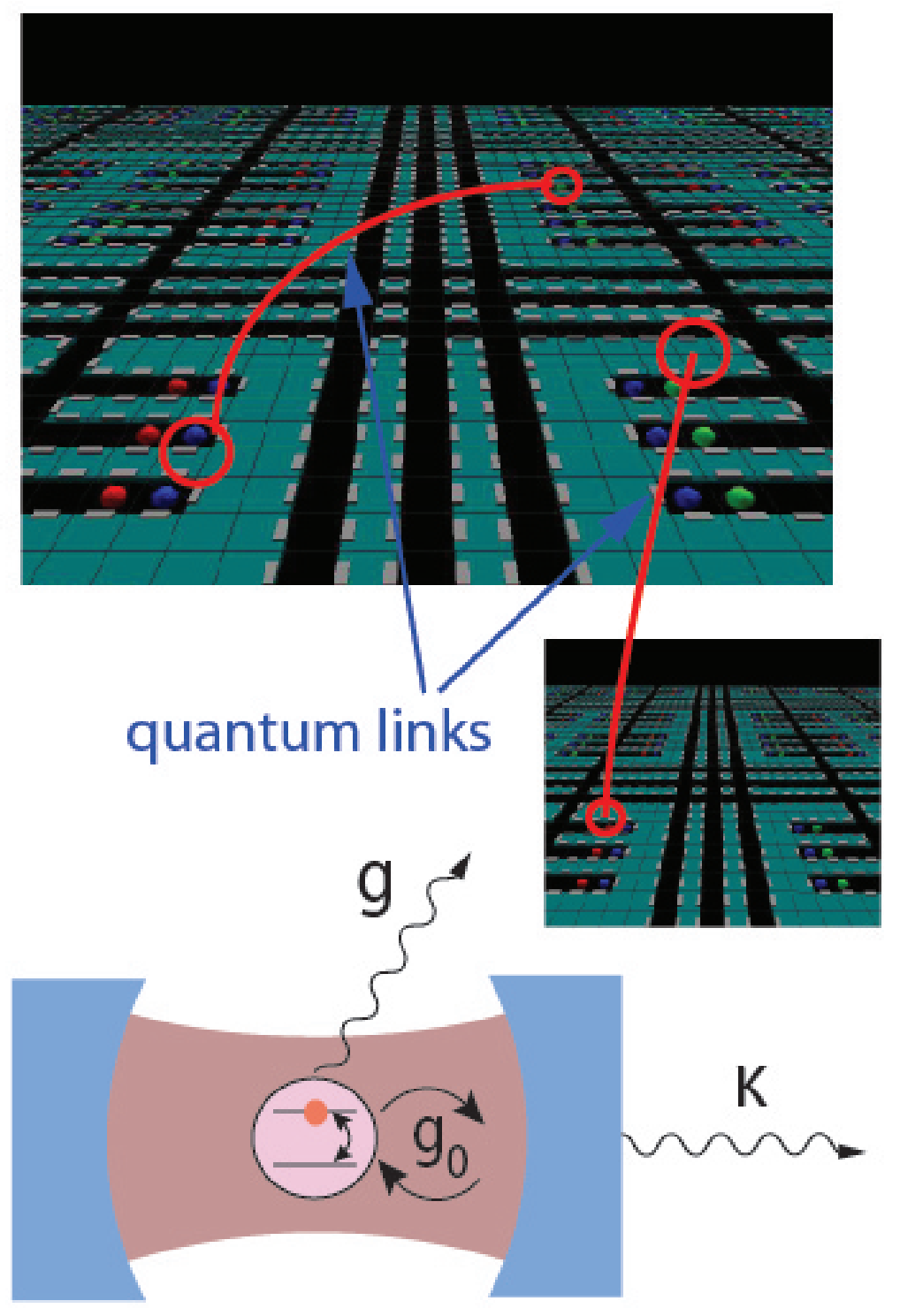
# A micro-fabricated surface ion trap on a high reflectivity optical mirror

M. Shi, P. F. Herskind, S. X. Wang, Y. Ge, W. Chen, M. Cetina, V. Vuletic, I. L. Chuang

Center for Ultracold Atoms, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

## Introduction



Motivation:
Multi-qubit operations in a large scale ion trap quantum computer must involve interconnecting trapped ions at several designated sites, without cross-talk to other ions. One suitable interconnection method maps quantum states of ions to photons, using strong atom-light interactions. This can be accomplished by coupling ions to high finesse optical cavities.

Challenges:

(i) the trapping potential can be perturbed in the presence of dielectric mirrors, which affect both the trap rf-fields and allows build-up of stray charges on the substrates via light-induced charging;

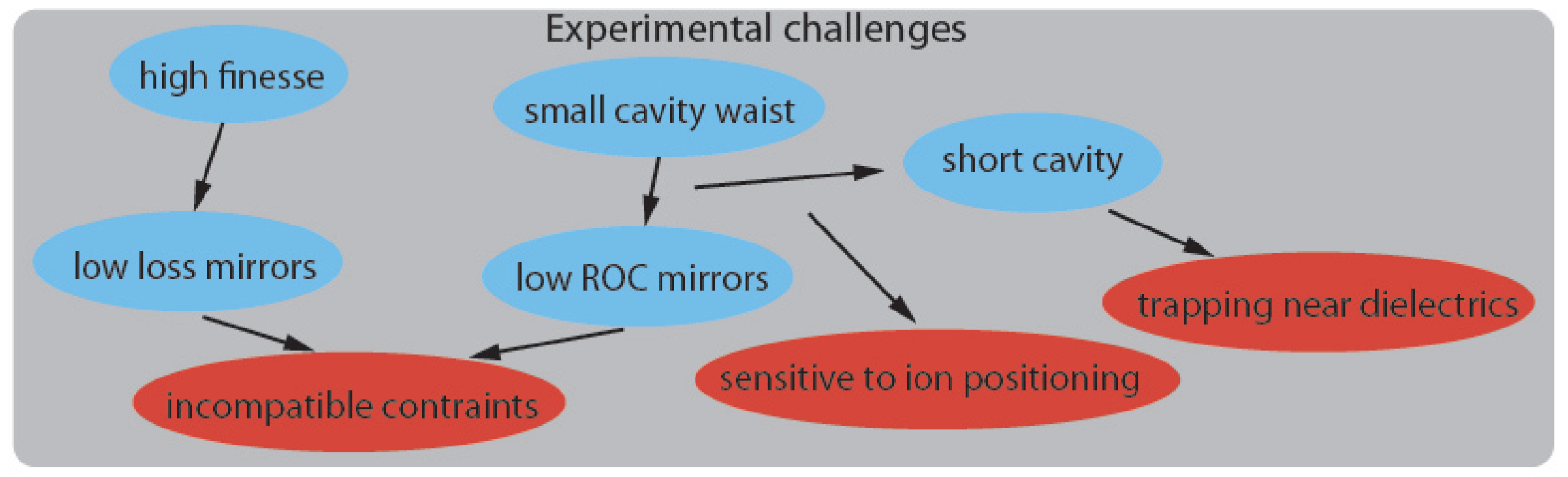
(ii) when close to material surfaces, anomalous heating of ions may lead to rapid decoherence of their motional states;

(iii) the need for scalable trap technology imposes severe design and fabrication constraints on the experiment.

