Scalable Technologies for Quantum Control in Trapped Ion Systems

- For Quantum Information Processing and Simulation -

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Duke University

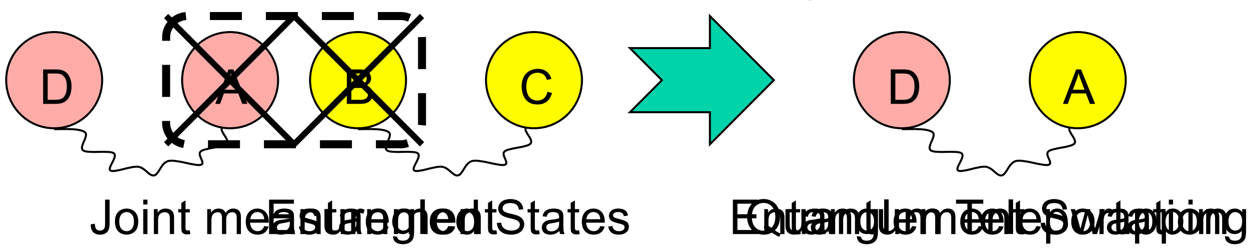
Workshop on Quantum Simulations with Trapped Ions (IQsim13)
Brighton, UK, Dec. 17, 2013

Outline

- Introduction
  - Quantum Computers and Quantum Simulators
  - Quantum "IC": Enabling Hardware Technology
- New Technologies for Trapped Ion Experiments
  - Physical System: Atomic Ions
  - Qubits Manipulation in Surface Traps
  - Better Optics: Fast Qubit State Detection
  - Adapting MEMS and Microsystems Technology
- Summary and Outlook

Elements of Quantum Computers

- Quantum Bits (Qubits)
  - A two-level quantum system that represents information
  - Must be able to initialize and measure
- Quantum Logic Gate Operation
  - Single-qubit and two-qubit operations
  - Coherent: works on superposition states
  - Universality Theorem: Single and two-qubit gates are universal
- Transporting Qubits between Quantum Logic Gates
  - Quantum wires are difficult to realize
  - Quantum teleportation: Use of entangled states to ship qubits

