

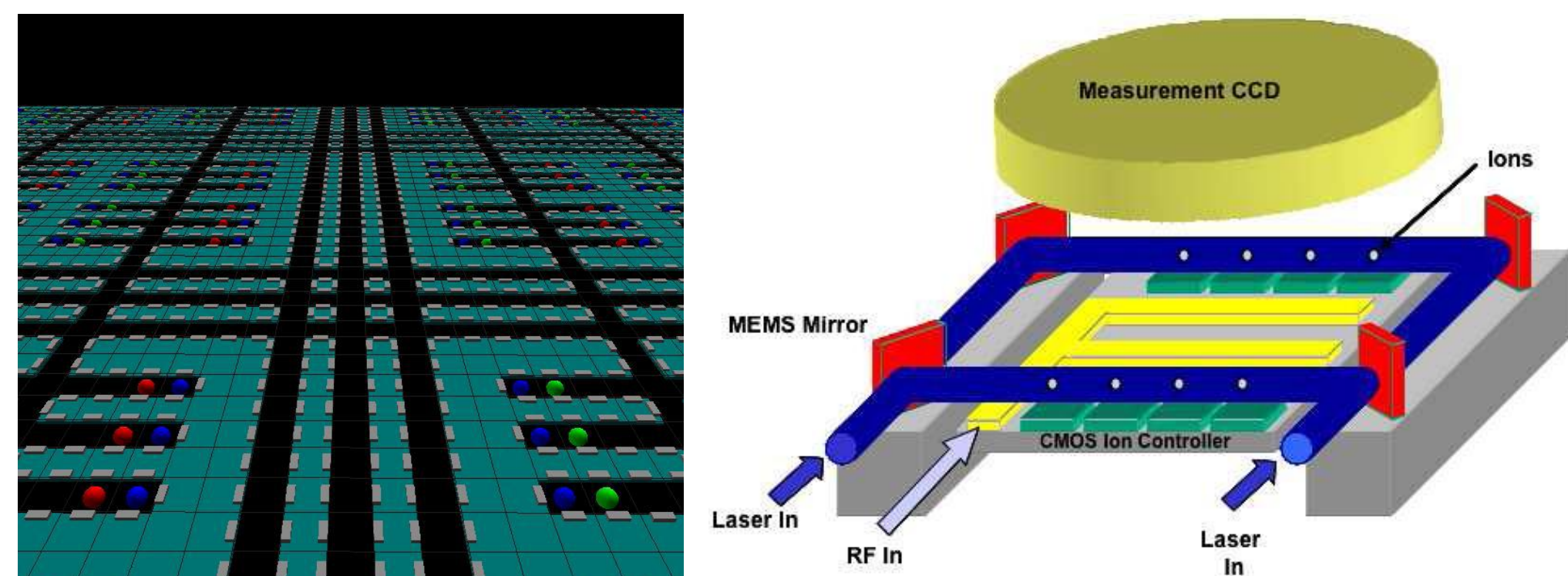
# Fiber-integrated Point Paul Trap

Tony Hyun Kim<sup>1</sup>, Peter F. Herskind<sup>1</sup>, Tae-Hyun Kim<sup>2</sup>, Jungsang Kim<sup>2</sup>, Isaac L. Chuang<sup>1</sup>

<sup>1</sup>Center for Ultracold Atoms, Massachusetts Institute of Technology, Cambridge, MA

<sup>2</sup>Department of Electrical Engineering, Duke University, Durham, NC

## Introduction



Surface-electrode ion traps represent a distinct advance in quantum information processing, in that the trap manufacturing process inherits the inherent scalability associated with conventional microfabrication. However, the construction of large-scale ion processors (see above) will require not only a sensibly scalable electrode architecture for trapping many ions simultaneously, but also additional infrastructure for optical readout and control of the many ion qubits, such as that offered by device-level integration of optical fibers.