Strong coupling criteria: $g_0 > \kappa, \gamma$

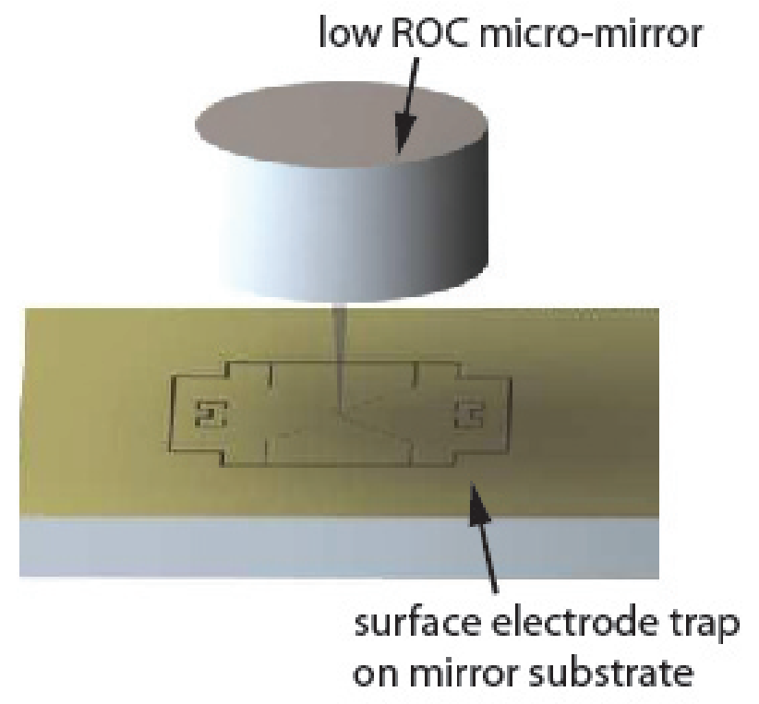
Cooperativity $C = \frac{g_0^2}{\kappa\gamma} = \frac{6F\lambda}{\pi^3 w_0^2}$

Figure of merit:
Fidelity of ion-photon mapping [4]: $\sim \frac{C}{C+1}$


Experimental challenges

high finesse
small cavity waist
short cavity
low loss mirrors
low ROC mirrors
trapping near dielectrics
sensitive to ion positioning
incompatible contraints

This work:
Here we present a new approach for integrating an optical cavity into an ion trap, by employing a surface electrode ion trap fabricated on top of a high reflectivity mirror. We evaluate optical losses incurred by the micro-fabrication, characterize basic trap performance, and describe plans for incorporating a second low ROC miror to form a high finesse cavity.



## Road map

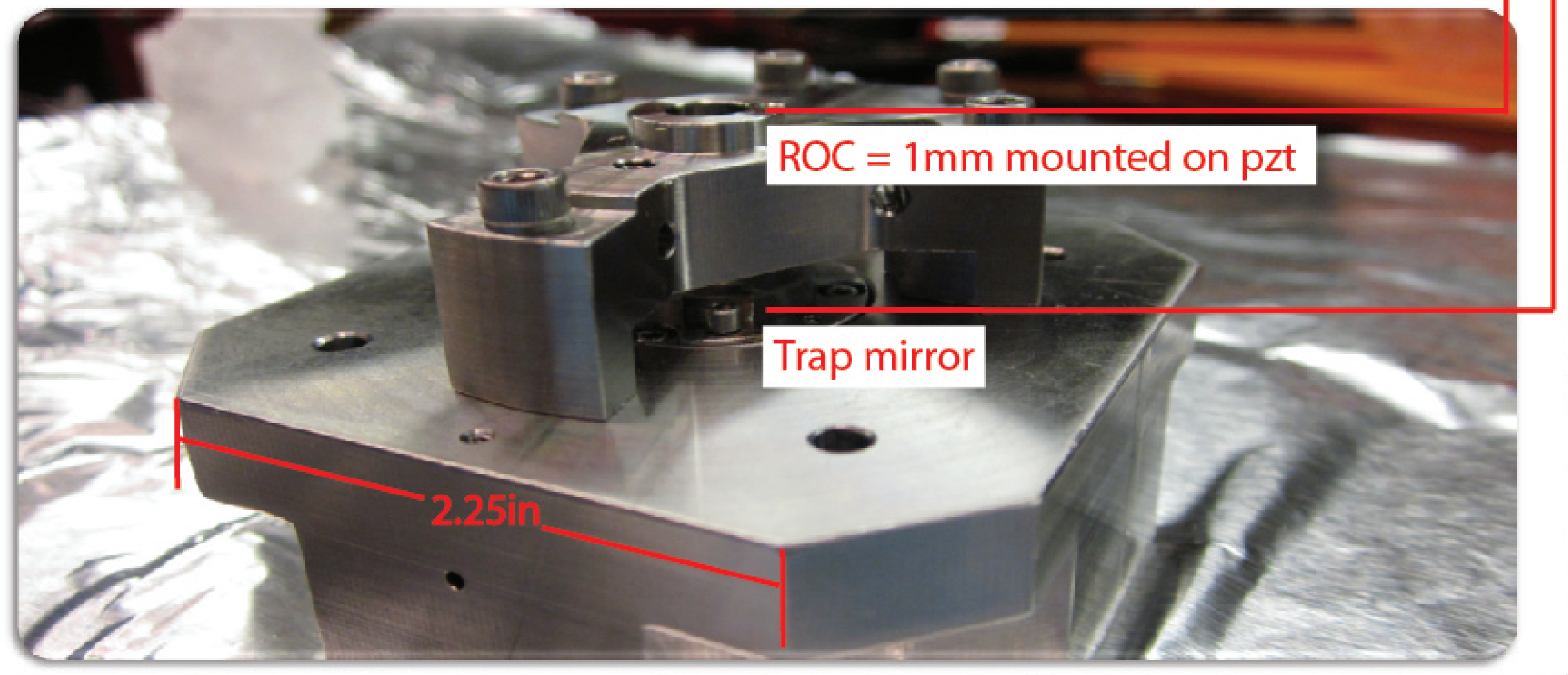
Ion trap on a high finesse mirror

- Fabrication of surface electrode ion trap on high-finesse mirror while leaving aperture in electrode underneath ion for optical access to mirror
- Study of ion trapping ~150um above surface of mirror
- Post-fab mirror loss characterization

