Making Dreams Into Reality: Machining a Vacuum Chamber to Stabilize a Laser

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Goals & Motivation

In order to **trap $^{40}Ca^{+}$ ions for quantum simulation,** a would-be experimenter must cool them below the intrinsic limit of Doppler cooling.

Since we will be working with strongly trapped ions that have been Doppler precooled, we intend to use **resolved sideband cooling** to cool the ions to their vibrational ground states.

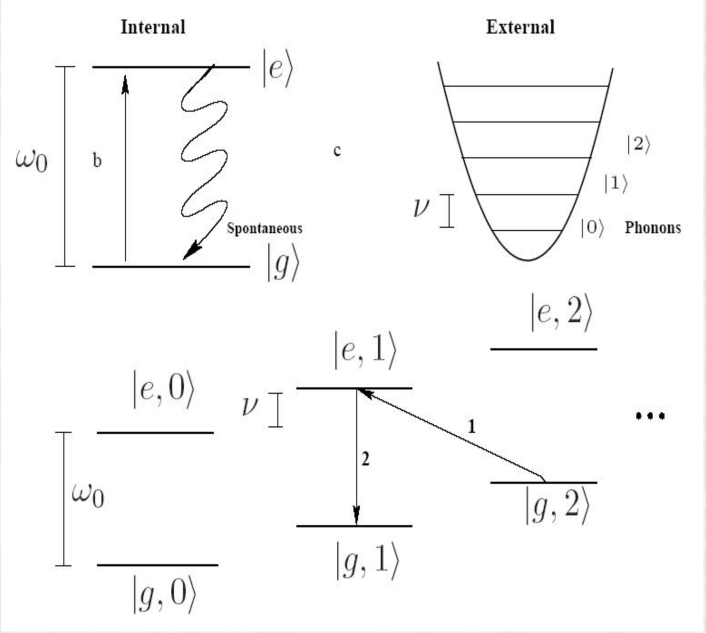
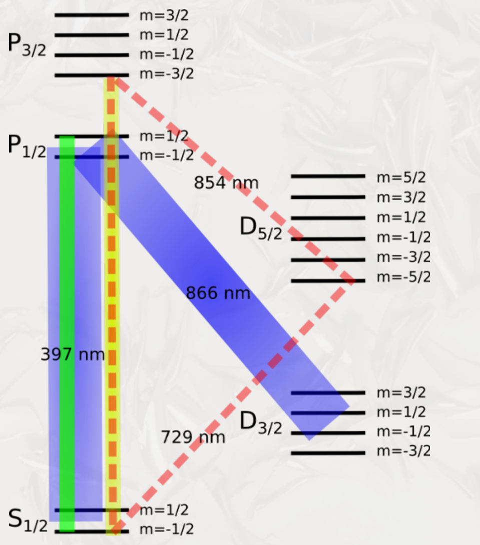


Fig. 1: Resolved sideband cooling takes advantage of the fact that a sufficiently cold trapped atom behaves as a quantum harmonic oscillator: it vibrates only at discrete energy levels, equally spaced by the atom's harmonic frequency v (this 'ladder' of motional states is labeled "External" in the figure).

To cool the hypothetical two-level atom pictured at left with ground state g and excited state e, we would tune the frequency of the laser to the red sideband, at $\omega = \omega_0 - v$, where ω_0 is the internal atomic transition frequency. Absorption of one of these photons prompts the atom to undergo the transition $|g, n\rangle \rightarrow |e, n\text{-}1\rangle$ (labeled [1] in the figure; where in $|a, m\rangle$ a represents the atom's internal atomic state and m represents its motional state).



If the recoil energy of the atom will be small compared to v, spontaneous emission will likely drive subsequent transition [2]: $|e, n\text{-}1\rangle \rightarrow |g, n\text{-}1\rangle$. This leaves the atom back in the initial internal state, allowing us to iterate this process until $|g, 0\rangle$ is reached with high probability.

Fig. 2: The $^{40}Ca^{+}$ energy levels addressed by various cooling processes. Purple corresponds to Doppler cooling, red to resolved sideband cooling, yellow to spontaneous decay, and green to spin polarization σ- pulses.