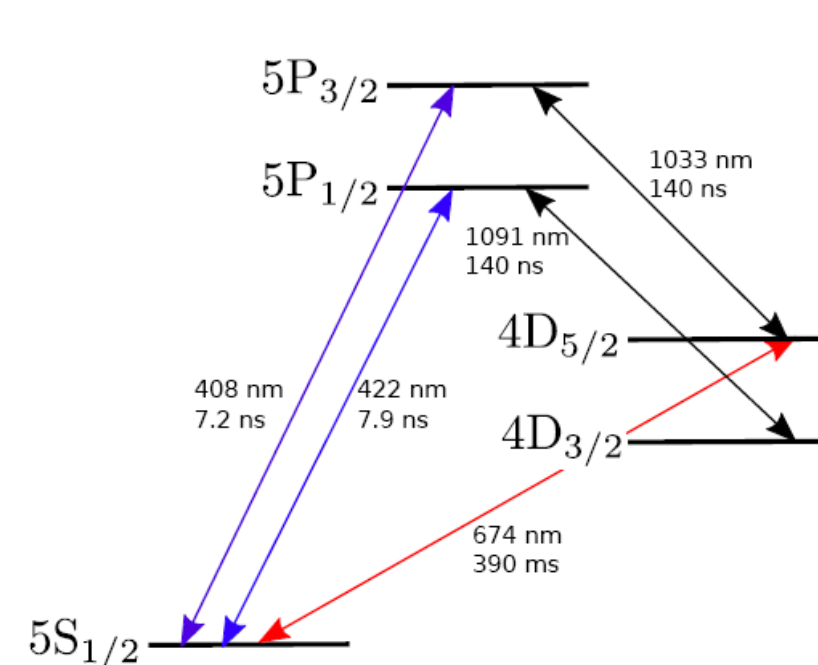
Additionally, a fiber-coupled ion trap enables novel structures such as ion trap quantum nodes on a fiber network[1], and a interface platform between ions and cold neutral atoms[2].

We present the design and progress towards an ion trap primitive with an integrated optical fiber for the purpose of light delivery and ion control.

## Fiber Integration: Motivations

### Trap engineering:

- Laser delivery. (For instance, all  $^{88}\text{Sr}^+$  transitions [see right] are supported by a photonic crystal fiber.)
- Site-specific ion readout [3]
- Clean loading through fiber



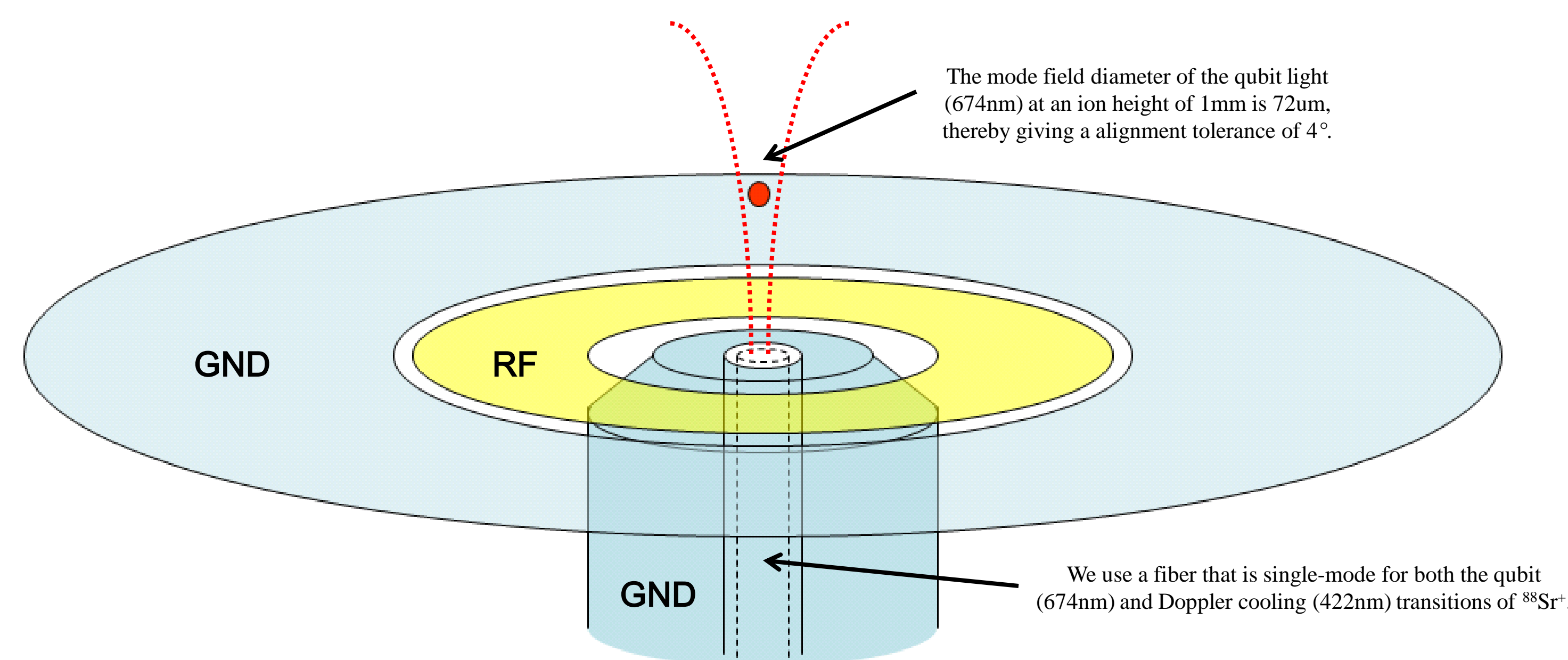
### Further applications:

- Interconnect for quantum networks, provided state transfer between ion and field mode.
- A hollow-core fiber as an interface between ion and neutral systems.

$$\begin{bmatrix} |i\rangle_1 \\ |i\rangle_2 \end{bmatrix} \begin{matrix} a_{1,ion}(t) \\ a_{1,mod}(t) \end{matrix} \begin{matrix} a_{2,ion}(t) \\ a_{2,mod}(t) \end{matrix} \begin{bmatrix} |i\rangle_2 \\ |i\rangle_1 \end{bmatrix}$$

$$a_{2,ion}(t) = a_{1,ion}(t - \tau)$$

## Trap Design and Assembly

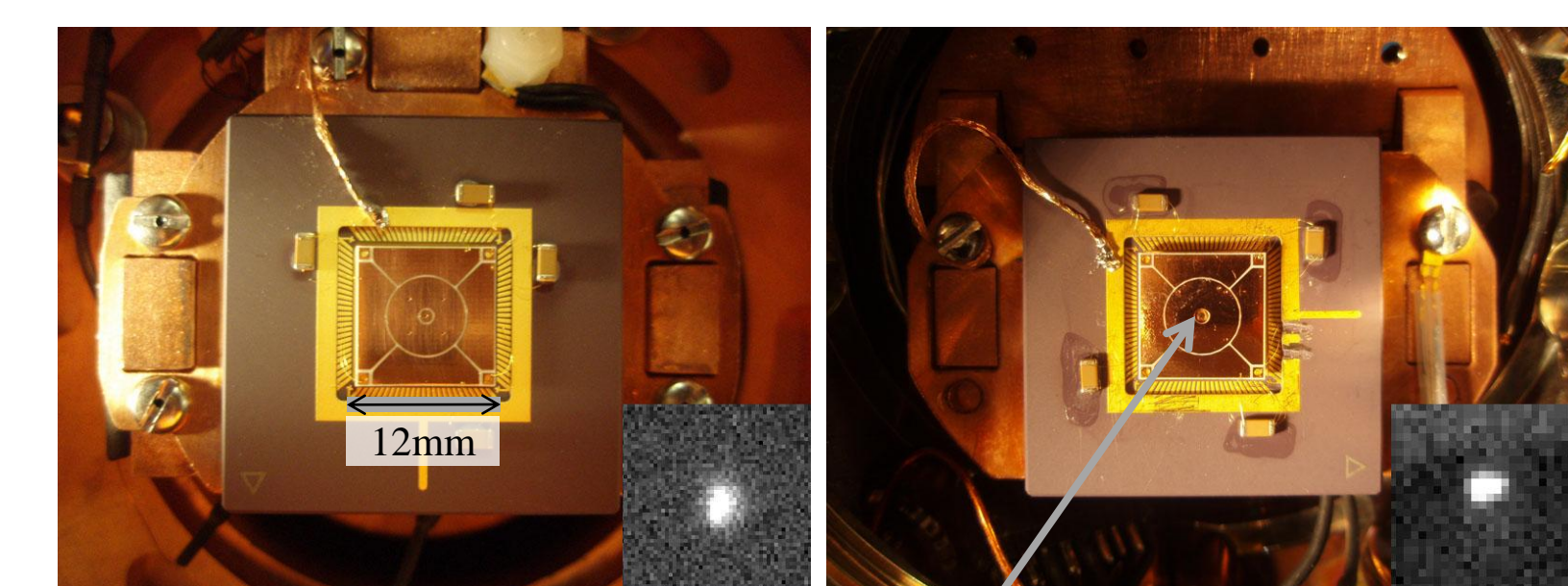
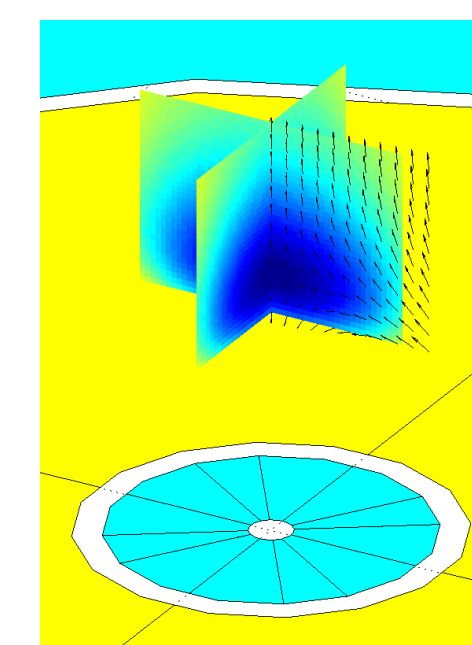