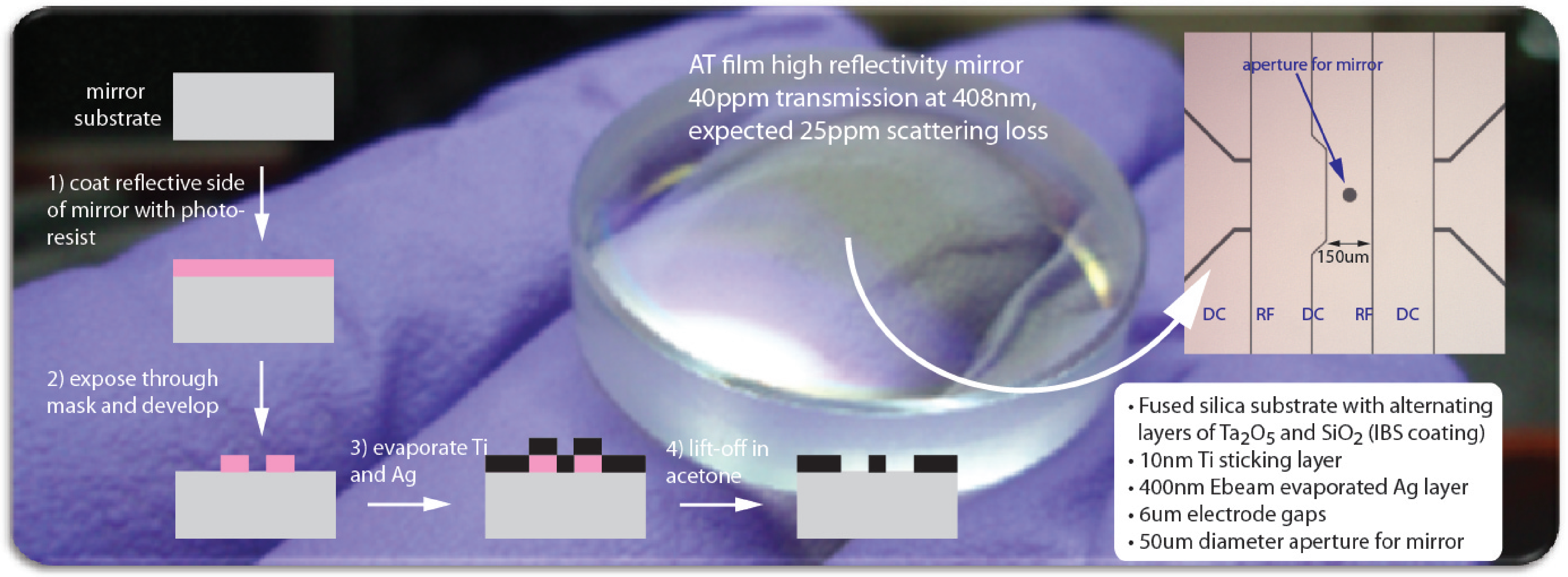
Laser machined low ROC mirror

- Laser machined micro-mirrors with ROC =50um-1100um for micro-avity
- Cavity finesse characterization

Future cavity + ion system



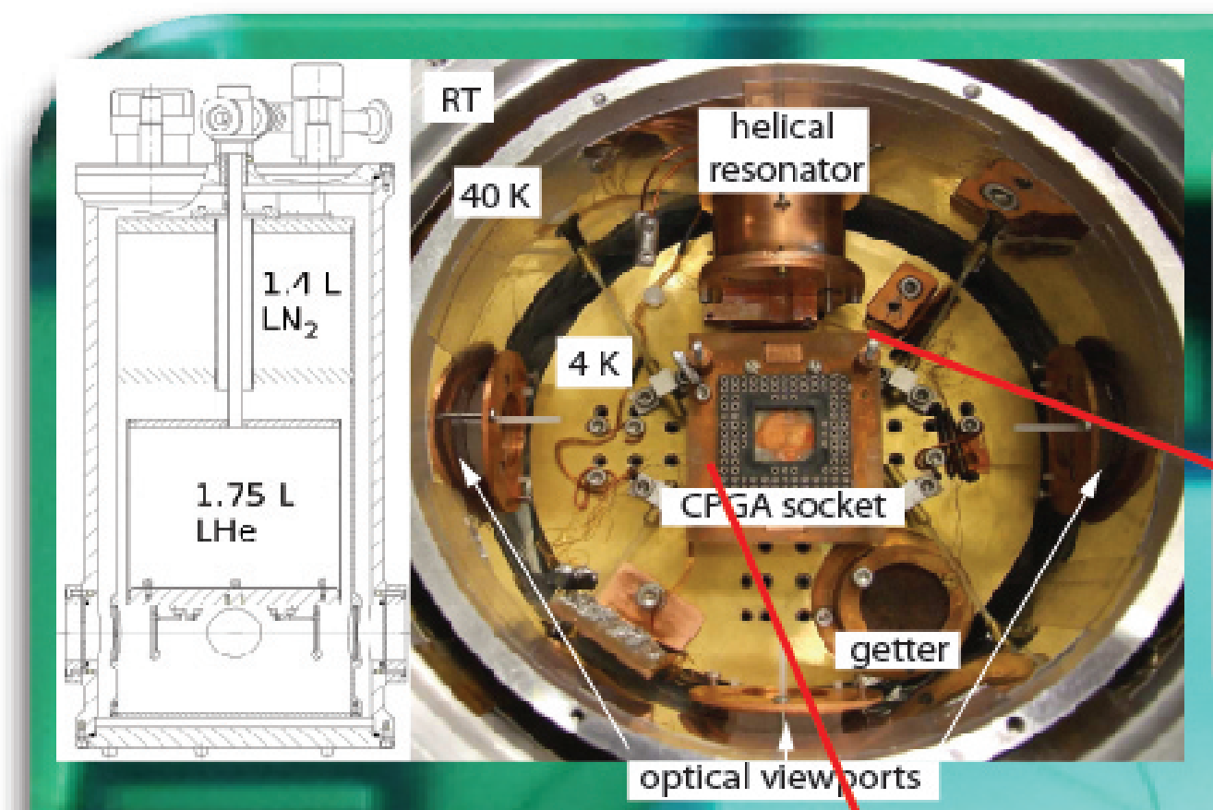
## Microfabrication of a surface electrode ion trap on a dielectric mirror



AT film high reflectivity mirror
40ppm transmission at 408nm,
expected 25ppm scattering loss

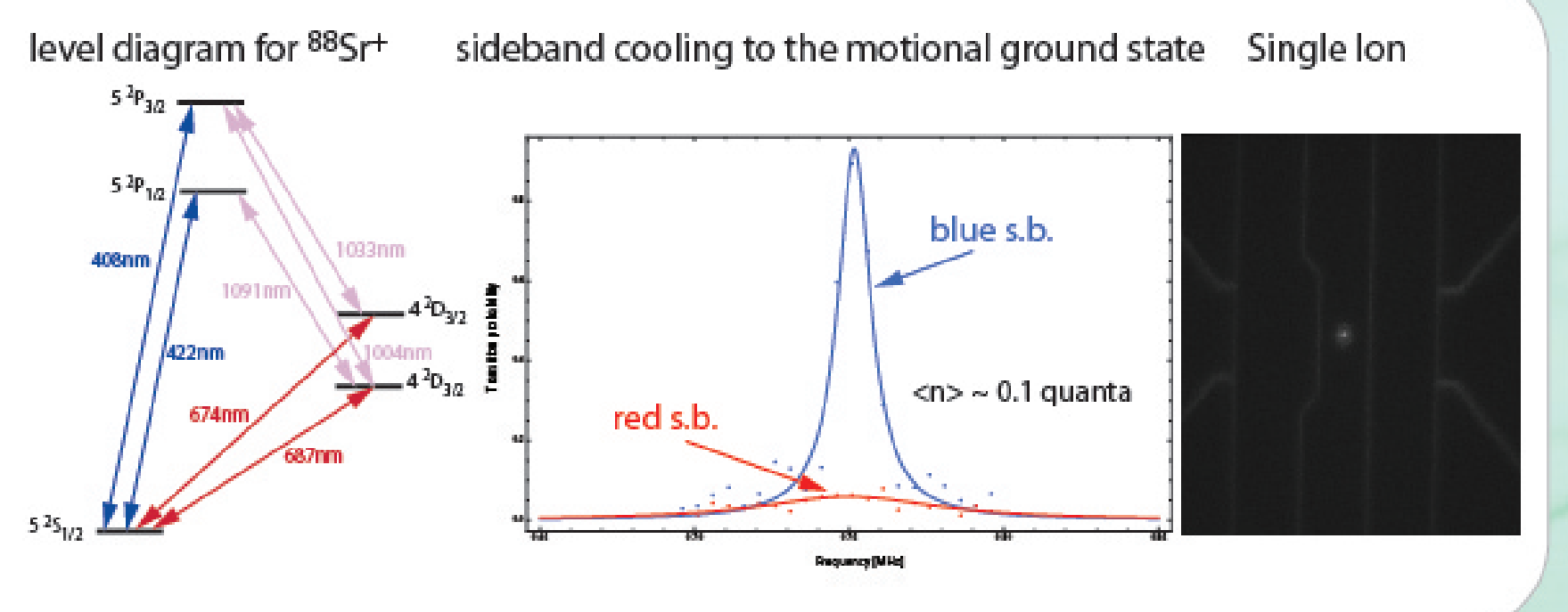
- Fused silica substrate with alternating layers of $Ta_2O_5$ and $SiO_2$ (IBS coating)
- 10nm Ti sticking layer
- 400nm Ebeam evaporated Ag layer
- 6um electrode gaps
- 50um diameter aperture for mirror