To drive resolved sideband cooling, we must address the exceedingly narrow 729 nm $S_{1/2} \rightarrow D_{5/2}$ transition. It has a full width at half maximum of about 1 Hz, requiring extreme stability from our laser. We can achieve this by **locking a (roughly) 729nm laser to a Fabry-Perot cavity**.

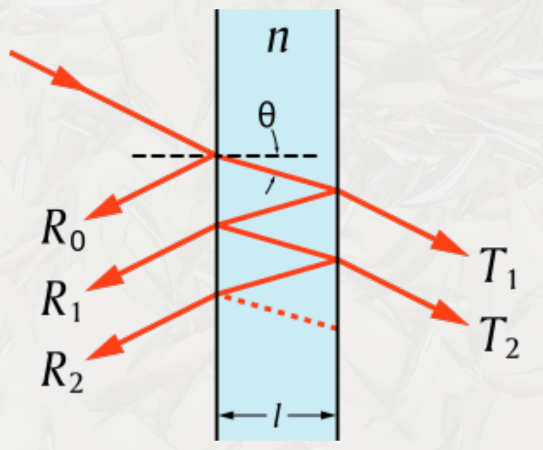


Fig. 3: A Fabry-Perot cavity is a chamber with partially reflective mirrors on either end. Light enters, bounces around, interferes constructively if an integer number of half-wavelengths fit neatly into the cavity length, and eventually exits the other side. We can monitor this released light: if our laser is initially resonant with the cavity but then the intensity of output light begins declining, we know that our laser is drifting, so we can send electronic feedback to the laser apparatus to tell it to nudge itself back in the direction of the desired wavelength.

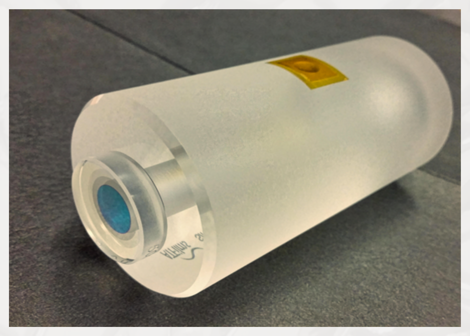


Fig. 4: The lab's Fabry-Perot cavity. It is constructed of a special glass with a coefficient of thermal expansion that is nearly zero at room temperature.

To integrate the Fabry-Perot cavity into an experimental optical setup, we needed to **build an enclosure** for it.

Design

Since it is critical to maintain a resonant relationship between the cavity and light of the right energy, the enclosure was designed with two primary goals in mind:

- Prevent cavity length from thermally or mechanically fluctuating
- Prevent changes in light wavelength due to travel medium's index of refraction

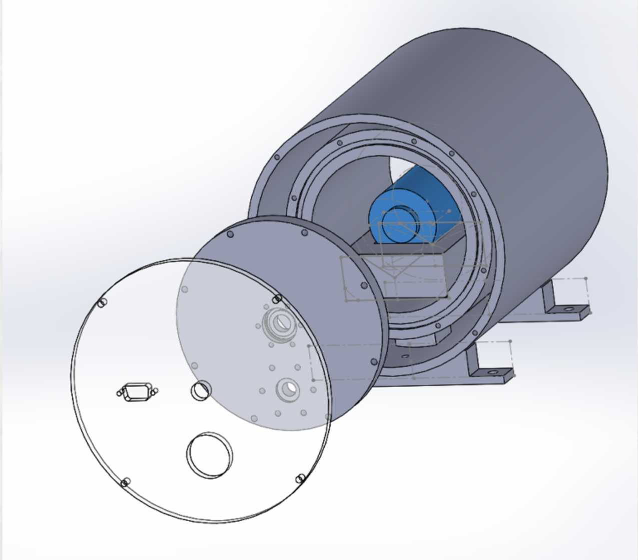


Fig. 5, at left: SolidWorks model of final design. The Fabry-Perot cavity (highlighted in blue) sits on a ceramic v-block inside of two concentric cylindrical chambers.