### We have addressed the following challenges in fiber-ion trap integration:

1. How to introduce fiber without perturbing the trapping fields?  
→ Design of a new “Point Paul” electrode geometry whose axial symmetry is compatible with that of the fiber.
2. How to reliably incorporate a fragile fiber to the trap?  
→ Rely on off-the-shelf optical components as much as possible, such as standardized optical ferrules.
3. How to fine-tune the ion-fiber mode overlap?  
→ The Point Paul trap is ideally suited for an ion micropositioning scheme through secondary RFs.

### TRAP GEOMETRY

- The Point Paul design achieves ion confinement with a single RF ring.
- Necessary electrode gaps due to fiber can be modeled numerically and analytically.
- Both fully PCB traps (no fiber; see below left) and ferrule-based traps (with fiber; below right) have trapped  $^{88}\text{Sr}^+$  ions stably for several hours.



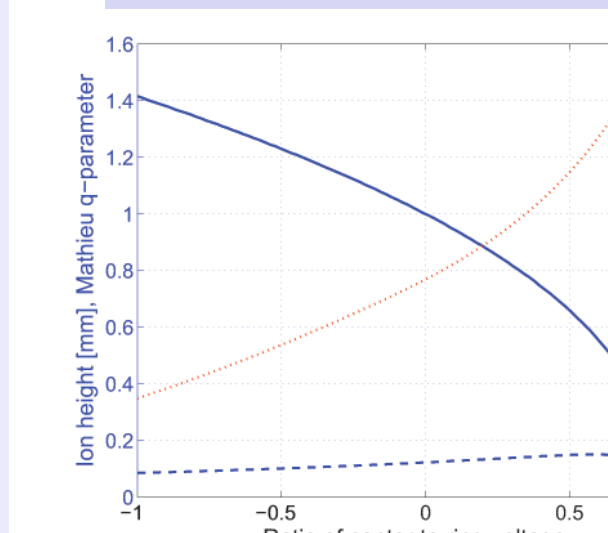
A single-mode fiber is introduced through the center via of the innermost electrode (actually a fiber ferrule).

### OPTICAL FERRULE

- Fiber and ferrule are polished as in conventional fiber connectorization procedure, providing robustness.
- Fiber-trap alignment can be performed with a typical precision of 25 microns.