## Trapping ions above the surface of a dielectric mirror

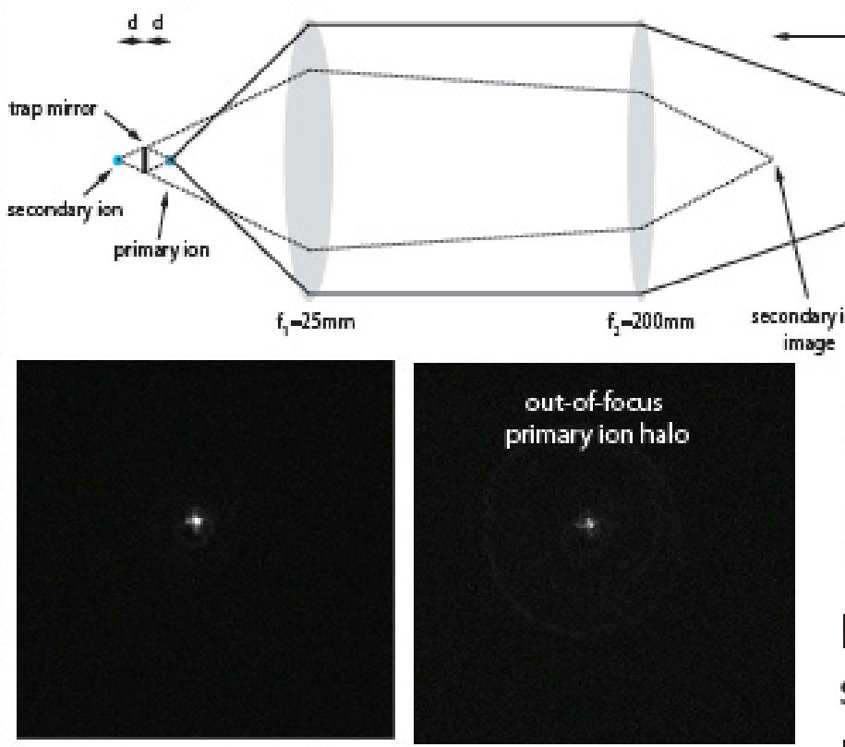


### Trapping and cooling

- Doppler cooling life-times of ~ hours
- Micromotion minimized and compensation tested stable for at ~ 1 hr
- Motional ground state cooling achieved



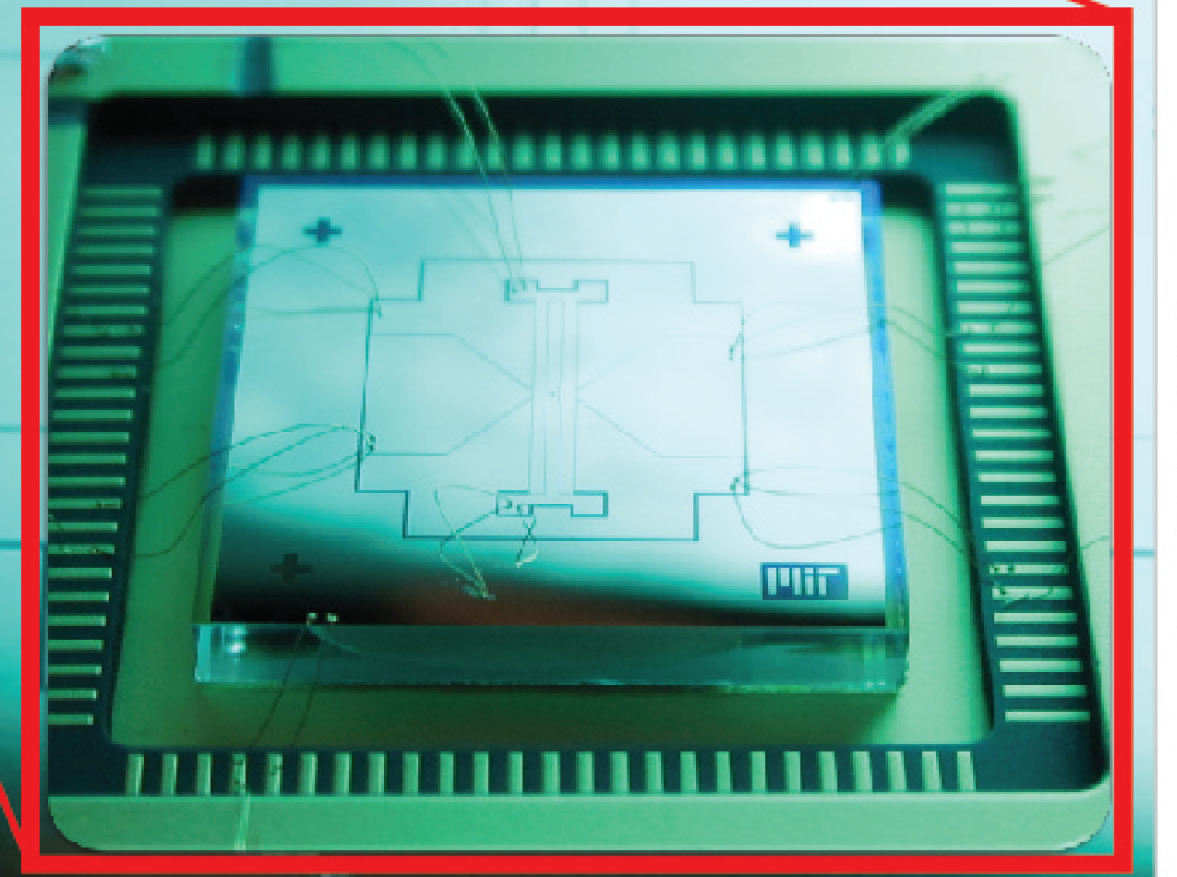
### An ion and its mirror image



primary ion image(left) seondary ion image(right)

Numerical simulations predicts ion height of 165mm

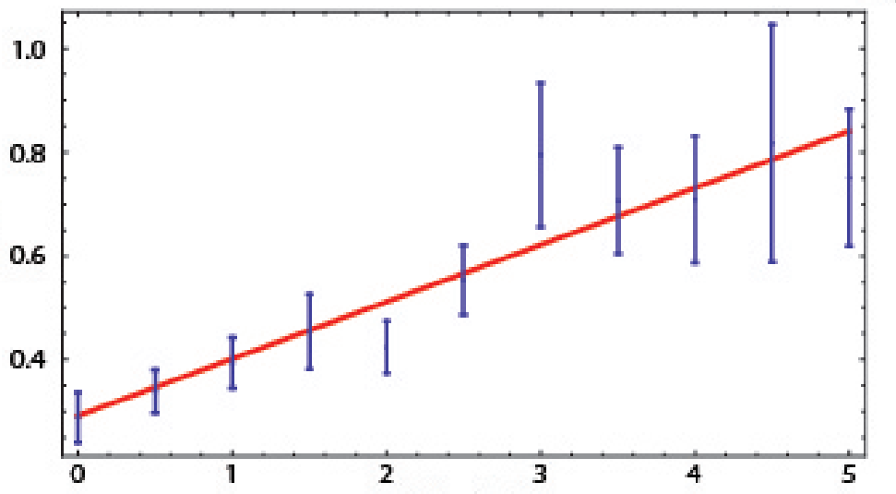
$$d \sim \frac{\Delta}{2}\left(\frac{f_1}{f_2}\right)^2 = 164 \pm 8\,\text{um} \quad (\text{for } d \ll f_1)$$



### Motional heating of trapped ion

Anomalous heating rate~1/[ion height]$^4$ [6]

At ~6K, heating rate measured to ~0.1 quanta/ms (compare against best result for similar Ag trap of 2quanta/s) [7].