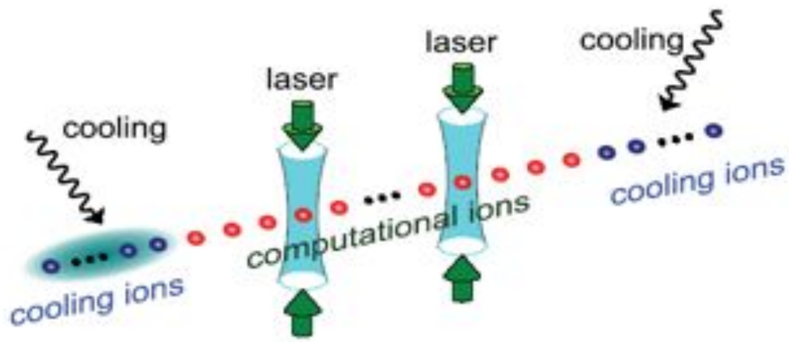


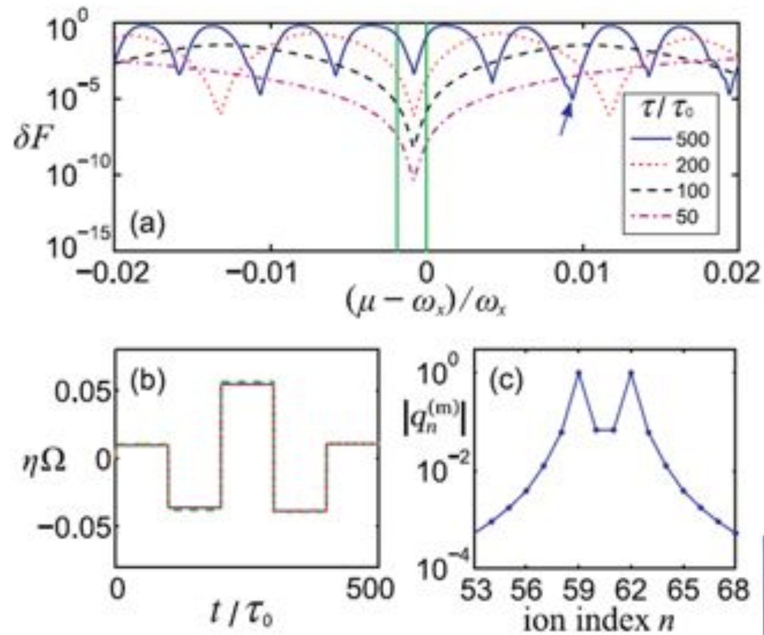
Elements of Quantum Simulators

- Quantum Bits (Qubits)
  - A two-level quantum system that represents a quantum spin
  - Must be able to initialize and measure
- "Hamiltonian Engineering"
  - Ability to implement "arbitrary" interaction Hamiltonian among the qubits to induce adequate state evolution
  - Coherent: works on superposition states
  - Can be "stroboscopic" if Trotterization is used
  - In some cases, dissipative process is helpful ("annealing")
- Complexity of Interaction Geometry
  - Underlying geometry (lattice structure) has huge influence on the evolution of interacting spin system
  - Interaction typically decays as a function of distance

Ion Chain Quantum Register

- Equally spaced long ion chain
- Use transverse phonon mode for multi-qubit gates
- Design and control of laser pulses that apply spin-dependent forces at the heart of quantum register operation
- Same hardware can be used for simulation of Ising spins





Zhu, Monroe and Duan, PRL 97, 050505 (2006); Europhys. Lett.73, 485 (2006)
Korenblit et al., New. J. Phys. 14, 095024 (2012)

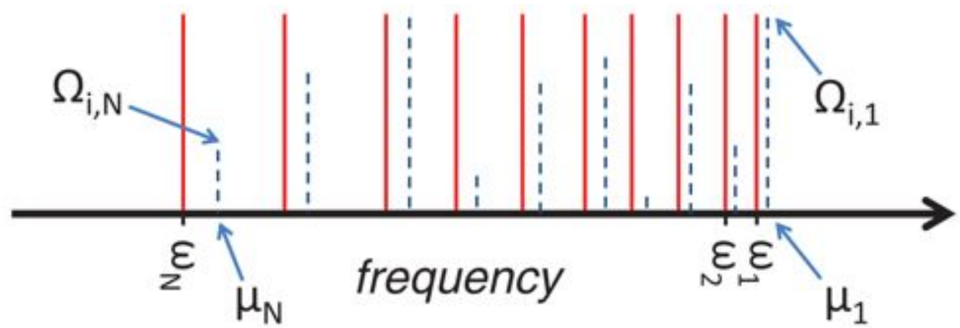
Ion Chain Quantum Simulator

- Arbitrary, fully connected Ising Hamiltonian with N spins

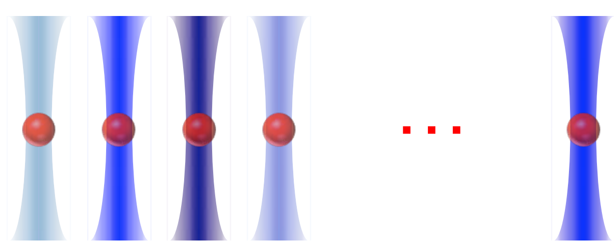
$$H = \sum_{i<j} J_{i,j}\sigma_x^{(i)}\sigma_x^{(j)} \qquad J_{i,j} = \sum_{n=1}^{N} \Omega_{i,n}\Omega_{j,n} \sum_{m=1}^{N} \frac{\eta_{i,m}\eta_{j,m}\omega_m}{\mu_n^2 - \omega_m^2}$$

${}_N C_2 \sim O(N^2)$ degrees of freedom $O(N)$ degrees of freedom

- In a linear N-spin chain, the transverse mode spectrum looks like



- Need laser beams with individual intensity control



Korenblit et al., New. J. Phys. 14, 095024 (2012)