### ION MICROPOSITIONING

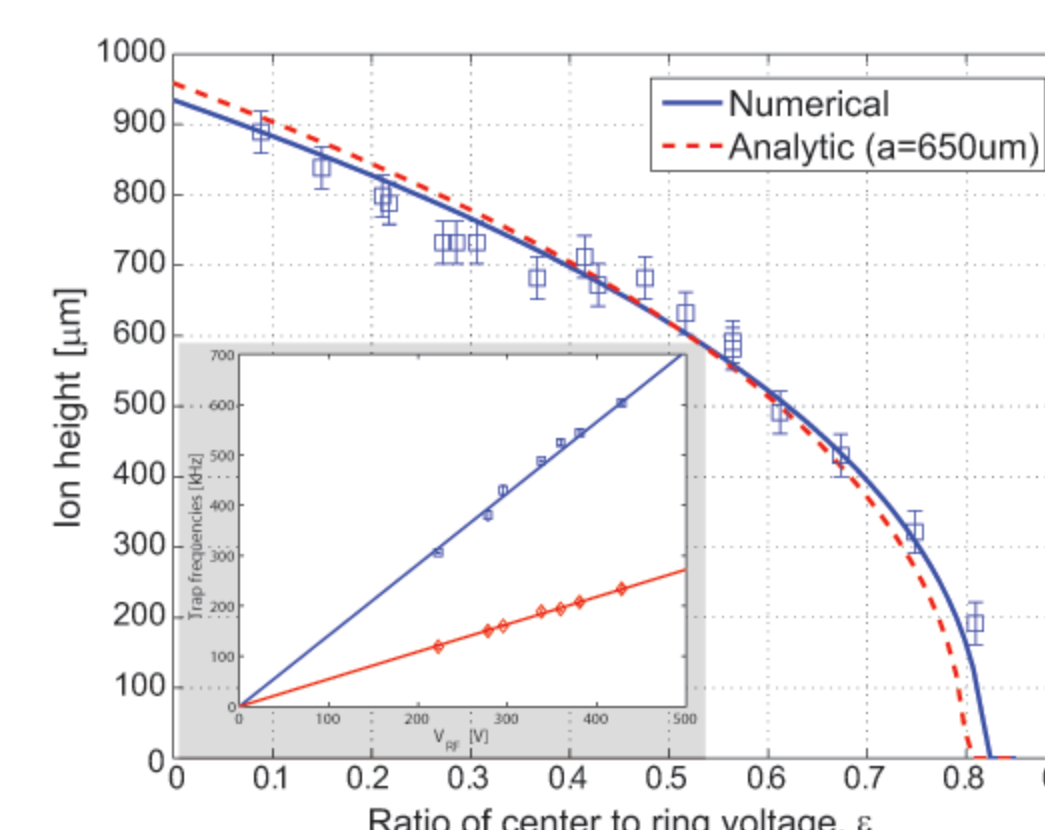