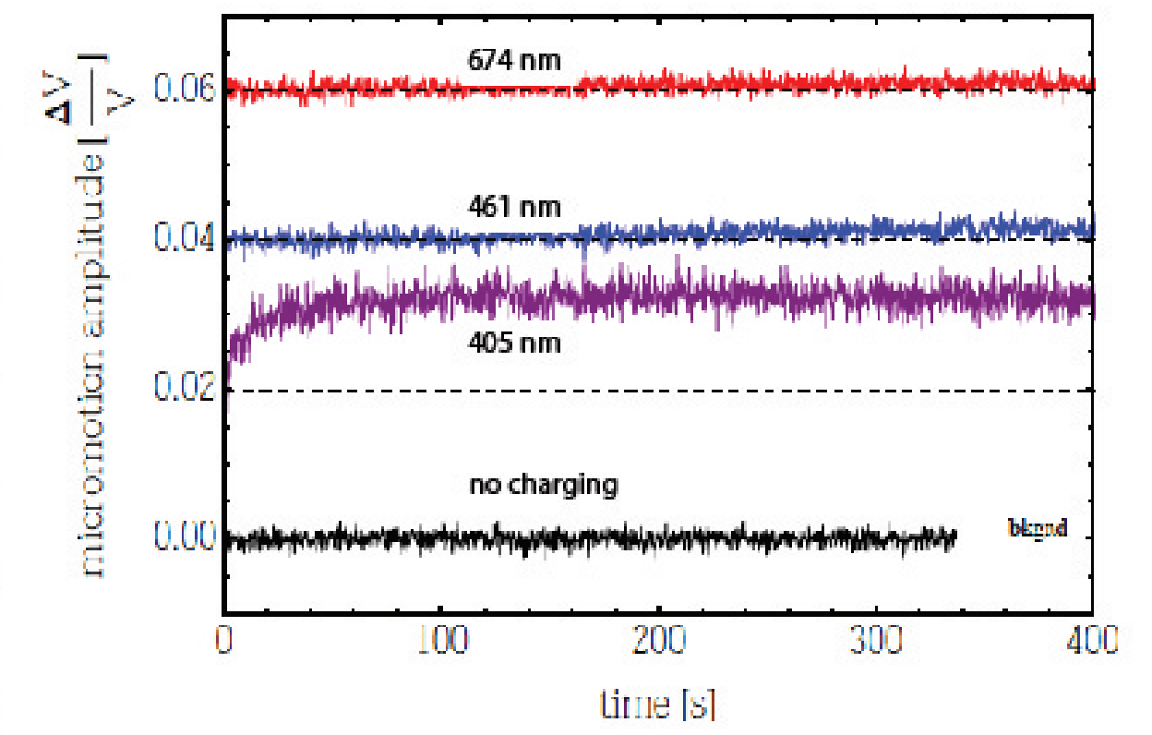


### Sensitivity to light-induced charging

Issue:
low ion height brings laser beams close to trap, which can result in photo-electric charging that perturbs

Results:

- effect evaluated via induced micromotion amplitude
- Wavelengths: 405nm, 461nm and 674nm.
- Intensity: ~100uW in 50um waist. Beams parallel with trap surface (grazing).
- priliminary tests show minimal effect

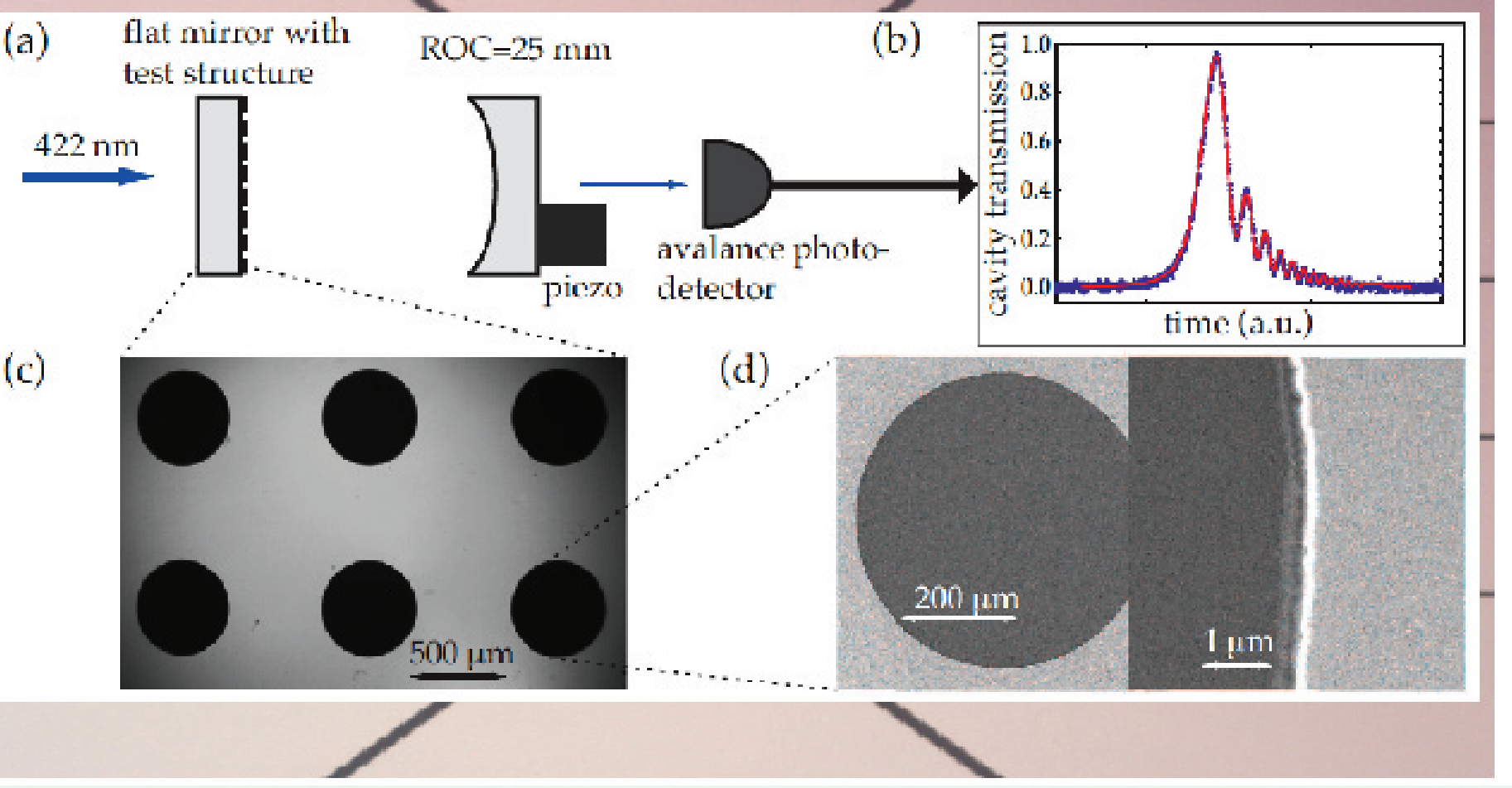


## Post-fab mirror loss characterization

Test structure fabricated parallel for loss tests: 500um apertures

- average losses evaluated by ring-down spectroscopy ~130ppm (80ppm in best cases) Finesse >20,000 @ 408nm within reach
- SEM show clean edges possible to scale to smaller apertures (e.g.8um)

