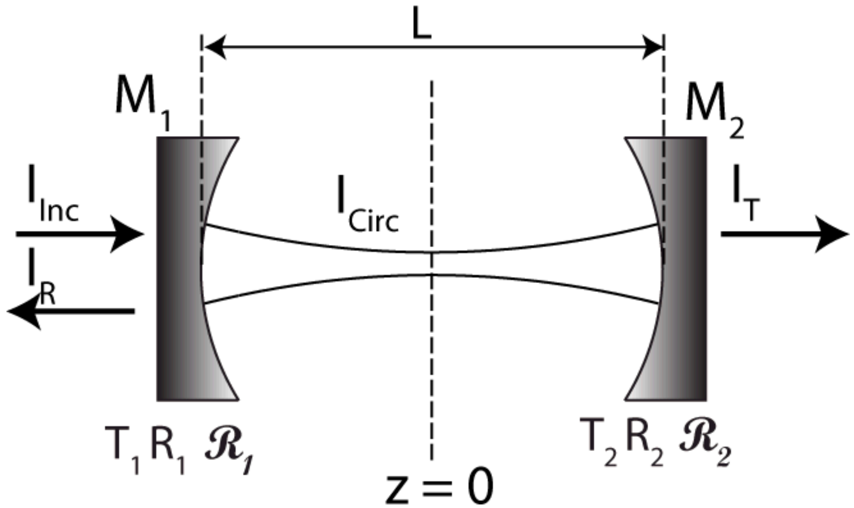
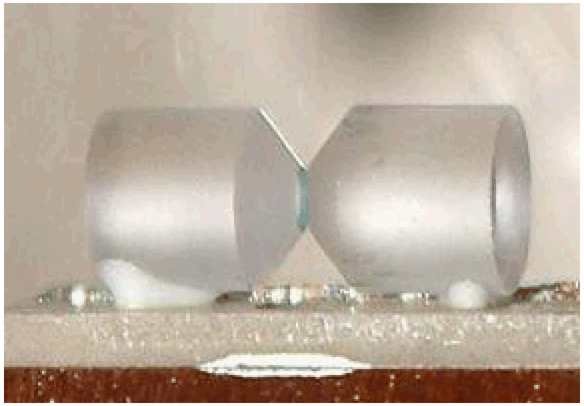
SAND2011-5671P

Coupling Single Ions to High Finesse Optical Cavities



Kevin M. Fortier
Sandia National Laboratories
Photonic Microsystems Department

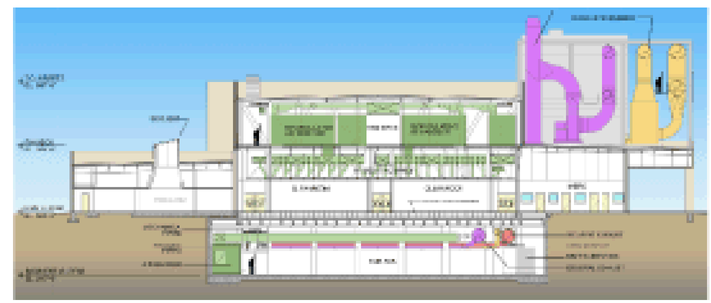


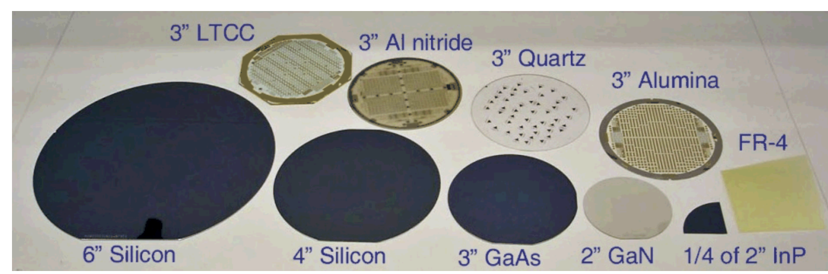
Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin company, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Facility specifications

- 2 Clean room facilities
- 13000 ft^2 Class 1 clean room for Si CMOS and Si MEMS
- 16,640 sq. ft. Class 10 and Class 100 clean room for Group IV and III/V devices
- Many tools reconfigurable from wafer pieces to 6" wafers
  - Many with little or no hardware changes required
- 6" silicon post-processing and packaging facilities to support device wire-out, hybrid substrates, and 3D integration

The "Machine Shop"