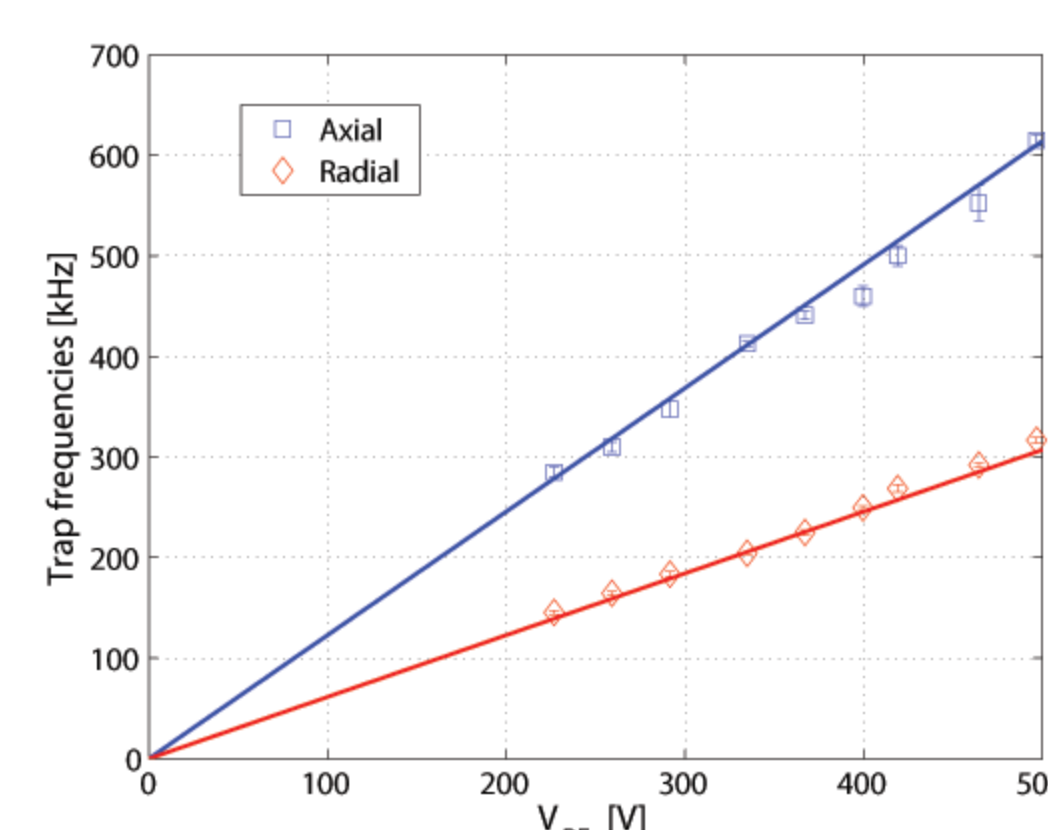
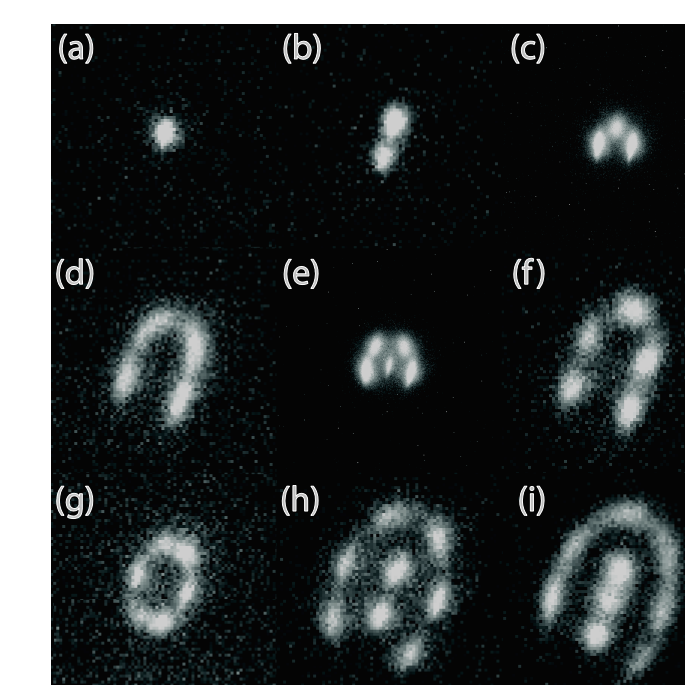