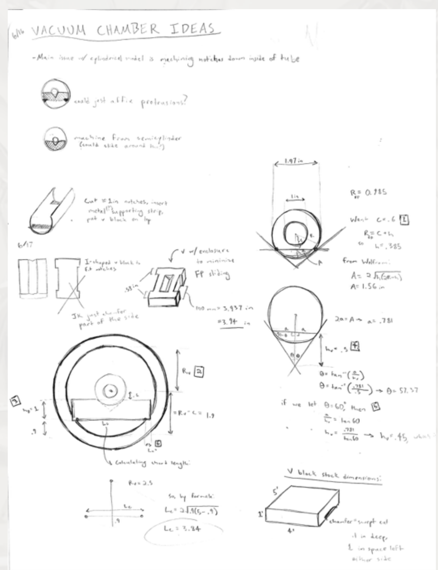


Fig. 6, at right: Preliminary calculations for proposed design.

Machining

Turning the design into something tangible was a process of acclimating to the many and varied tools the machine shop has to offer. As the summer progressed the vacuum chamber steadily neared completion, one part at a time.

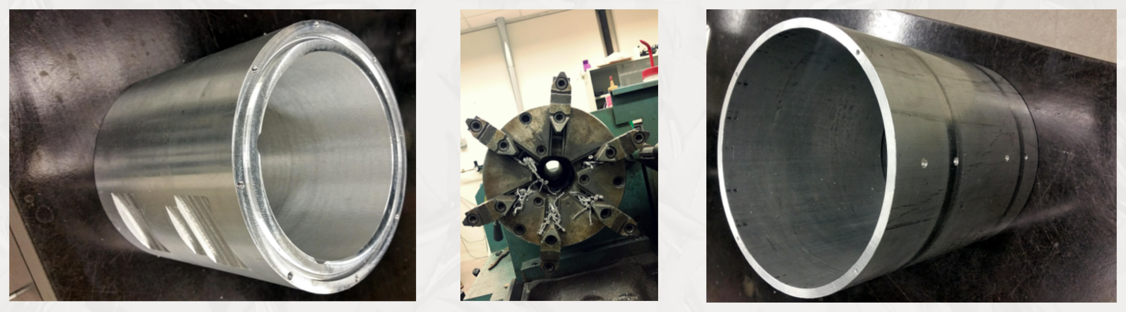
TEC Support Posts

Machined in the CNC, these posts support the weight of the inner assembly and thermally connect the thermoelectric coolers to the outer tube body (which acts as a heat sink).

Supporting Cradles

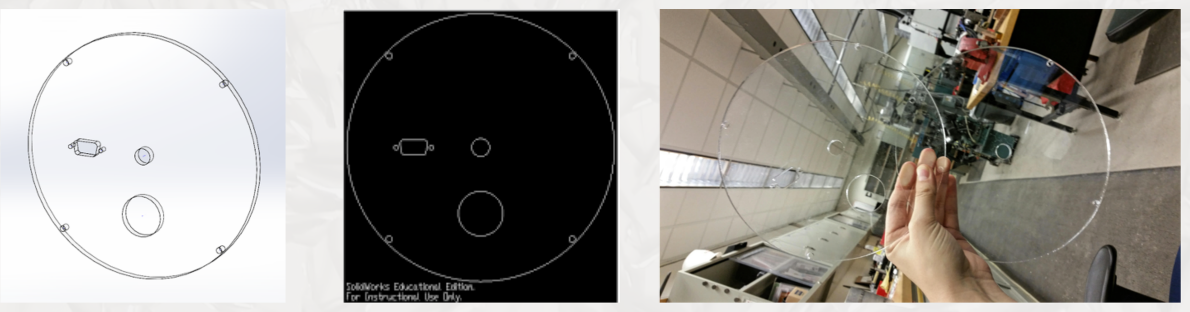
These parts support the weight of the entire assembly and allow mounting on an optical table. They were machined in the CNC.

Inner & Outer Tubes



The inner tube (at left) holds the v-block and vacuum, while the outer tube (at right) provides space for insulating the inner tube. Both tubes were shaped on the lathe, then brought to completion through manual and CNC work.

