Faster quantum operations and control for trapped ions

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Workshop on Trapped-ion Technology

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Or: How I learned to stop worrying and love small traps

- **Reflective optics integrated with surface-electrode traps for rapid ion state measurement**
  - Reflector avoids insulator near ion
  - Fresnel geometry allows straightforward integration
- **Excess micromotion scaling**
  - As traps shrink, micromotion due to stray fields will drop
  - Control requirements on arrays of small traps can be significantly reduced
- **Reconfigurable trap array architecture**
  - Provides complete ion movement within array without junctions
  - Limits exposure of ions to noise on the RF potential

Quantum operation speed

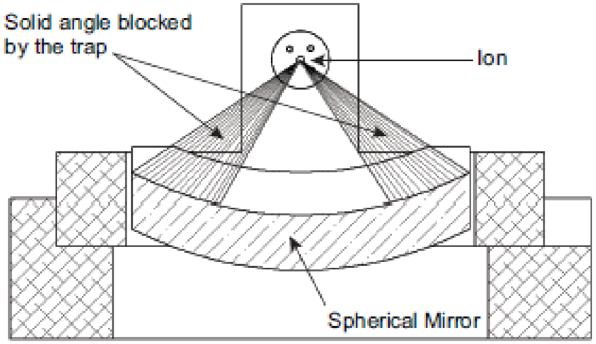
- **High fidelity measurement is slow**
  - **An order of magnitude slower than other basic operations**
- **Measurement time may limit processing which includes quantum error correction**
  - **Operations dependent on measurement outcome are required**
  - **Coherence must be maintained during this time**
- **Ion movement also of same order, though this could scale with decreasing trap size**
  - **Also, not needed for some apps (emulation, comm.)**

Operation	Time demonstrated for high-fidelity
Preparation	~2 us
Single-qubit op.	1 us
Two-qubit op.	10 us
Measurement	150 us (avg)

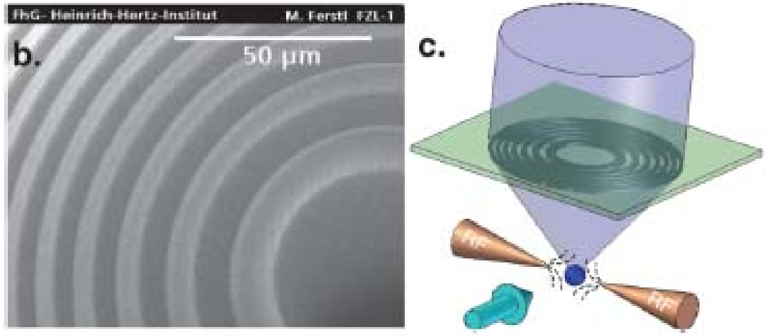
Some work to enhance collection

- Large reflectors
- Fresnel lenses
- Fibers in substrate
- Concavities in substrates
- Traps on flat mirrors

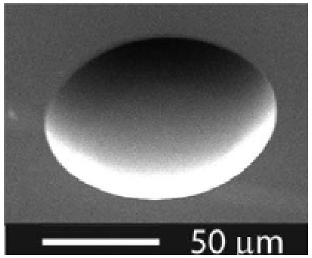
- How well do these integrate with the trap for large scale QIP?
- Is charging an issue?



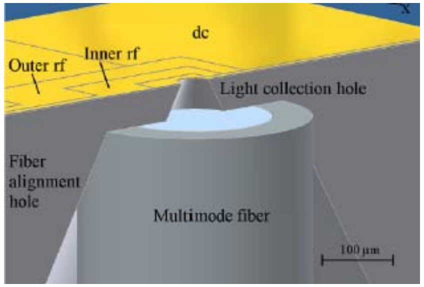
Shu et al. PRA 81, 042321 (2010)



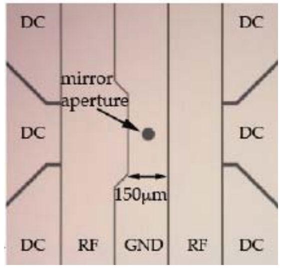
Streed et al. PRL 106, 010502 (2011)



Noek et al. Opt. Lett. 35, 2460 (2010)