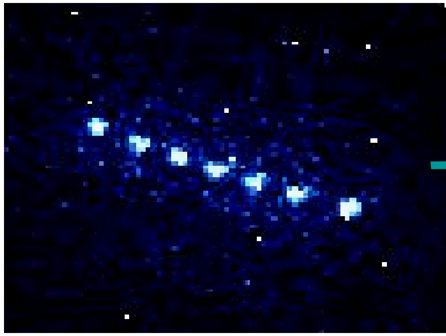


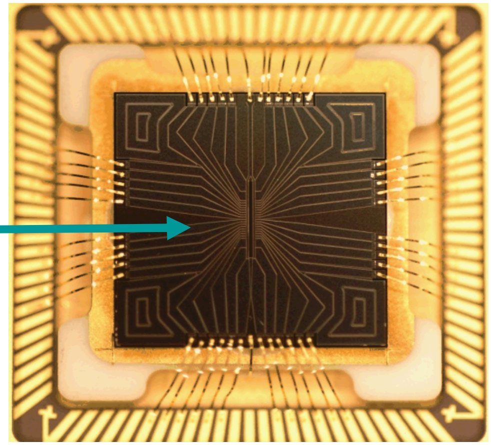


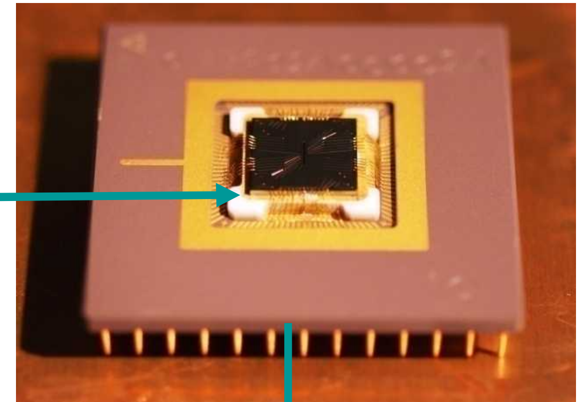
AMO physics lab is here

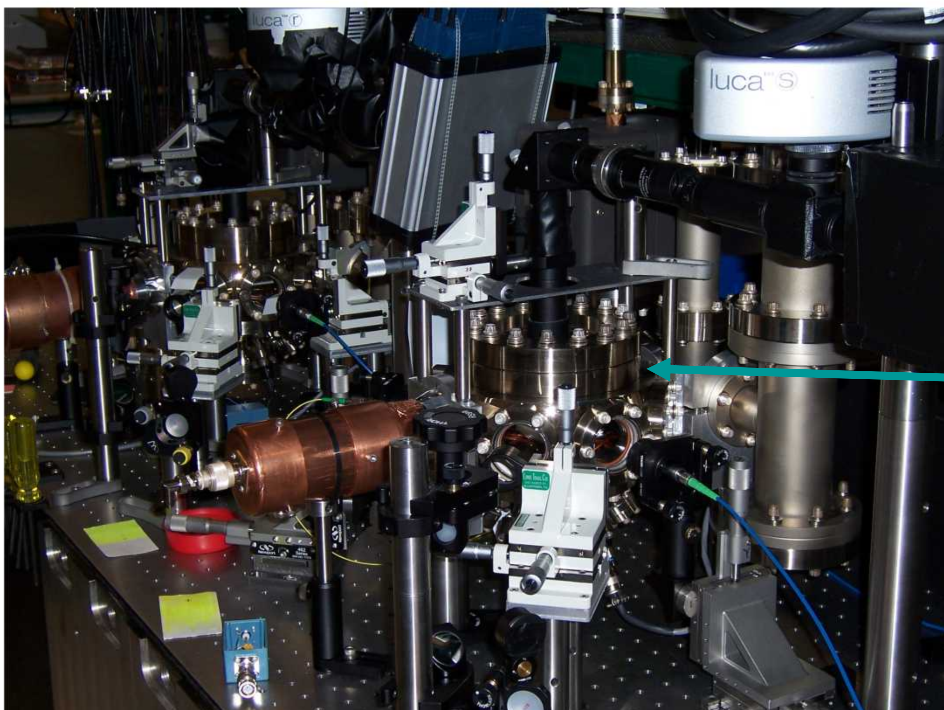
Trap operation and testing

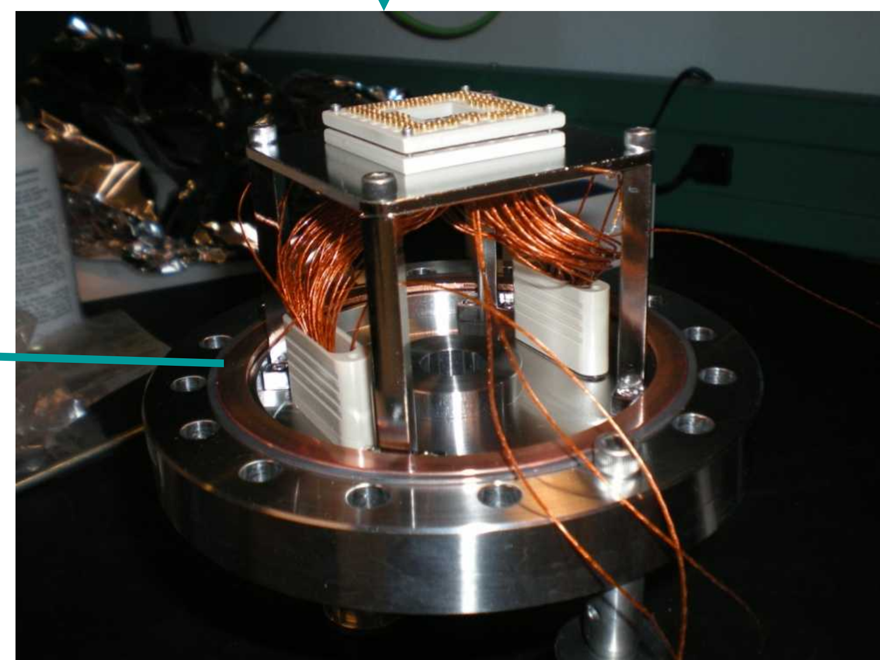
7 Ca^+ ions



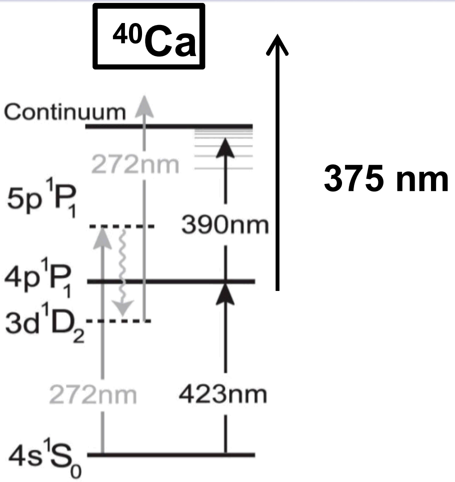


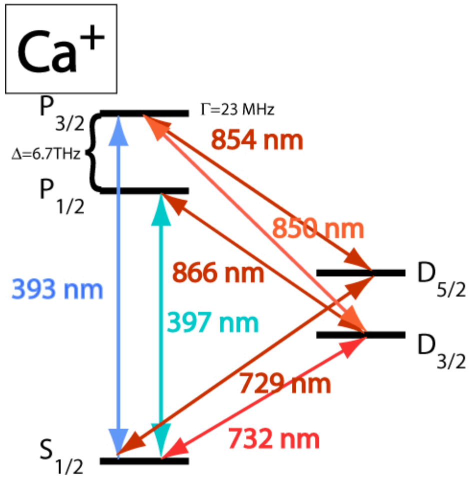


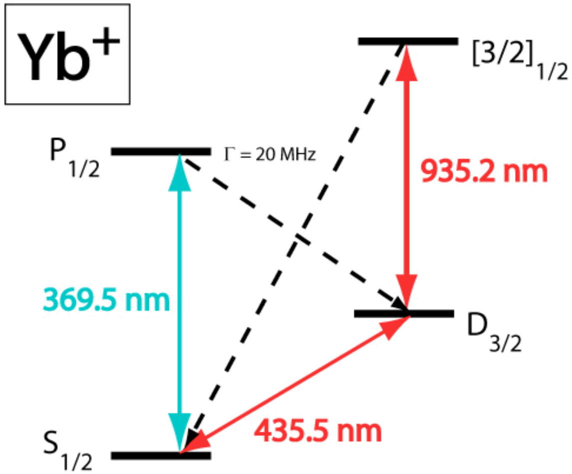




Lasers Cooling and Trapping Single Ca⁺ ions and Yb⁺







Laser Infrastructure for Ca^+

•Diodes:

1. ECDL: 846 -> SHG to 423 in PPKTP
2. Fabry-Perot: 375nm
3. Fabry-Perot: 850 nm
4. DFB: 854 nm
5. ECDL: 866 nm
6. ECDL: 729 nm

•SHG for 397 nm

7. ECDL pumped TA with SHG cavity

Laser Infrastructure for Yb^+

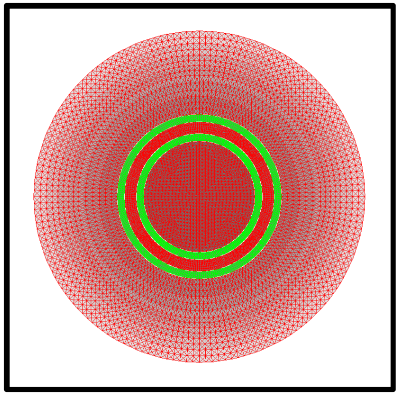
