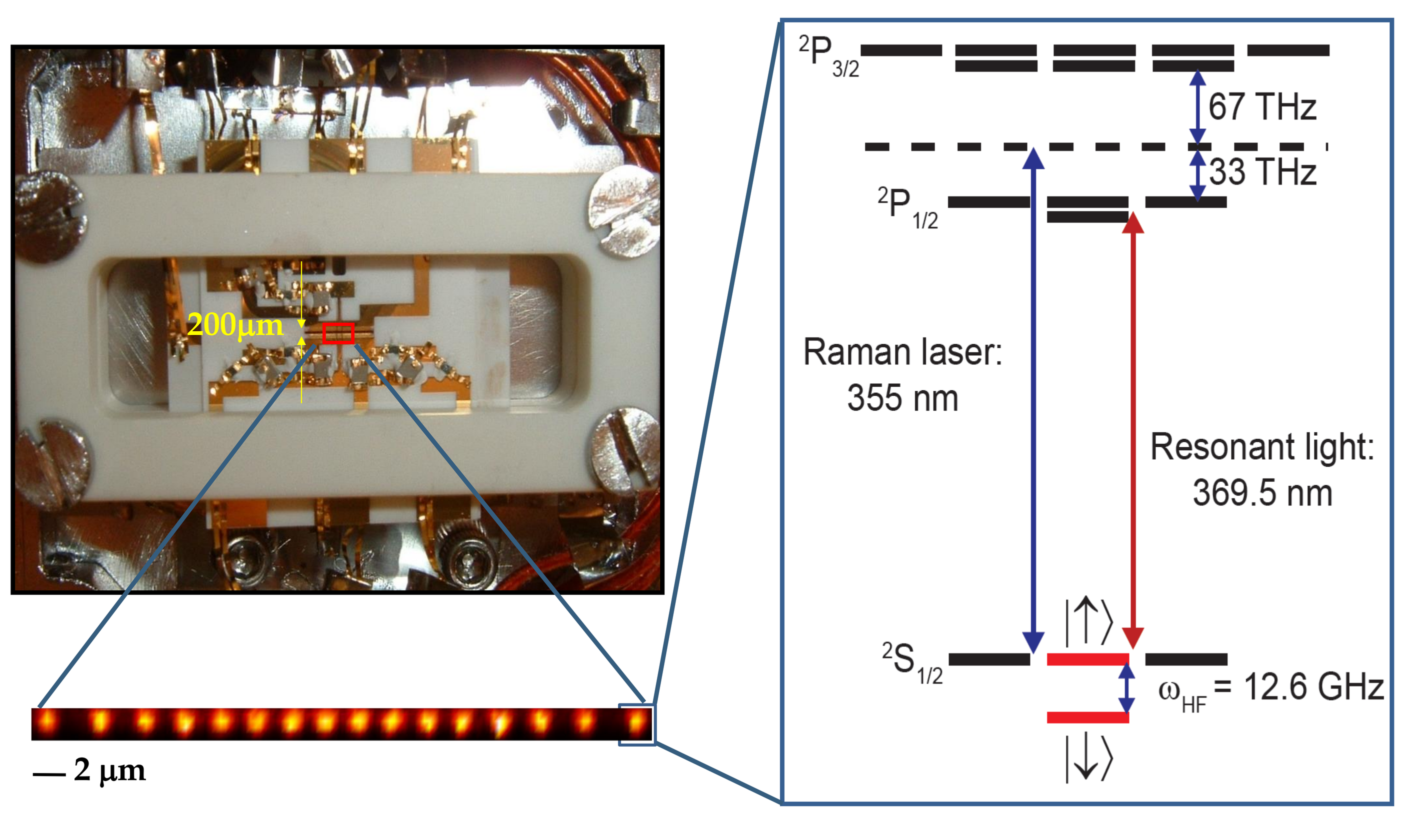
This work is supported by the ARO Atomic Physics Program, the AFOSR MURI on Quantum Measurement and Verification, and the NSF Physics Frontier Center at JQI

Simulating Quantum Spin Models

Trapped $^{171}Yb^{+}$ ions provide an excellent platform for simulating quantum magnetism. With current technology, such a quantum simulator can be used to study many-body phenomena like quantum phase transitions, frustrated quantum systems, ground state magnetic spin phases, or excited state dynamics [1].