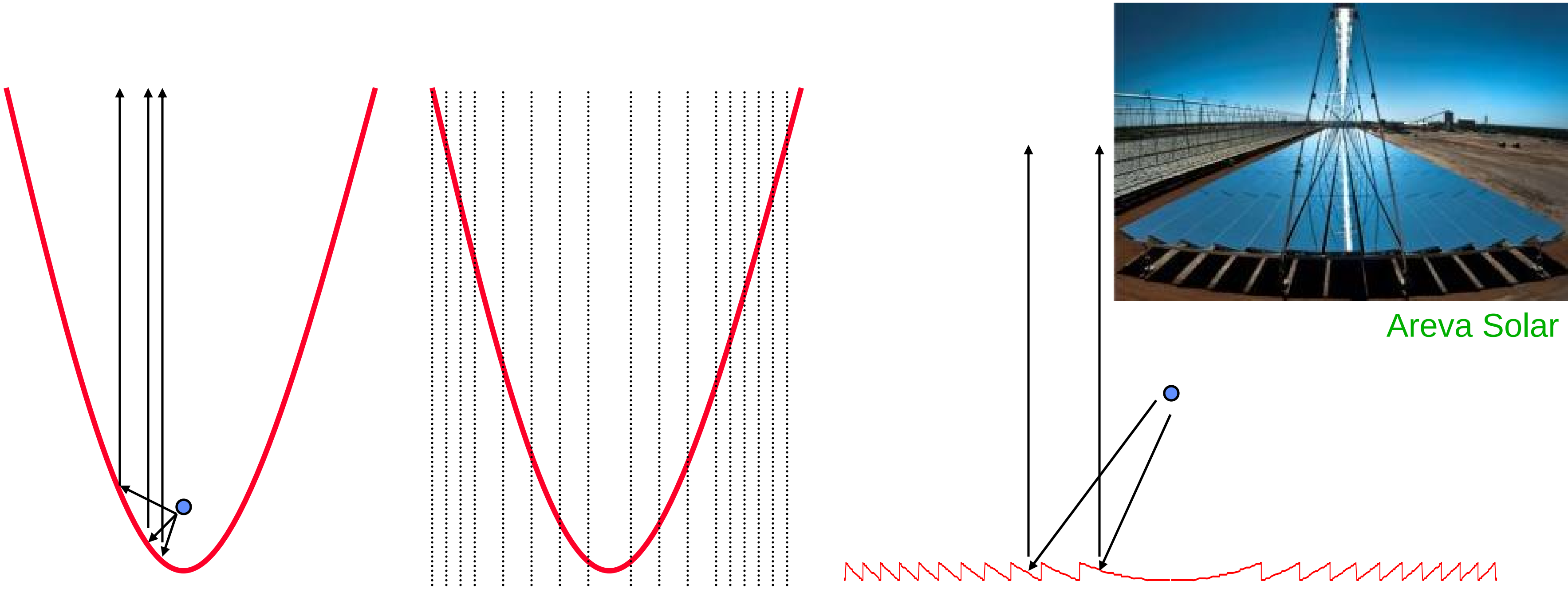


VanDevender et al. PRL 105, 023001 (2010)



Herskind et al. arXiv:1011.5259 (2010)