•Diodes:

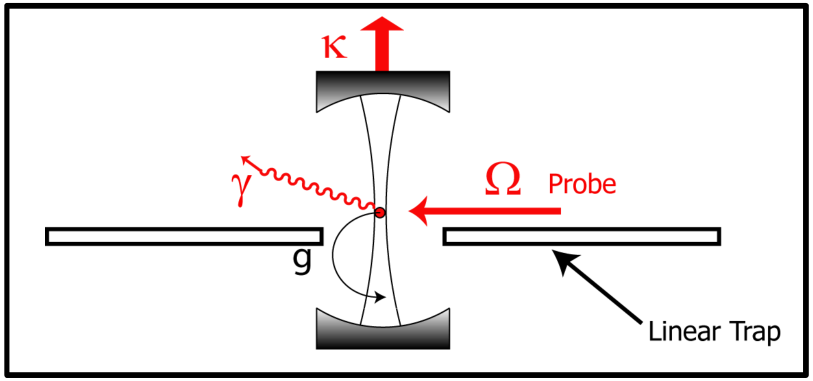
1. ECDL: 398 -> SHG to 398 in PPKTP
2. ECDL: 935 nm
3. ECDL: 729 nm

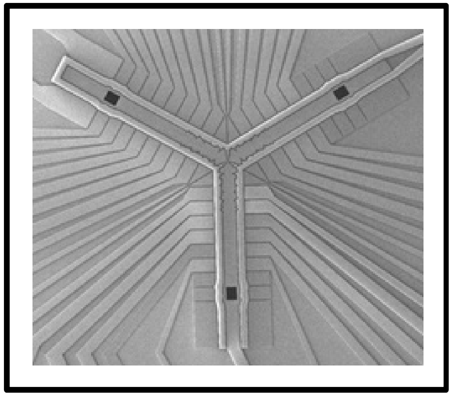
•SHG for 369.5 nm

4. ECDL pumped TA with SHG cavity

11 Lasers on 5' x 12' optical table brought to the experiments via optical fiber







Experimental:
D. Moehring
D. Stick
K. Fortier
C. Highstrete
F. Benito
B. Tabakov

Packaging
L. Fang
R. Haltli
J. Gallegos
B. Thurston

Optics
S. Kemme
R. Ellis
G. Brady

Fabrication
M. Blain
J. Stevens
D. Udoni
R. Jarecki
B. Loviza
S. Volk
P. Clews
A. Ortega
C. Wakefield

Modeling:
C. Tigges

Management
M. Descour

Quantum Information provides an exponential speedup for ***particular*** algorithms (most notably Shor's factoring algorithm)