(a) mirror loss test set-up: pzt scans across the cavity resonant peak faster than its decay rate
(b) Ring down signal
(c) Microscope image of the 500um diameter test mirror array fabricated parallel to mirror trap
(d) SEM image of mirror array, showing clean edges



## Fabrication of low ROC mirrors

Motivation:

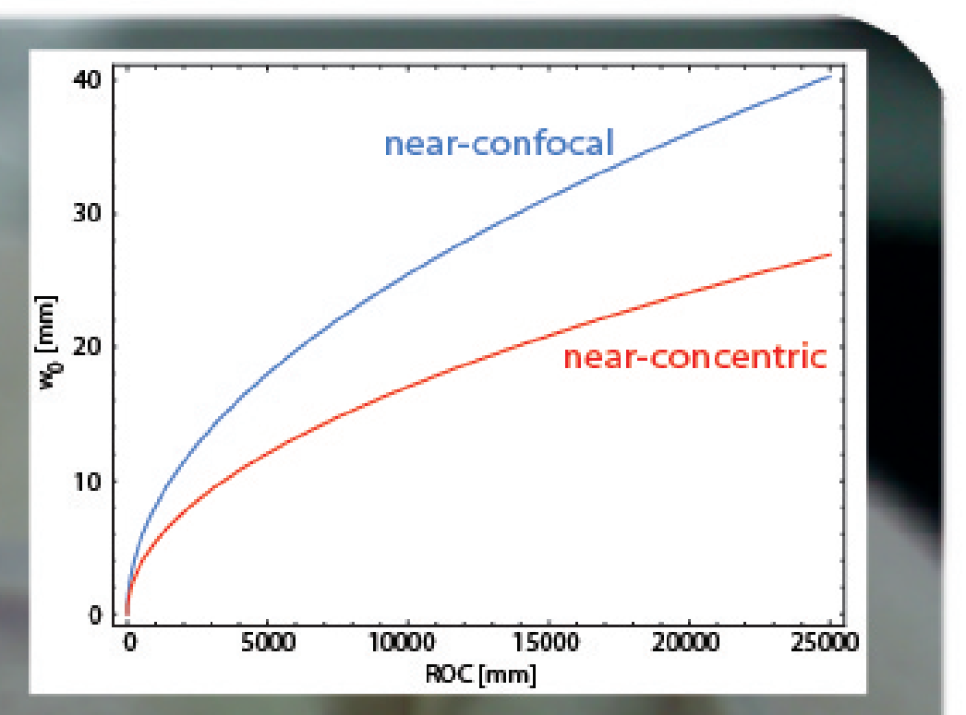
- Commercial low loss mirrors (super-polished) presently limited to radius of curvature (ROC) of ~ 25mm
- Resulting waist in confocal cavity geometry ~ 25-50mm

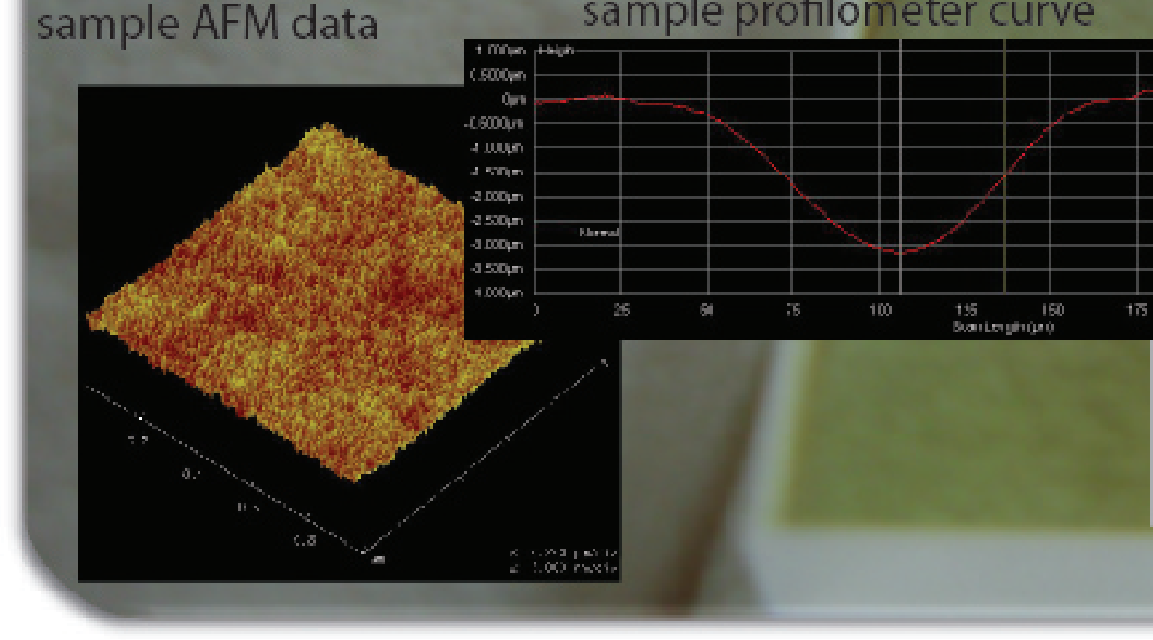
New approach [9]:

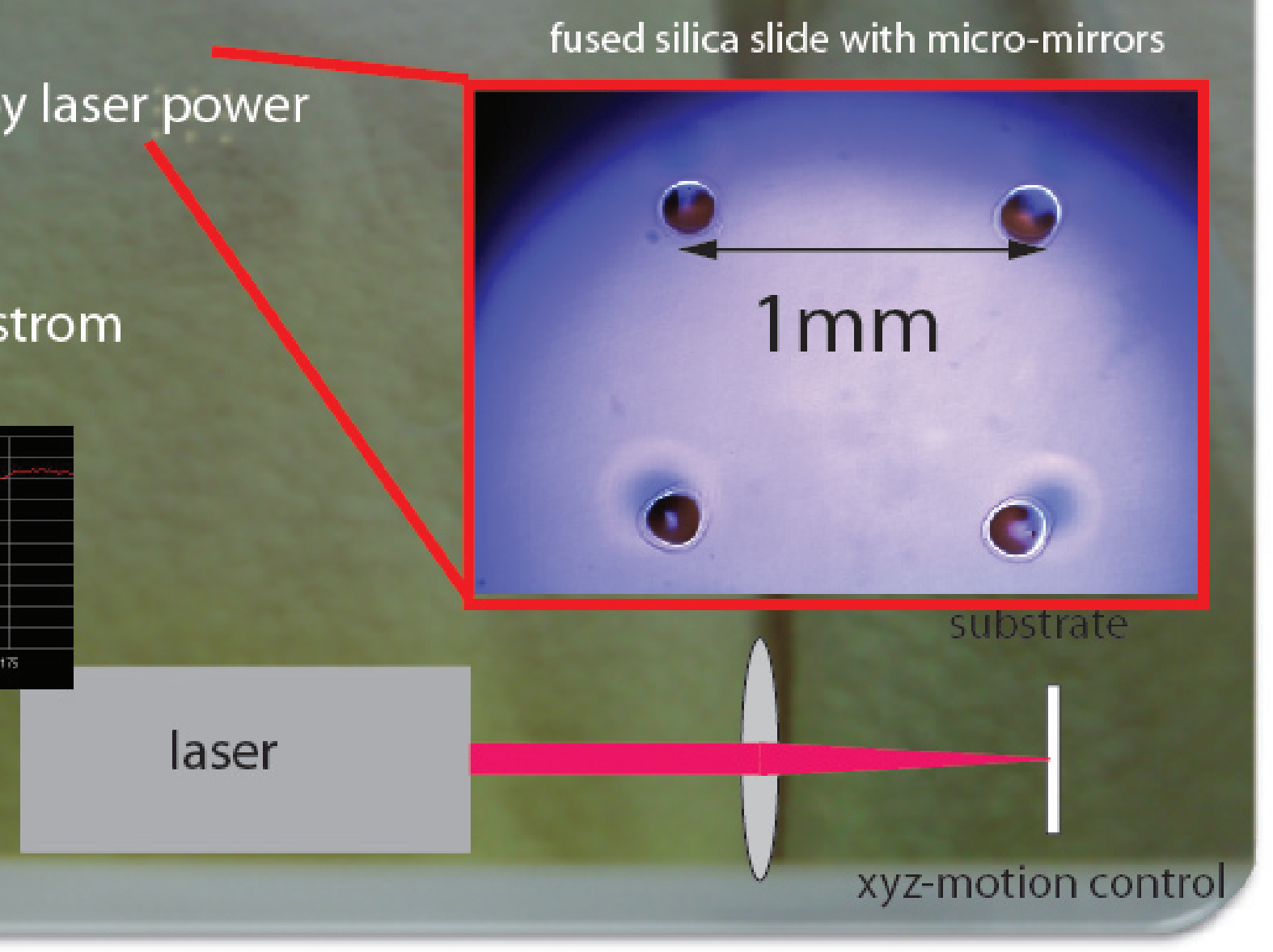
- high-power laser causes evaporation and melting of glass substrate
- mirror shape reflects the laser intensity profile
- ROC controlled via waist of laser
- mirror diameter and depth controlled by laser power