Reflective Fresnel optics

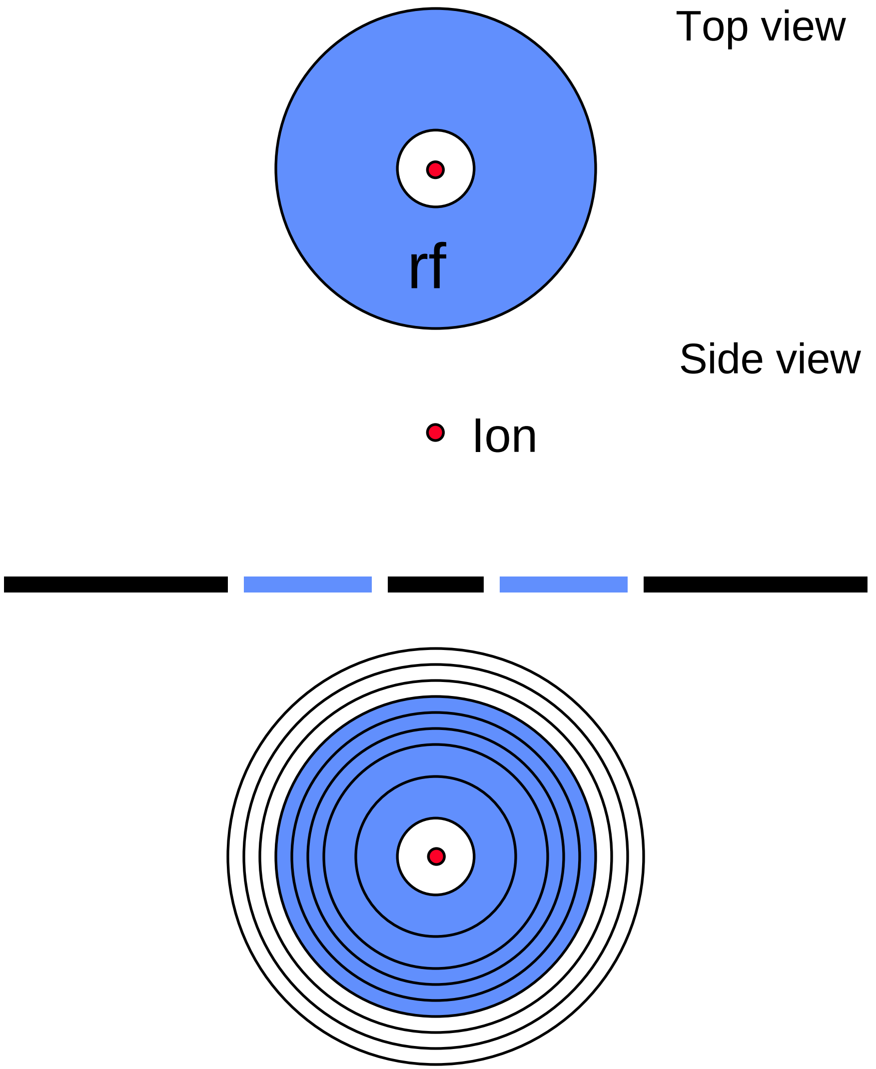


Areva Solar

- **Best collection would be with parabolic reflector**
  - **Drawbacks include optical access, integrating trap**
- **Try breaking it up**
  - **Makes if (sort of) flat**
  - **Can be placed on surface that also contains trap electrodes**

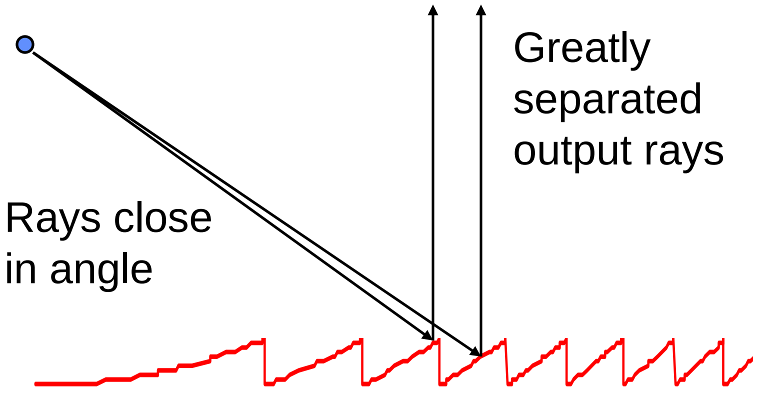
Integration with surface traps

- **Surface electrode “ring” trap**
  - **Like a 5-wire in cross-section, then revolved** (Pearson et al. PRA 73, 032307 [2006]; Wesenberg PRA 78, 063410 [2008])
- **Subsets of Fresnel zones can be identified with concentric rf and rf-ground electrodes**
- **Ion sees only metal surfaces**
- **Parabolic focus is separate parameter from trap height**
  - **Control former with curvature of gray-tone lithography/etch**
  - **Control latter with lateral rf electrode spacing**
  - **Can split up rf electrode to vary height** (cf. recent work at NIST and MIT-campus)
- **Should be able to collect from ~1/3 of the solid angle (assuming localized structure); 2π str theoretically possible**
- **Surface Penning traps, too**



Applications and considerations

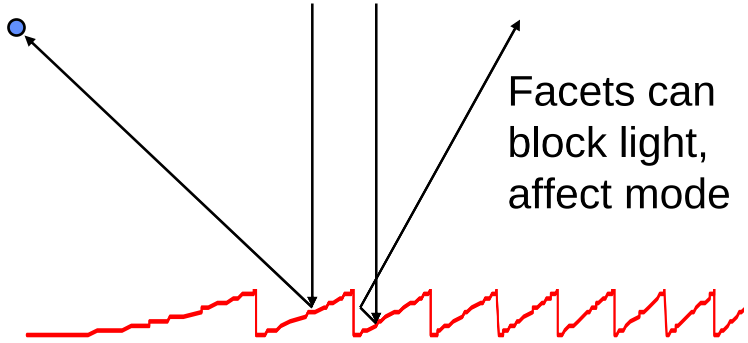
- **Large-scale QC**
  - **Measurement zones with SET traps**
- **Quantum simulations in 2D arrays**
  - **Fresnel ref. under each ion**
- **Quantum communications**
- **Fresnel optics considerations**
  - **For imaging, dilution will affect image quality**
  - **For focusing light onto ion, blocking will limit mode quality**
- **For simple collection, these are not concerns**