Outer Endcaps

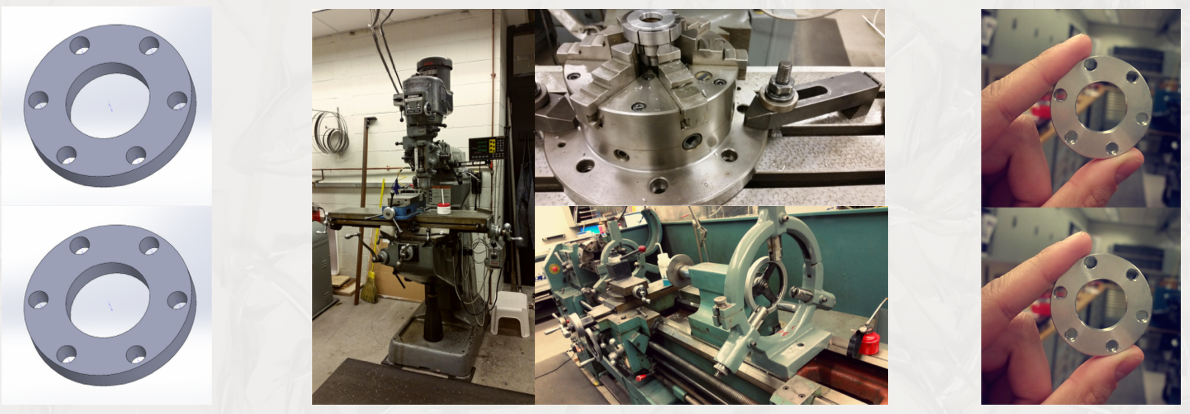


The outer endcaps mount on the ends of the outer tube. They were laser cut from acrylic to accommodate vacuum fittings and electronic connections.

Inner Endcaps

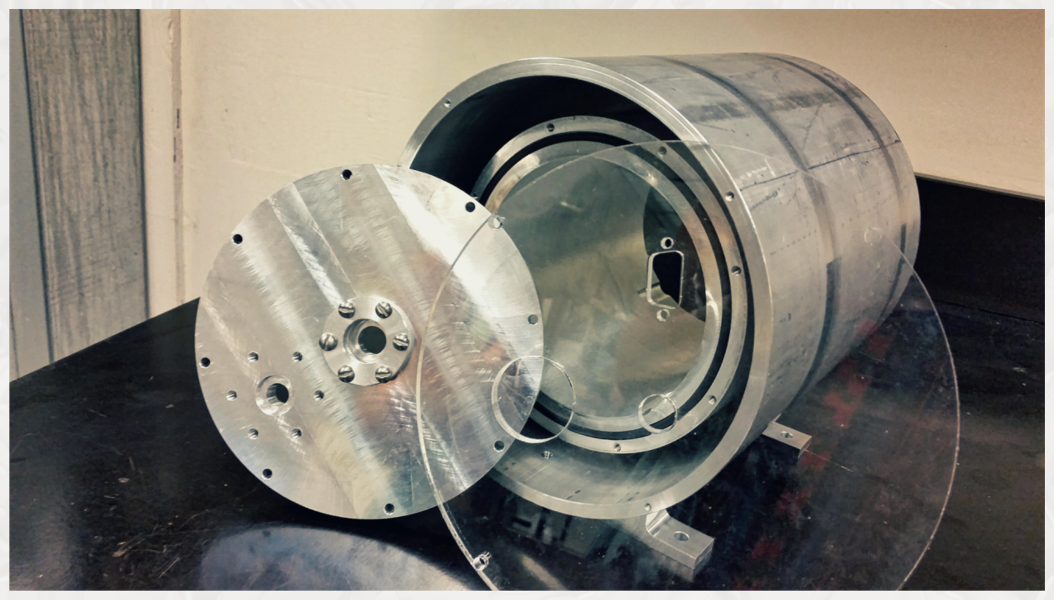
These endcaps hold an o-ring vacuum seal against the inner chamber. Machined in the CNC, they also accommodate the chamber's mirror and vacuum fittings.

Flat Plate Retainer



The flat plate retainer affixes the chamber windows to the inner endcaps. It was shaped on the lathe, and the bolt hole pattern was added on the mill.

Final Product



The parts fit together as designed!

Not pictured: the v-block (cut on the CNC as the poster printed); the Fabry-Perot cavity; mirrors; vacuum fittings; a lot of screws that'll hold the parts together; the optical table that'll be the assembly's eventual home.