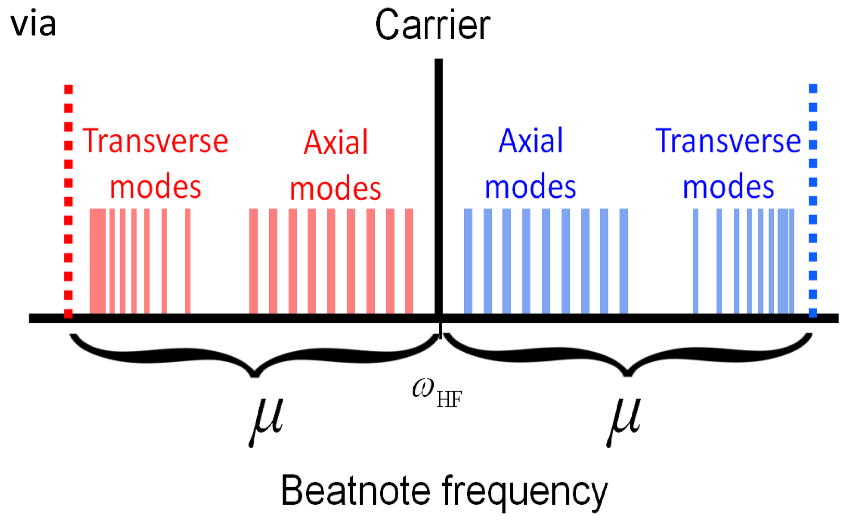
An Isolated Quantum System

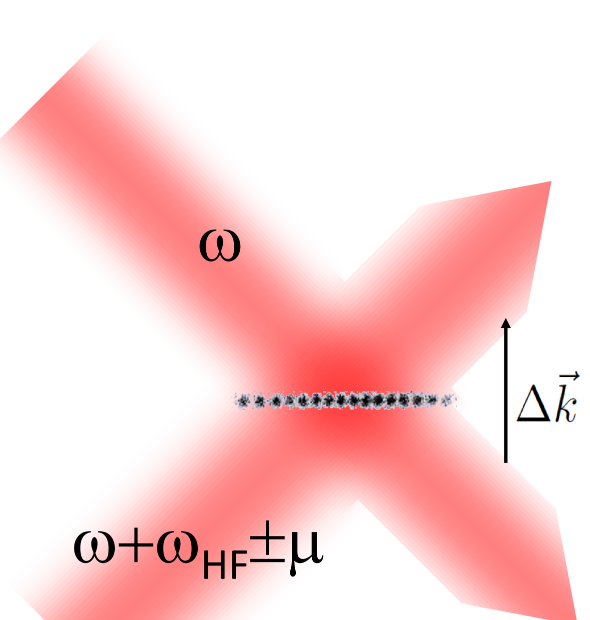
The effective spin-1/2 qubit is encoded in the hyperfine clock states of $^{171}Yb^{+}$. Resonant laser beams allow for cooling, state preparation, and measurement, with spin-dependent fluroescnece captured on a camera.



Engineering Long-Range Spin-Spin Couplings

Counter-propagating laser beams at 355 nm allow for coupling of spin and motion via stimulated Raman transitions. Coupling to both red and blue sidebands simultaneously generates a spin-dependent force via the Mølmer-Sørensen process [2]





$$H_{eff} = \sum_{i \neq j} J_{ij} \hat{\sigma}_x^{(i)} \hat{\sigma}_x^{(j)}$$

$$J_{ij} = \frac{\hbar \Omega_i \Omega_j (\Delta k)^2}{2m} \sum_k \frac{b_i^k b_j^k}{\mu^2 - \omega_k^2} \approx \frac{J_0}{|i-j|^\alpha}$$

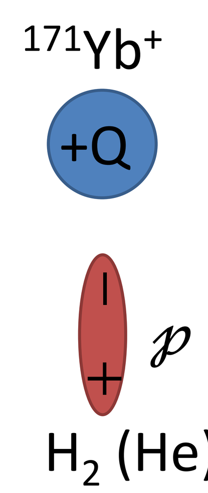
[1] See K. Kim et al., NJP **13**, 105003 (2011) and references therein
[2] K. Mølmer and A. Sørensen PRL **82**, 1835 (1999).