Greatly separated output rays

Rays close in angle

Imaging



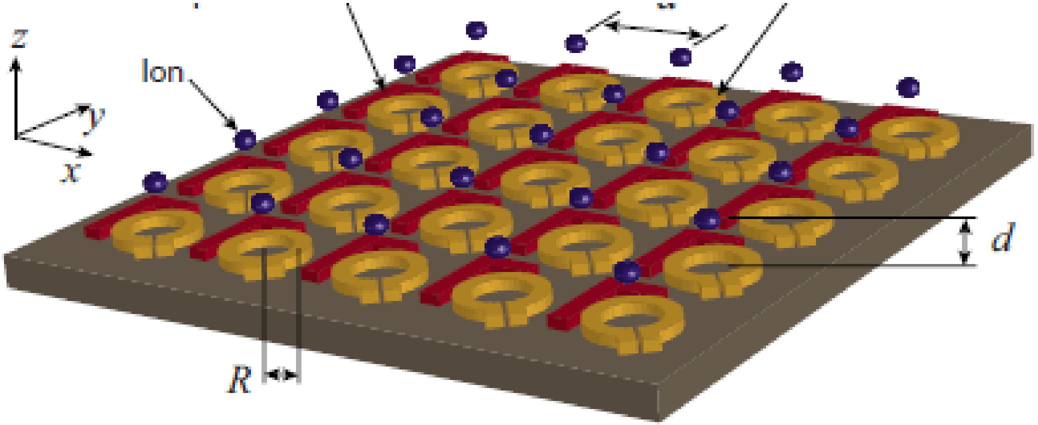
Facets can block light, affect mode

Focusing

Shrinking traps to ease the control burden

Problem with using large trap arrays?

- Excess micromotion
  - Due to stray fields pushing ion from rf null
  - Leads to reduced flourescence, rf heating, etc.
- Leads to control problem on large scale in an array
  - DC fields from nearby traps can be a stray field
    - In a surface-trap, not much shielding from this
  - “Real” stray fields are still there



Do we need a million knobs (i.e. a large overhead in control electrodes)?!?

How does micromotion scale with size?

- **Excess micromotion amplitude A**
  - **Proportional to how far off rf null external field pushes ion**
- **Pick displacement along x dir.**
- **Assume stability parameter q>>a for this analysis**
- **Now requiring q constant as R goes down (**JC et al. QIC 5, 419 [2005]**):**
  - **With rf amplitude going as R to prevent breakdown,**
  - **We get scaling for rf frequency**

R is trap size

$$A = \frac{1}{2} u_{0i} q_i$$

$$A = \frac{1}{2} \frac{Q\vec{E}_{dc} \cdot \hat{u}_i}{m\omega_i^{\;2}} \frac{2QV_0}{mR^2\Omega^2}$$

$$A = \frac{Q^2 E_{dc} V_0}{m^2 R^2 \omega_x^{\;2} \Omega^2}$$

$$\text{for } q >> a, \;\; A = \frac{4QE_{dc}}{mq\Omega^2}$$

$$V_0 \propto R$$

$$\Omega \propto R^{-1/2}$$

Smaller traps, less to worry about?

- **This leads to EMM amplitude that scales as *R***
- **Now look at this in relation to ground state wave funtion spread:**
  - **Use same scalings for trap parameters**
  - **Spread will go as *R*$^{1/4}$**
- **Therefore, normalized EMM amplitude still scales reasonably to small scales**
- **This also assumes stray field is constant as a function of *R***
  - **This will be true for a random stray field**
  - **Should also be true for stray dc field from array electrodes since V_{dc} will go as *R***
- **NB: weak scaling on *m***

$$A \propto \frac{Q}{mq} E_{dc} R$$

$$\Delta x = \sqrt{\frac{\hbar}{2m\omega}} \propto m^{-1/2}\omega^{-1/2}$$

$$\begin{aligned}\Delta x &\propto m^{-1/2} q \Omega^{-1/2} \\ &\propto m^{-1/2} q \left(R^{-1/2}\right)^{-1/2} \\ &\propto m^{-1/2} q R^{1/4}\end{aligned}$$

$$\frac{A}{\Delta x} \propto \frac{Q}{m^{1/2} q^2} E_{dc} R^{3/4}$$

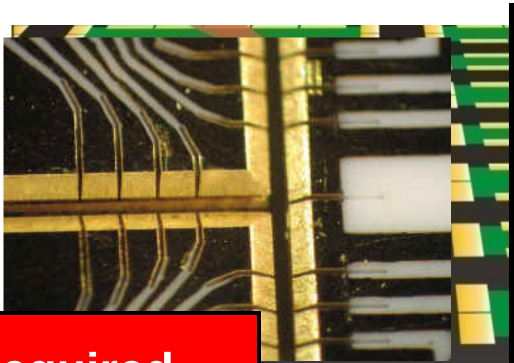
Reconfigurable ion array architecture

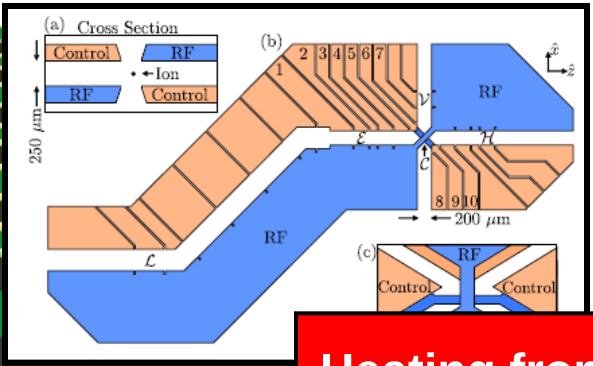
Reconfigurable trap arrays

In conjunction with W. Lybarger, Jr. at LANL

- **Analytical results:** J. Wesenberg PRA 79, 013416 (2009)
  - **Lowest order for ideal X junction is 6-pole**
  - **Even w/6-pole, X cannot be close to 90 degrees**
  - **Lowest order for right angle is 8-pole**
  - **Ideal straight-leg Y's and T's are ruled out**