- Ion height can be adjusted *in situ* by adding a second RF onto the ferrule electrode. Several 100um variation is achieved.
- Up to 100um variation possible in radial plane using RF on compensation electrodes.

## Results

### Point Paul trap design:

- Ions trapped with and without the fiber.
- Planar ion crystals of up to nine ions observed with individual ion resolution.
- Measured secular frequencies in excellent agreement with theory. (See below left.)

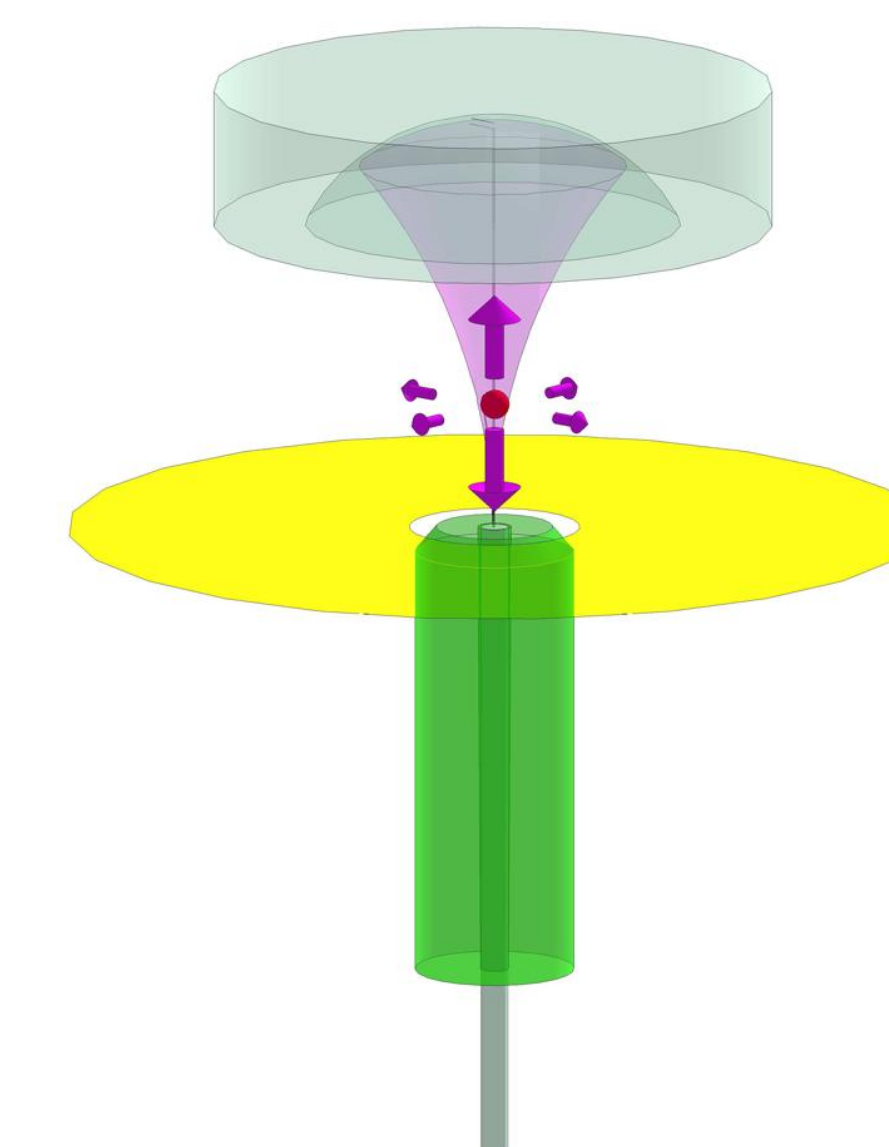


### Ion micropositioning:

- In situ* ion height range of 200-1100 microns achieved. Height variation (see above right) in good agreement with theory.

## Future work and Outlook

- Improve ion-fiber alignment. (Prototype fiber/ferrule trap used a different fab procedure than one outlined above.)
- Re-optimize the point Paul geometry for greater ion positioning ability in the radial plane.
- Perform stringent test of anomalous ion heating near metal surfaces, currently believed to scale as  $1/z^4$ . [4]
- Point Paul trap yields 2D ion crystals with the requisite structure for quantum spin simulation.
- Integration of optical cavity to realize a node in a quantum network. (See right.)



[1] J. I. Cirac, P. Zoller, H. J. Kimble, and H. Mabuchi. *Phys. Rev. Lett.*, **78**, 3221 (1997)  
[2] C.A. Christensen, S. Will, M. Saba, G.-B. Jo, et al. *Phys. Rev. A* **78**, 033429 (2008)  
[3] A. P. VanDevender, et al. *Phys. Rev. Lett.*, **105**, 023001 (2010)

[4] L. Deslauriers, et al. *Phys. Rev. Lett.*, **97**, 103007 (2006).