Increasing the Number of Ions

Our ability to coherently drive chains of more than 20 ions is currently limited by collisions with residual background gas. For a chain of this length the time between collisions is comparable to the time to recapture and stabilize the ion crystal.

Langevin Collision Rate

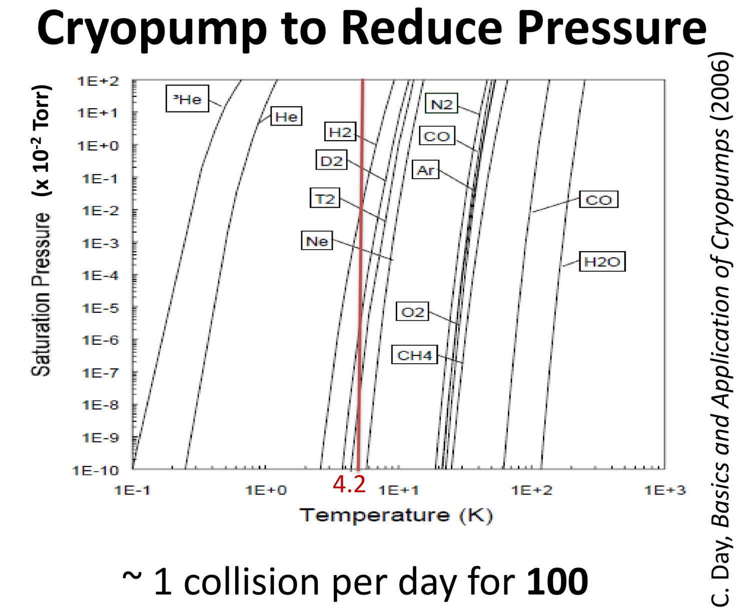
$$\gamma \approx \frac{PQ}{k_B T}\sqrt{\frac{\wp \pi}{2m\epsilon_0}}$$



P = Pressure
Q = Ion Charge
$\wp$ = H_2 or He Polarizability
m = Mass of H_2 or He