Michigan/ Maryland

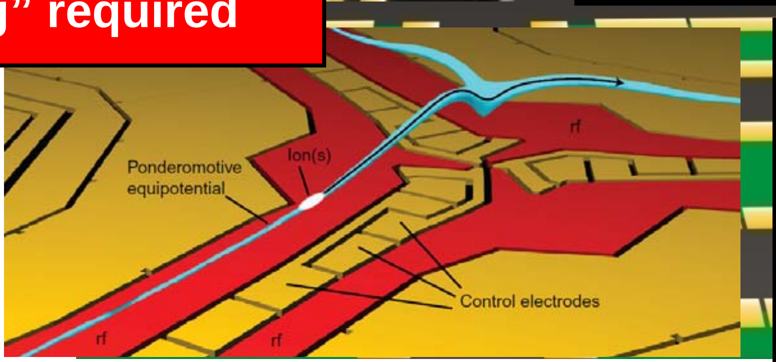




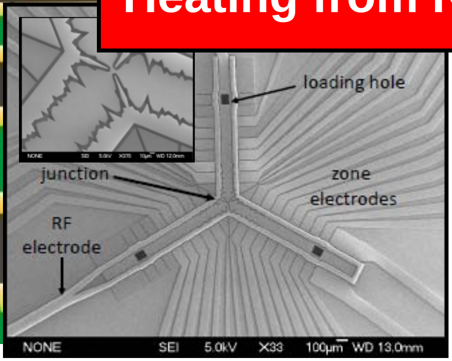
NIST

"Surfing" required

Heating from RF bumps



NIST



Sandia

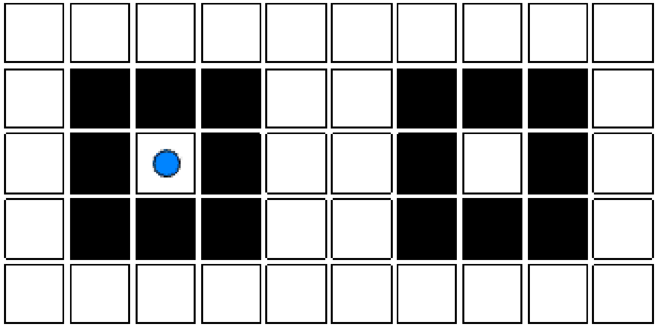
Field-programmable trap array

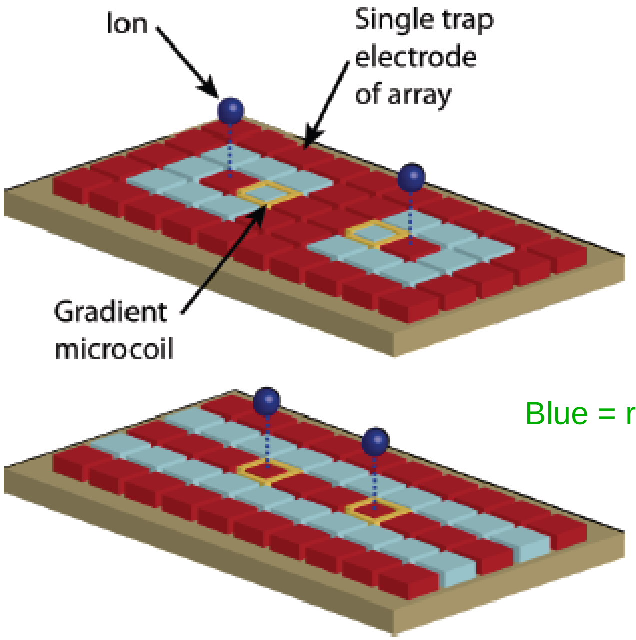
- Regular array of switchable RF or DC electrodes
  - Arbitrary layout
  - Plaquette of ~25 per ion
  - For sims, array can be static
  - For QC, traps change each step of calc.
- Switch between ring and linear traps
  - Dynamic (within experiment)
  - Smooth deformation
  - Static potential takes over in Z direction
  - Bring ions closer together for interaction

See poster by W. Lybarger, Jr.