Results

- ROC varied from 50um to 1100um
- Measured surface roughness ~ 2.7 Angstrom



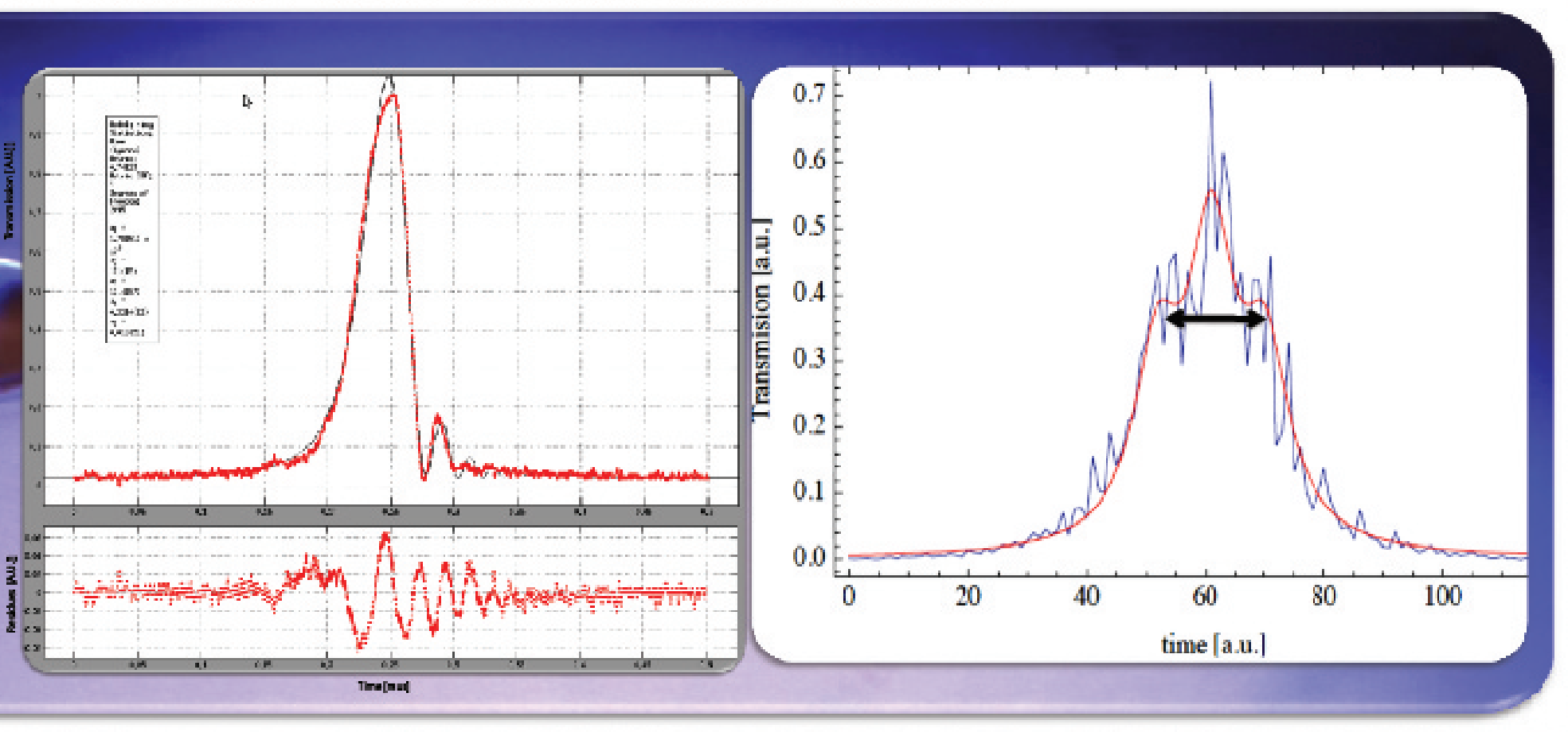




## Micro-mirror loss characterization

Preliminary test results

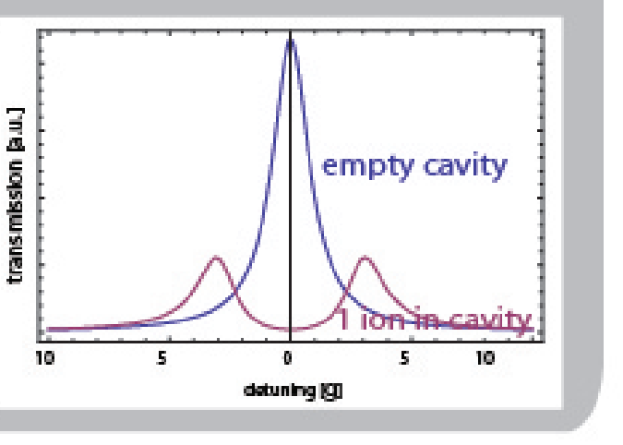
- Finesse ~ 30,000@405
- Inferred mirror scattering loss = 50ppm (from AT film coating) + 88(12)ppm (additional)



## Trap + resonator: design and predicted performance

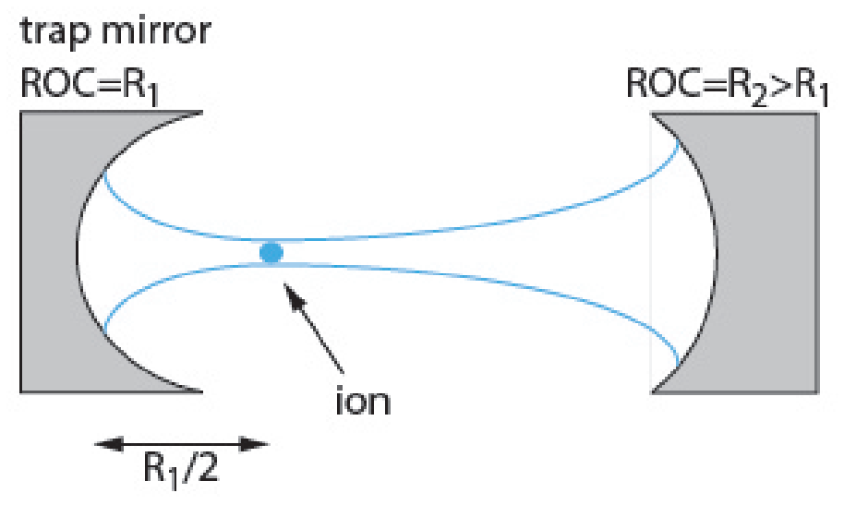
Design parameters:

- wavelength: 408nm
- $R_1$=300um
- $R_2$=1000um
- Transmission mirror 1= 40ppm
- Transmission mirror 2= 800ppm
- absorption and scatter losses pr mirror: 100ppm
- Finesse: 6000
- cavity length: 1.1mm
- waist: 5um
- Cooperativity: 8
- $g_0=2\pi$ 32MHz
- kappa=$2\pi$ 9MHz
- gamma=$2\pi$11MHz

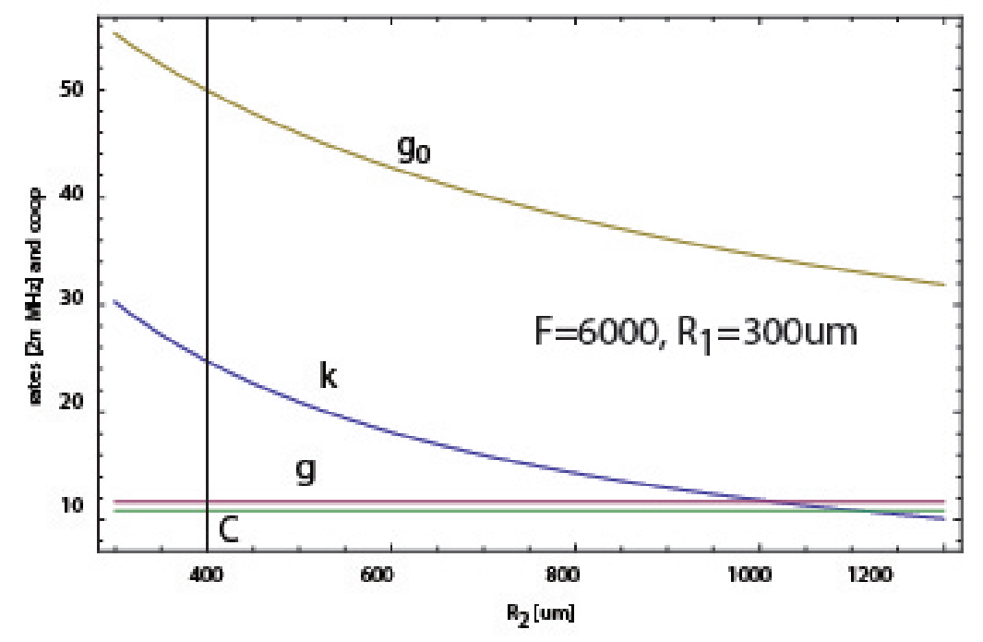


### Cavity geometry

- Trap on low ROC micro-mirror #1
- Ion height ~ $R_1/2$
- mirror #2: larger ROC micro-mirror in near-confocal geometry



### Dependence on $R_2$

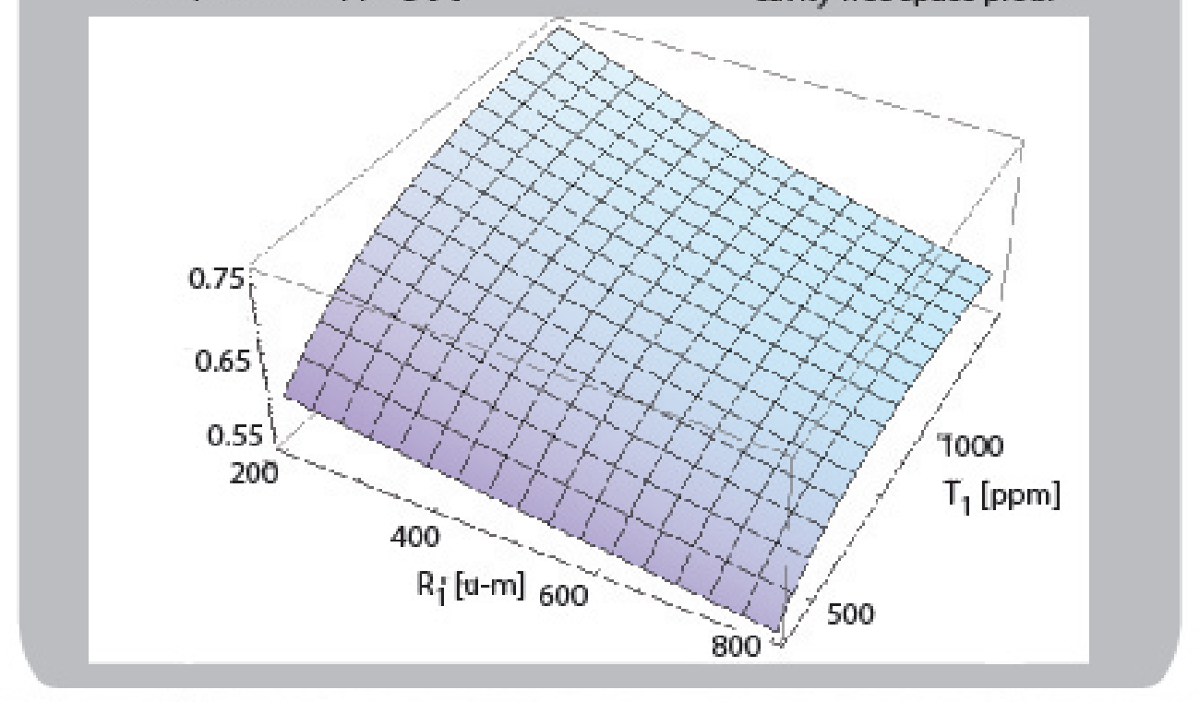


### Fidelity of ion-photon mapping:

$$\sim \frac{C}{C+1} \times \frac{T_1}{T_1+T_2+2\text{Loss}} \sim 0.7$$

ion-photon mapping [4]

cavity-free space prob.



References:
[1] D. Kielpinski, C.R. Monroe, and D.J. Wineland, Nature 417, 709-711 (2002)
[2] J. I. Cirac, P. Zoller, H. J. Kimble, H. Mabuchi, Phys. Rev. Lett., 78, 3221 (1997)
[3] C. Pearson. Theory and Application of Planar Ion Traps. S.M. thesis, MIT (2006)
[4] A. V. Gorshkov, A. Andre, M. D. Lukin and A. S. Sorensen, Phys. Rev. A, 76, 033804 (2007)
[5] P. B. Antohi, D. Schuster, G. M. Akselrod, J. Labaziewicz, Y. Ge, Z. Lin, W. S. Bakr, and I. L. Chuang, Rev. Sci. Instrum., 80, 013103 (2009)
[6] L. Deslauriers, S. Olmschenk, D. Stick, et al. Phys. Rev. Lett., 97, 103007 (2006)
[7] J. Labaziewicz, Y. F. Ge, P. Antohi, D. Leibrandt, K. R. Brown, I. L. Chuang, Phys. Rev. Lett., 100, 013001 (2008)
[8] M. Harlander, M. Brownnutt, W. Hänsel, R. Blatt, arXiv:1004.4842v1 (2010)
[9] D. Hunger, T. Steinmetz, Y. Colombe, C. Deutsch, T. W. Hänsch, J. Reichel, arXiv:1005.0067v1 (2010)
[10] P. F. Herskind, S. X. Wang, M Shi, Y. Ge, M. Cetina, I. L. Chuang, arXiv:1011.5259