⇒ 1 collision every 2 min for 20 ions @ 300 K and 1×10^{-11} Torr

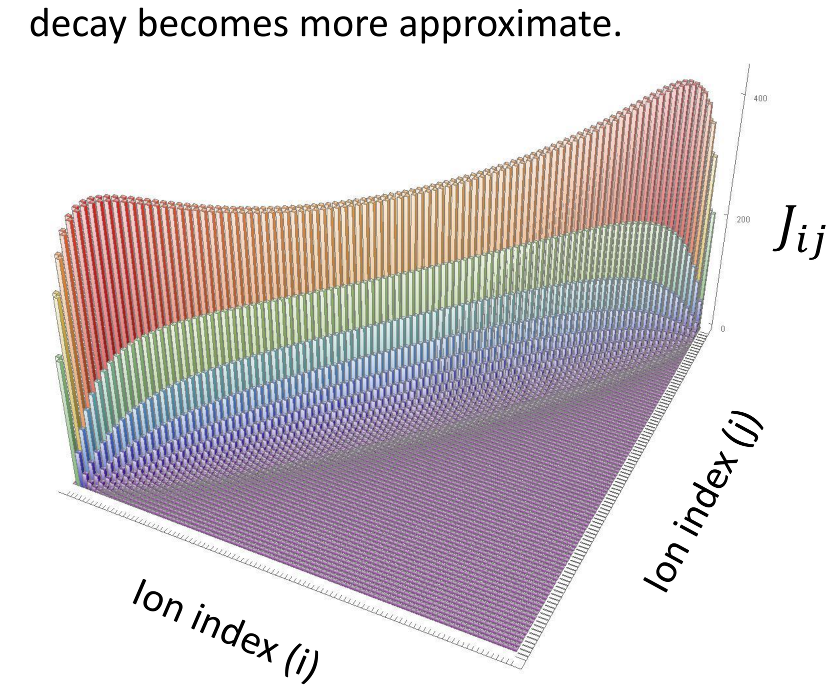
Cryopump to Reduce Pressure

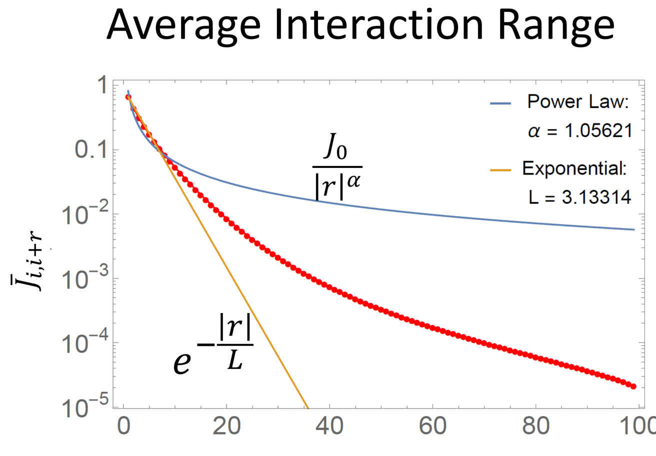


~ 1 collision per day for **100** ions @ 4.2 K and 1×10^{-17} Torr

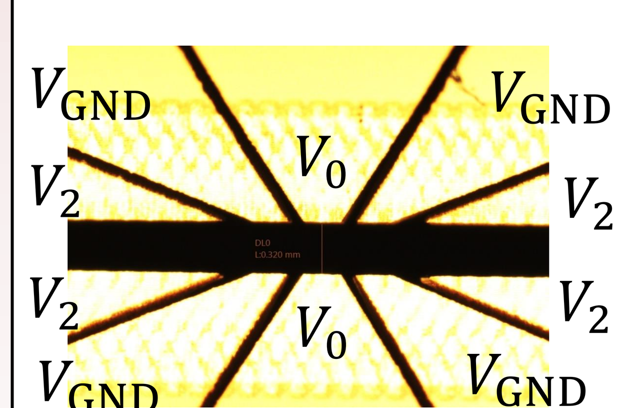
Spin-Spin Coupling Matrix for 100 Ions

The Spin-Spin coupling matrix J_{ij} can be tuned from an infinite range "all-to-all" to an $|i-j|^{-3}$ "dipolar" coupling. For long range couplings ($\alpha < 2$) the fit to a power law decay becomes more approximate.





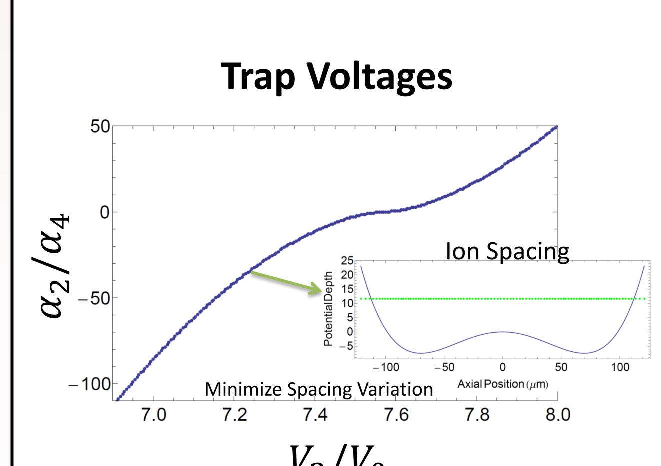
Shaping the Interaction with Quartic Potentials