JC IAS 2009 talk (2009); Lybarger PhD thesis UCLA (2010)

Black = rf

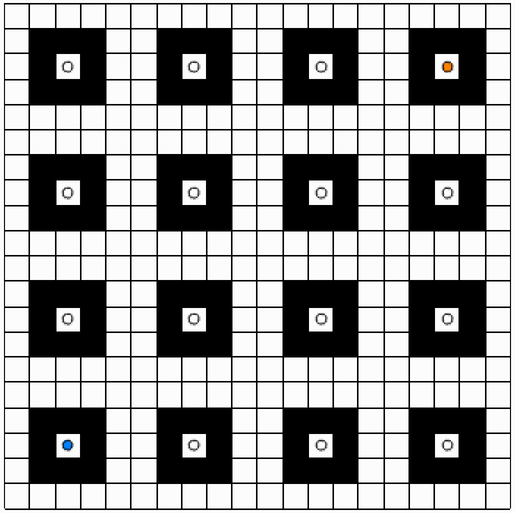




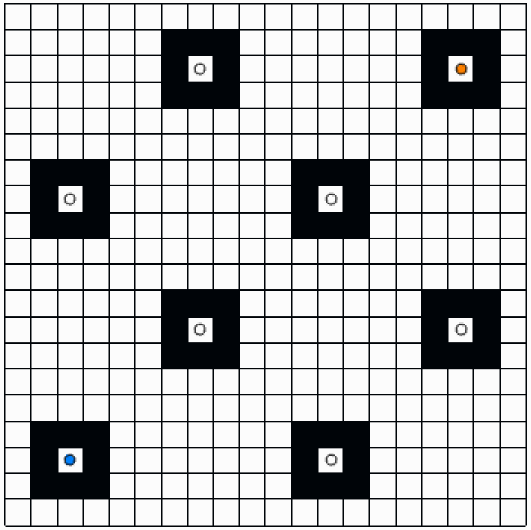
No junctions; always 0- or 1-D

- **Move any ion next to any other**
- **Ions move around in 1D racetracks**
  - **Tracks dynamically variable**
  - **Still small RF bumps if paths not circular**
- **Alternatively: have gaps and move ions a few at a time**
  - **Like sliding block puzzle**
  - **No heating from RF bumps**
  - **Maybe slower (compare with SWAPs)**

JC IAS 2009 talk (2009); Lybarger PhD thesis UCLA (2010)



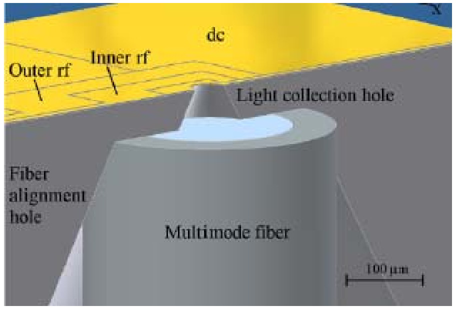
Hungarian Rings



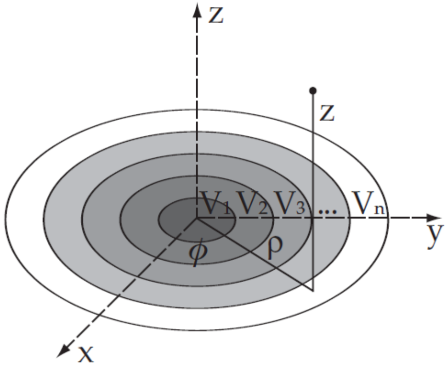
Sliding-blocks puzzle

Recent work along these lines

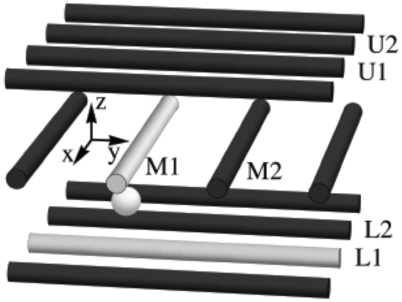
- Varying rf potential
  - Multiple rf electrodes for varying height of ion above surface (NIST group and MIT-campus group)
  - Subset of electrode have variable rf amplitude for transport (Berkeley group)
- Pixelated trapping electrodes
  - Penning trap for transport of ions (Ulm group)



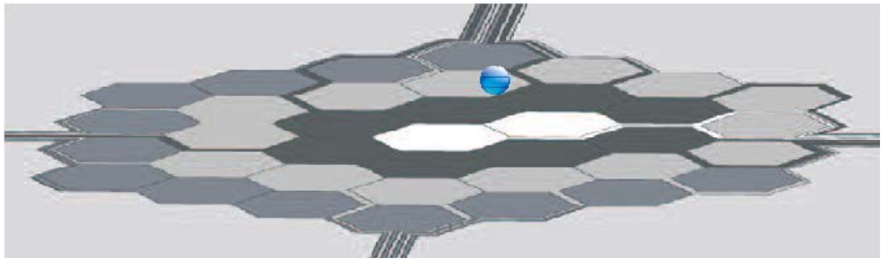
VanDevender et al. PRL 105, 023001 (2010)



Kim et al. PRA 82, 043412 (2010)



Karin et al. arXiv:1011.6116 (2010)



Hellwig et al. NJP 2, 065019 (2010)