IARPA

Cavity QED requirements for MUSIQC

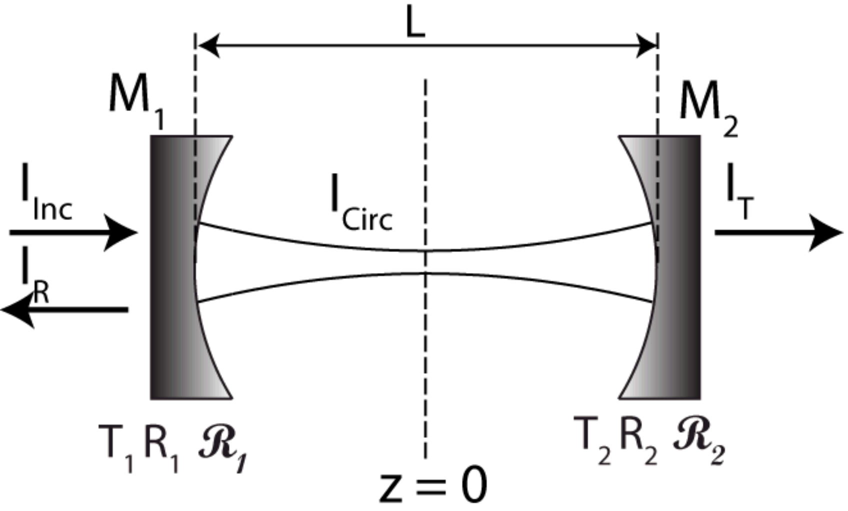
Customer engineering specifications (from Physicists):

A. Demonstration of high optical quality for the cavity structure, with minimum finesse >1,000 at 369.5nm. Finesse of >3,000 desired at 369.5nm.
B. Low enough loss in the mirror coatings to guarantee that cavity finesse is dominated by output mirror transmission rather than scatter/absorption losses (<<500ppm at all wavelengths of interest).
C. Adequate trap-cavity integrated structures to achieve a cooperativity parameter $\mathbf{C_1 > 0.2}$.
D. Adequate mechanism for ion loading should be provided.
E. Mechanical packaging and assembly scheme to align and stabilize the optical cavity should be provided.
F. Development of fabrication approach that is compatible with an anharmonic linear trap structure and more complex trap geometries (e.g., junctions, etc.).
G. Details of trap dimensions: Exact ion location with respect to the cavity mode, length of optical cavity and cavity mirror reflectance to achieve the desired Purcell enhancement factor (or cooperativity parameter) to be determined.

from “Trap needs for IARPA MUSIQC Program” document

IARPA

Cavity QED Geometry



Using mirror geometry and reflectance we can compute the relevant CQED parameters:

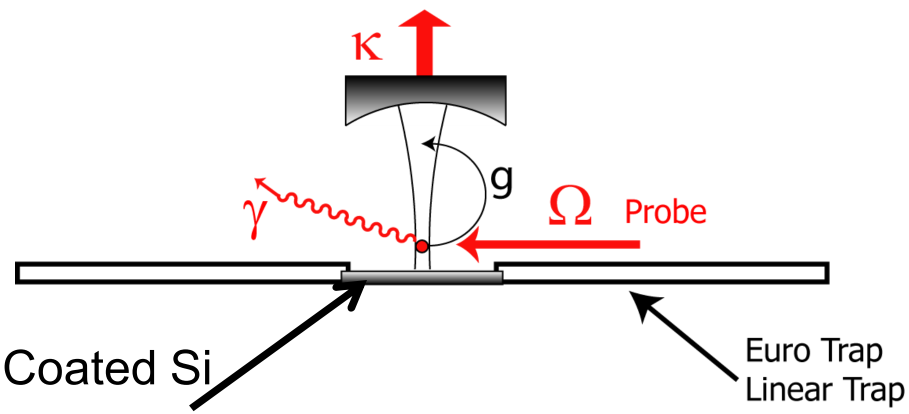
- Finesse = 2 π/Loss
- w_0 – Beam Waist
- V_m – Mode Volume
- κ – Cavity Line Width
- g – Coherent Coupling Rate
- C – Single Atom Cooperativity

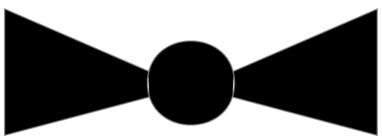
$$g \propto \frac{1}{\sqrt{V_M}}$$

$$C = \frac{g^2}{\kappa \Gamma}$$

Hybrid Integrated Cavity

Hybrid Integrated cavity





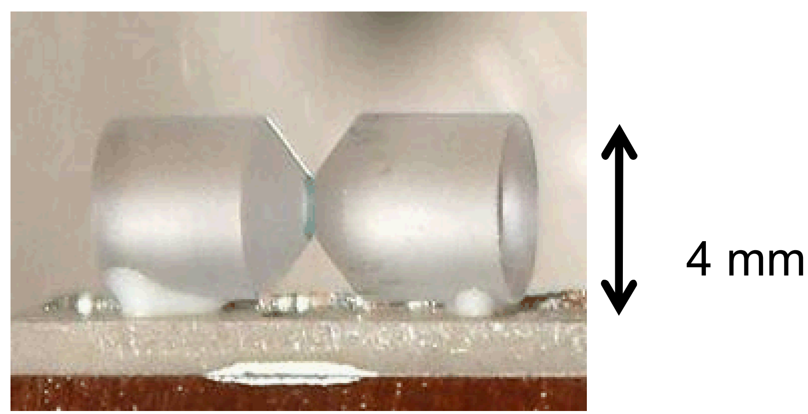
Ion Beam Sputter Si
"puzzle piece"

Advantages:

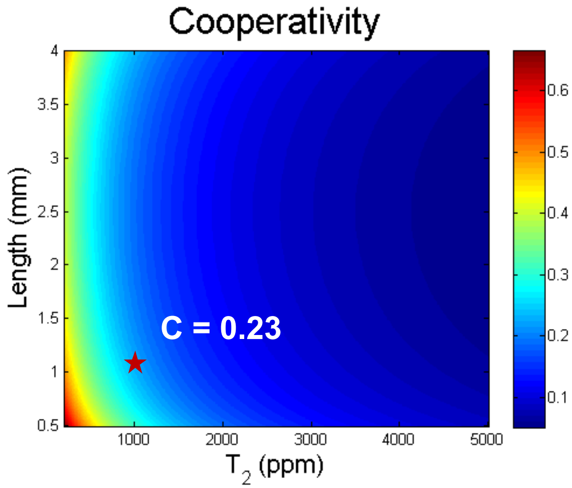
- Cavity Mirrors are protected from neutral atoms
- "Simple construction"

Disadvantages:

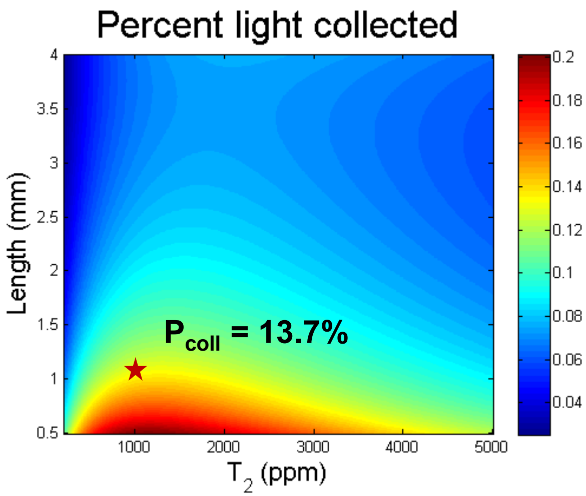
- Ion isn't located at the minimum waist
- Transmitted cavity beam not available using Si



Clasiical and Quantum Optics Design of Optical Cavity



$$C = g^2 / \kappa\Gamma$$



$$P_{col} = \frac{T_2}{\mathcal{L}}\left(\frac{2\kappa}{2\kappa+\Gamma}\right)\left(\frac{2C}{1+2C}\right)$$

$L = 1\ \mathrm{mm}$

$\mathrm{RoC}_1 = \infty$

$T_1 = 200\ \mathrm{ppm}$

$\mathrm{RoC}_2 = 5\ \mathrm{mm}$

$T_2 = 1000\ \mathrm{ppm}$

$\frac{\kappa}{2\pi} = 17.905\ \mathrm{MHz}$

$\frac{g_0}{2\pi} = 9.061\ \mathrm{MHz}$

$\frac{\Gamma_{Yb}}{2\pi} = 19.600\ \mathrm{MHz}$

$C = 0.2339$

$P_{col} = 13.73\%$

$\Im = 4188$

scatter loss per mirror $= 150$ ppm

$w(z_1) = 15.34\ \mu\mathrm{m}$

$w(z_{\mathrm{chip}}) = 15.35\ \mu\mathrm{m}$

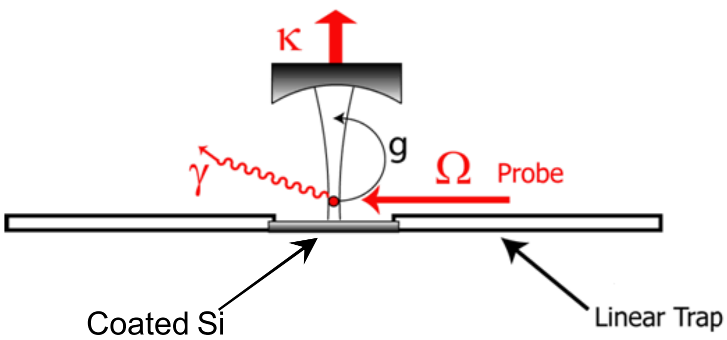
$w(z_{\mathrm{ion}}) = 15.38\ \mu\mathrm{m}$