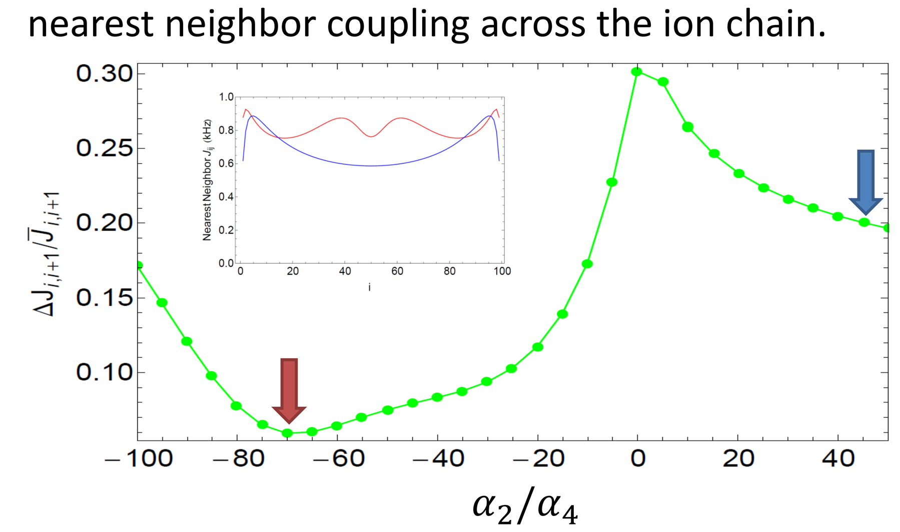


By generating a quartic axial potential from our 5 segment trap, we can tune the ion spacing, normal mode structure, and coupling matrix.

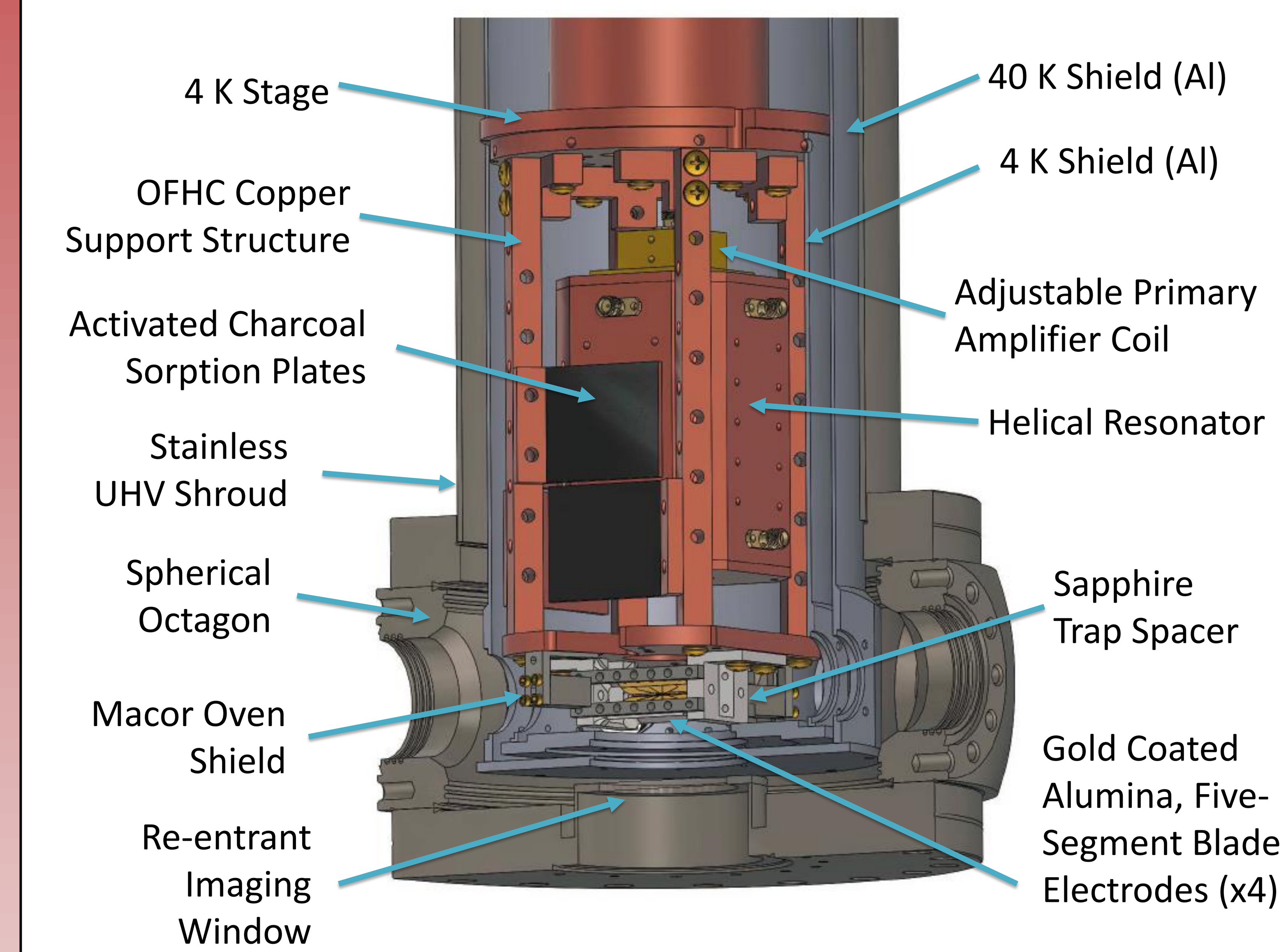
$$U = \frac{1}{2} M \omega_A^2 \left(\alpha_2 z^2 + \frac{\alpha_4}{2l^2} z^4\right)$$