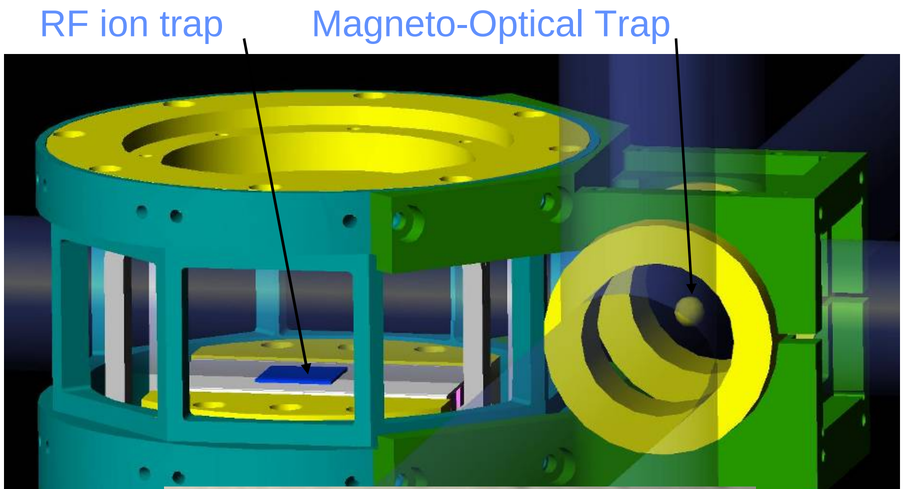
Ions (almost) at LL

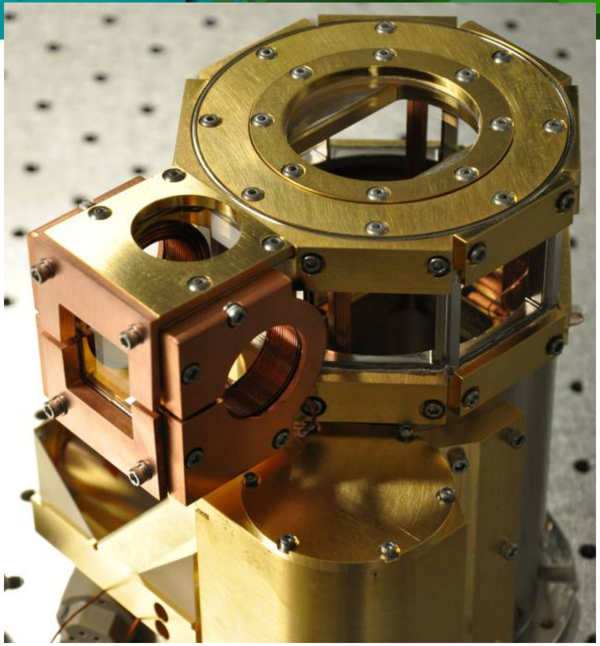
Highly efficient, pure qubit loading

Working at LL with J. Sage and A. J. Kerman

- **Concept for loading ions into trap arrays:**
  - **Start with cold neutral atoms in a MOT**
  - **Use pushing laser beam to accelerate atoms**
  - **Photoionize atoms at trap location, cold ions remain in trap**

- **Enables high loading rates**
  - **Several orders of magnitude faster than typical ~Hz rate**
  - **No contamination from atom beam in vicinity of trap**
  - **Isotope-selective**
  - **Can enable atom-ion experiments**