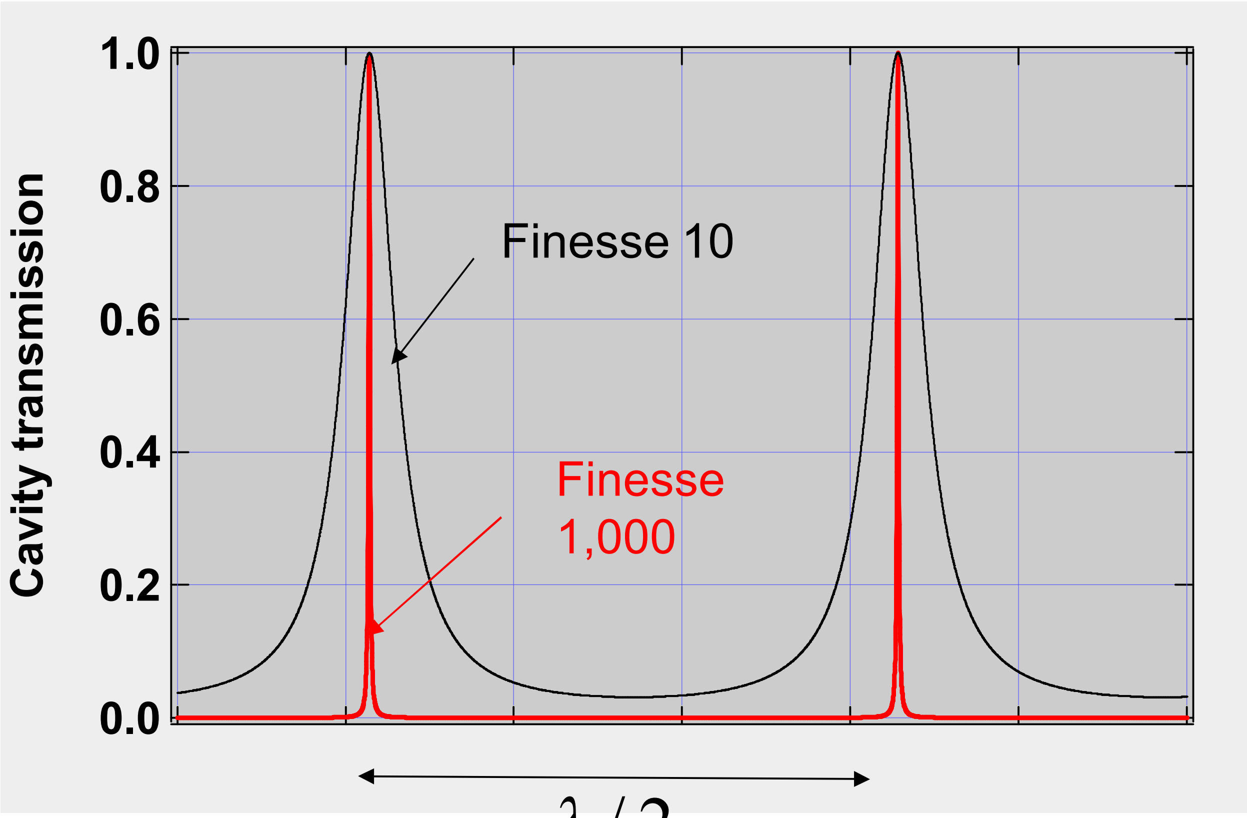
$w(z_2) = 17.15\ \mu\mathrm{m}$

$g_1 g_2 = 0.8$

stability

$0 \le g_1 g_2 \le 1$





$\lambda / 2$

Cavity Linewidth
in terms of length

$$\Delta L \sim \frac{\lambda / 2}{\Im}$$

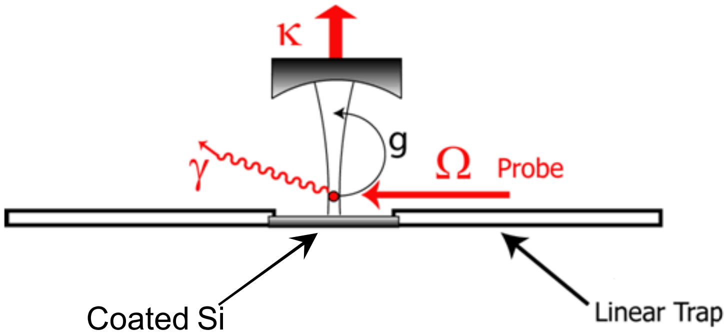
$$\Im = 10,000$$

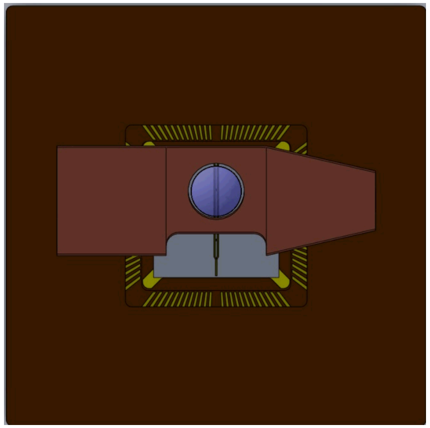
$$\Delta L \approx 3 \times 10^{-12}$$

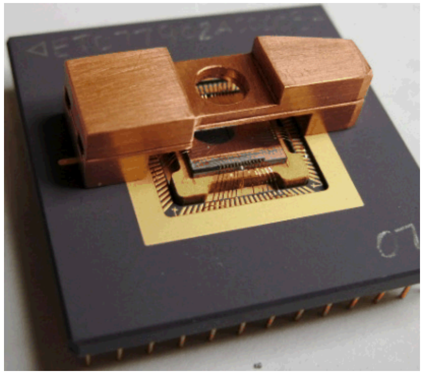
100 times smaller than an atom

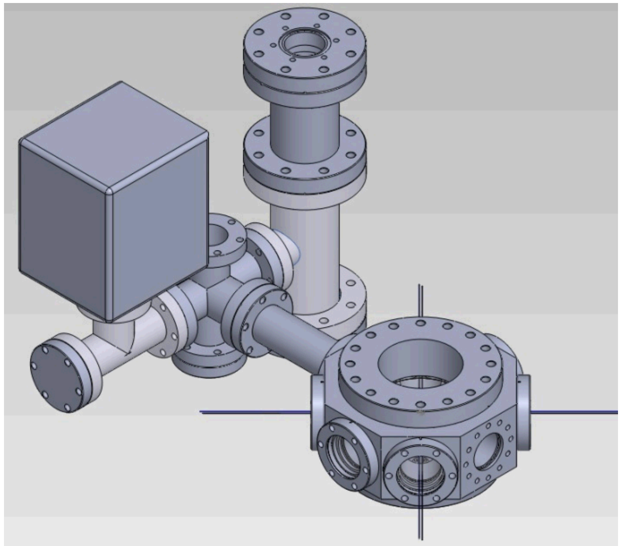
Requires: vibration isolation,
vacuum,
quiet electronics $V_{PZT} \sim 1$ kV, $V_{noise} < 1$ mV
1 ppm