For example, we can minimize the variation in nearest neighbor coupling across the ion chain.

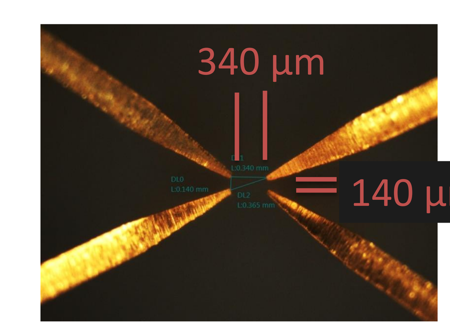


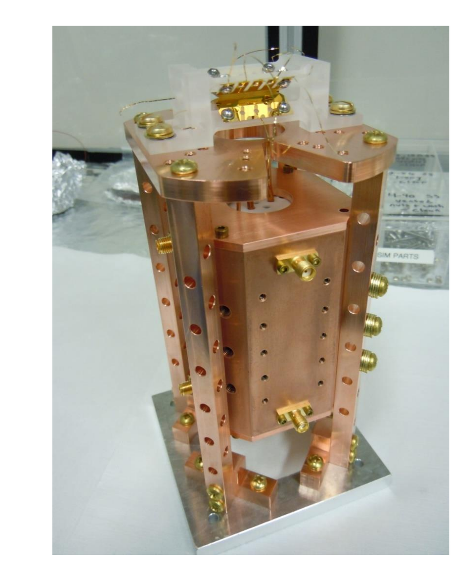


Cryostat and Trap Construction

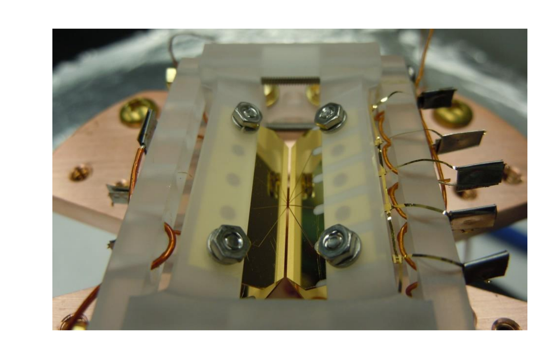


Hand aligned blade trap 360 μm between RF blades





Optically open trap design for high NA ≤ 0.6 light collection



Thermal Management and Vibration Control

Source	Heat Load Estimate
Blackbody - 40 K Shield	< 1 mW
Blackbody – 1" Windows	< 1 mW
Wiring	< 1 mW
Oven	~ 1 W (Transient)
RF Drive	~ 500 mW
Lasers	~ 100 mW
Cooling Power	**~ 700 mW**

Cryostat designed to maximize cooling power at 4.2 K while minimizing vibrations on sample stage.

He exchange gas chamber provides the thermal link between cold head and vacuum chamber 4K stage.
⇒ **Vibrations < 100 nm**

← Careful optimization will be necessary to manage RF and oven heat loads