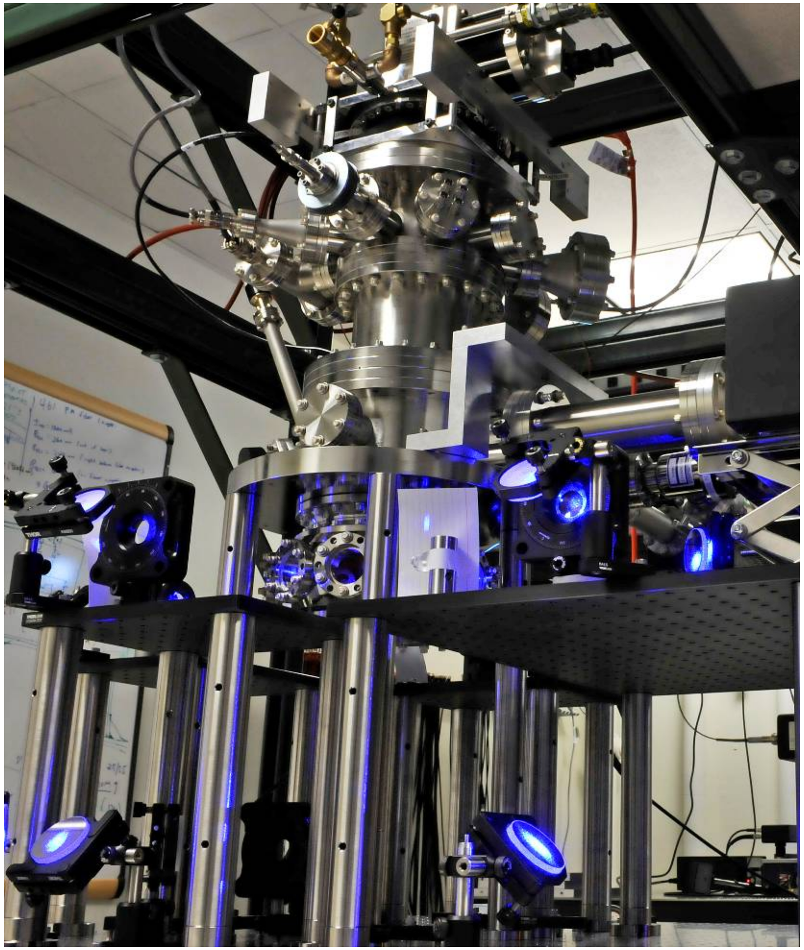




Current status

- Main chamber includes cryocooler to attain low temperature trap electrodes
- Lasers installed
- Design of first ion traps ongoing
- Near term goals:
  - MOT production optimization
  - Push atoms to ion region
  - Ion trapping
- Will investigate:
  - Integrating trap technologies
  - Trap electrodes/heating
  - Arrays of microtraps

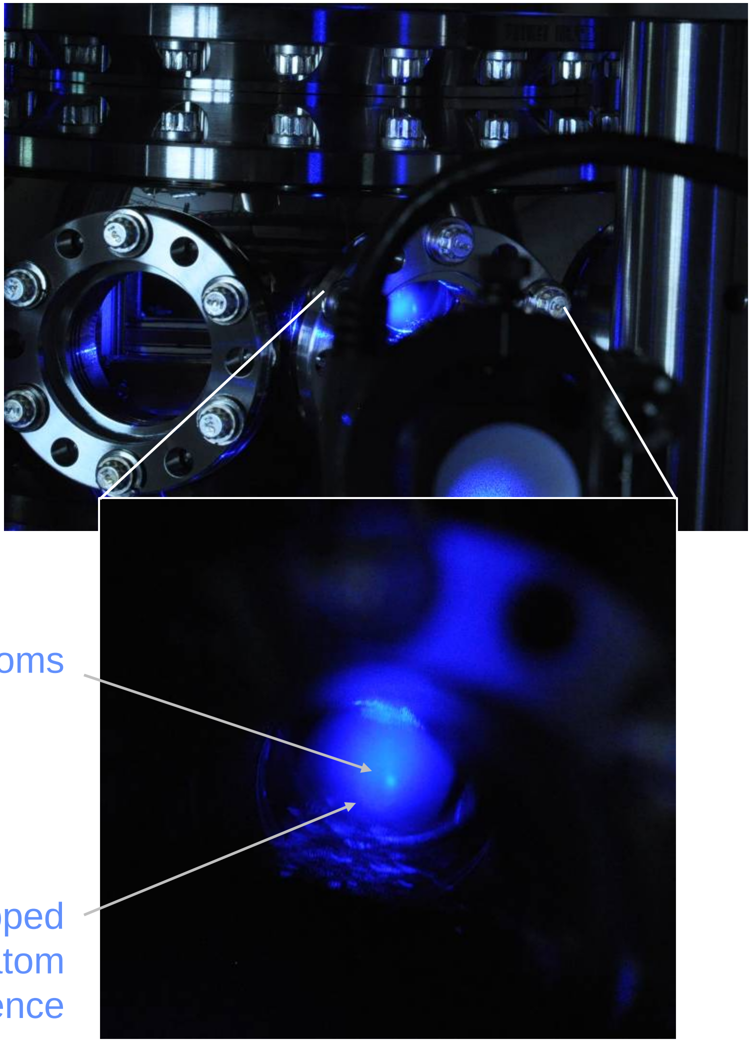
Main chamber with cryocooler



MOT coils, field coils, and rf resonator cooled and in-vacuum

Latest news: MOT achieved

- Sr MOT produced
  - ~ 3 x 10^5 atoms (no repumpers or Zeeman slower)
  - Lifetime and temperature consistent with expected
  - Can empty MOT with resonant beam (will use this to push atoms to ion trap region)



MOT atoms

Untrapped atom fluorescence

END

Collaborators:

MIT LL

- **Jeremy Sage**
- **Andrew “Jamie” Kerman**

LANL

- **Warren E. Lybarger, Jr.**

Bringing them together

- **Atom-chip/surface-ion-trap combination**
  - **Same electrodes used for DC currents needed for atom traps can be used for ion RF**
  - **Alternatively, larger magnetic trap wires can be on back of chip (or top of bottom chip) with ion electrodes on front**
- **Ion and atom positions controllable**
  - **Registered to high precision**
  - **Ions can be easily moved through atoms**