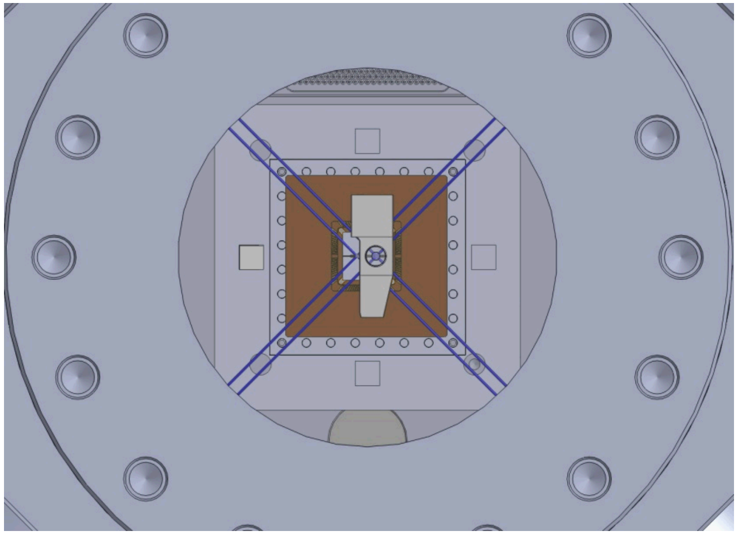
Mechanical Design of Cavity QED mount and chamber

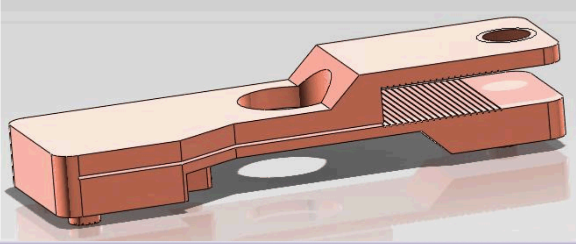




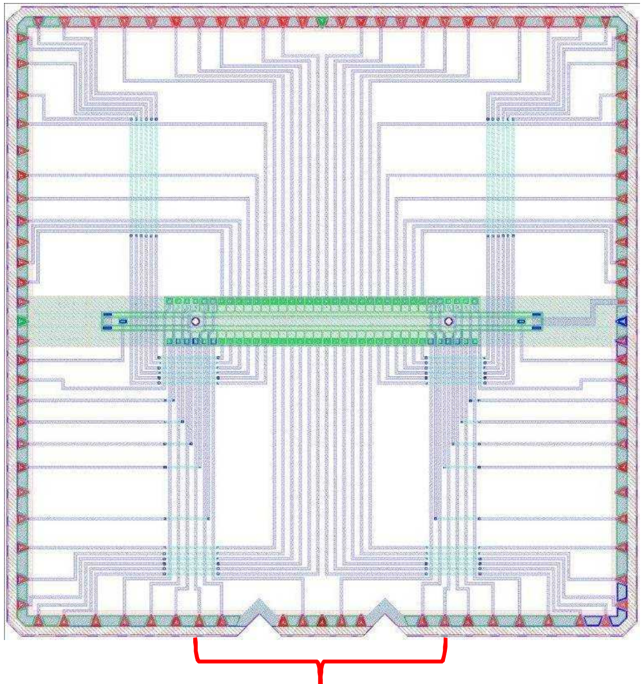


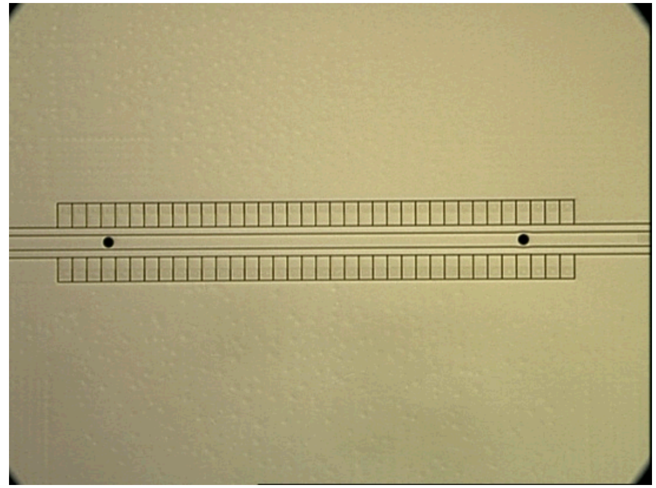


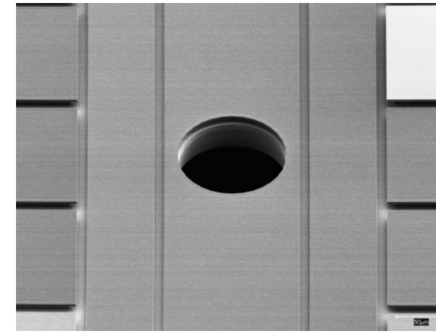


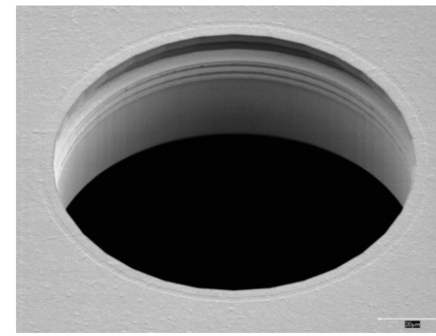


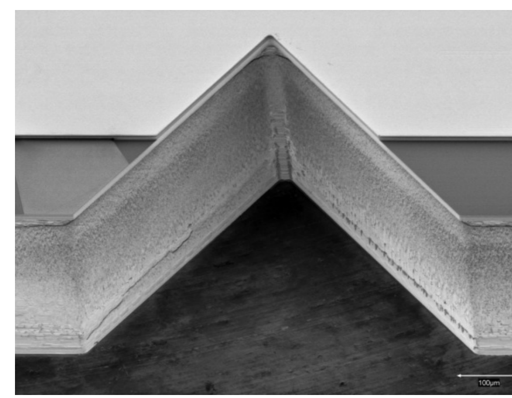
Integrated optical cavity in with ion trap: Trap Design and Fabrication



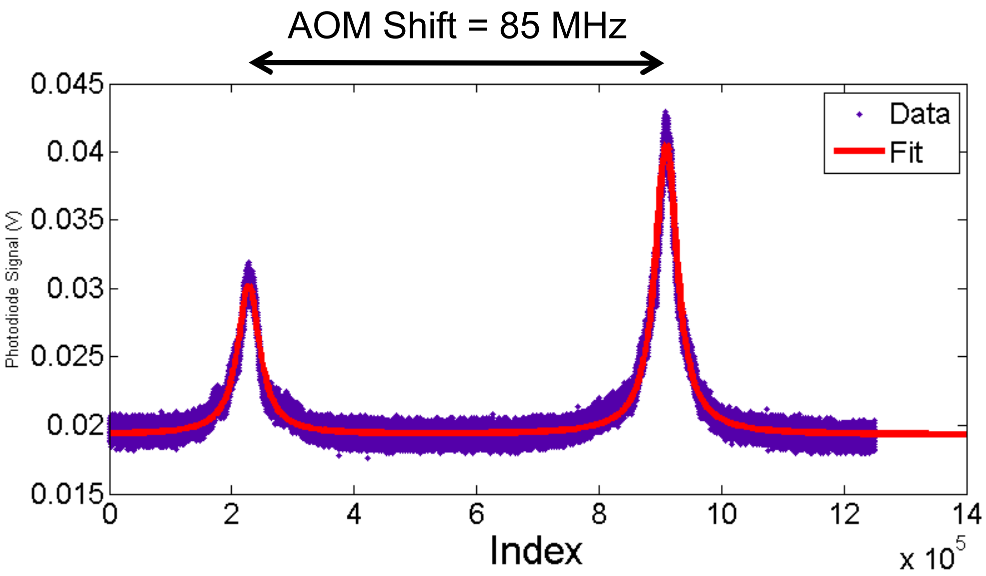








Integrated Cavity QED: Mirror Characterization



Measured Results

$L = 7\ \mathrm{mm}$

$\mathrm{RoC} = 2.5\ \mathrm{cm}$

$\mathrm{FSR} = 21.44\ \mathrm{GHz}$

$\Delta\upsilon_T = 5.233\ \mathrm{GHz}$

$\kappa = 2.55\ \mathrm{MHz}$

$T = 215\ \mathrm{ppm}$

$\text{Scatter Loss} = 532\ \mathrm{ppm}$

$\text{Total Loss} = 1495.3\ \mathrm{ppm}$

$\text{Finesse} = 4403$

Acknowledgments

<u>Ion Trap Heroes:</u>

Daniel Stick

Francisco Benito

Jon Sterk

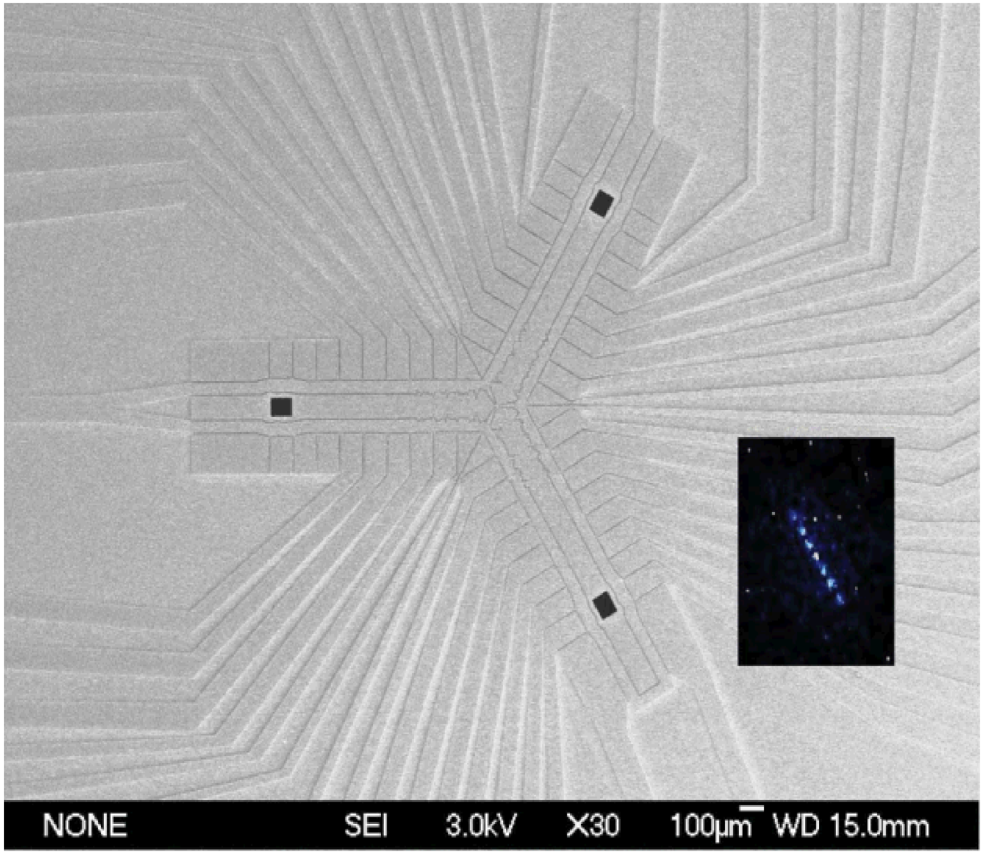
Tom Hamilton

David Moehring

Clark Highstrete

Matt Blain

Chris Tigges



$$$: I A R P A