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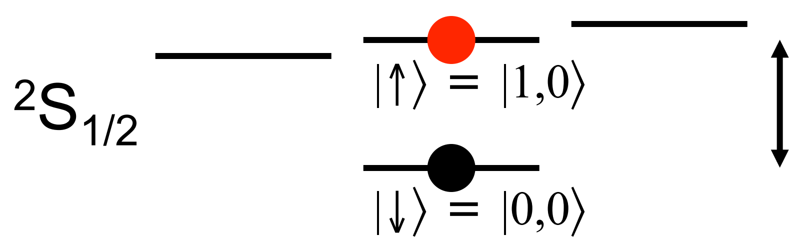
The $^{171}Yb^{+}$ Hyperfine Qubit : Coherence

- Qubit states are two internal (clock) states of the atomic ion
- Carefully chosen states have long coherence times
  - $T_2 \approx 1\text{sec}$ "without trying much"
  - $T_2 \approx 15$ min with "some effort"



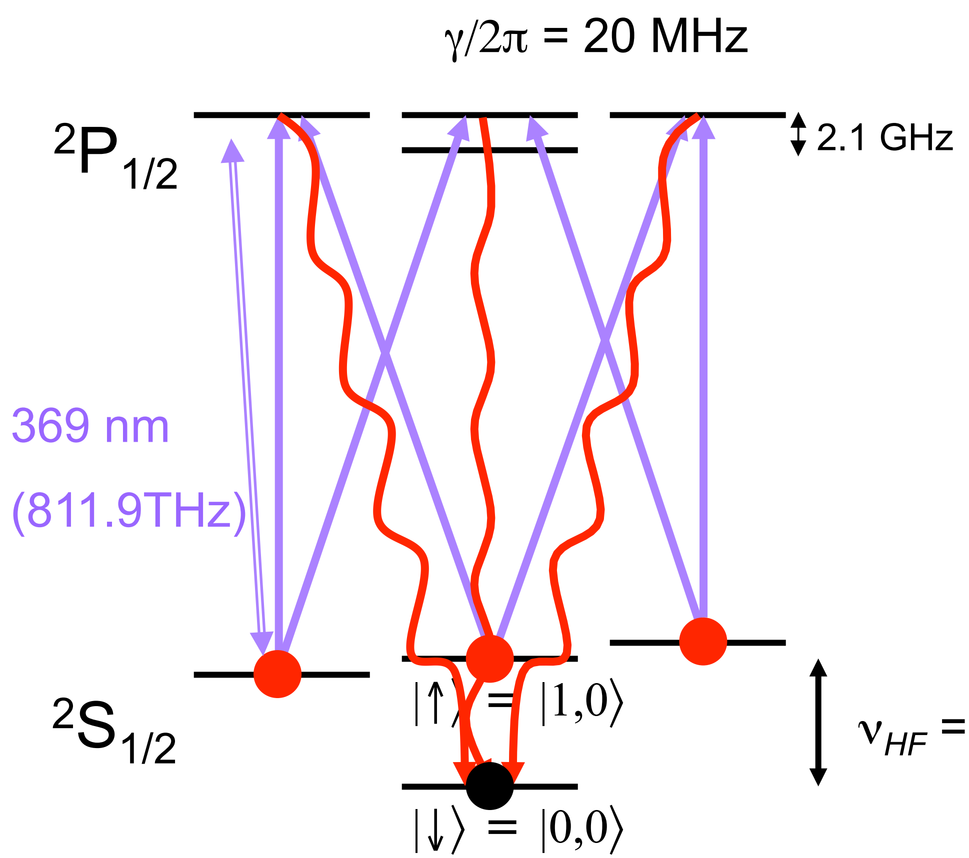
ν_{HF} = 12 642 812 118 + 311B^2 Hz

(600 Hz/G @ 1 G)

S. Olmschenk et al., PRA 76, 052314 (2007)

The $^{171}Yb^{+}$ Hyperfine Qubit: Initialization

- Optical pumping into the dark state prepares initial qubit state
- High preparation fidelity (>99.99% after scattering ≈ 10 photons)



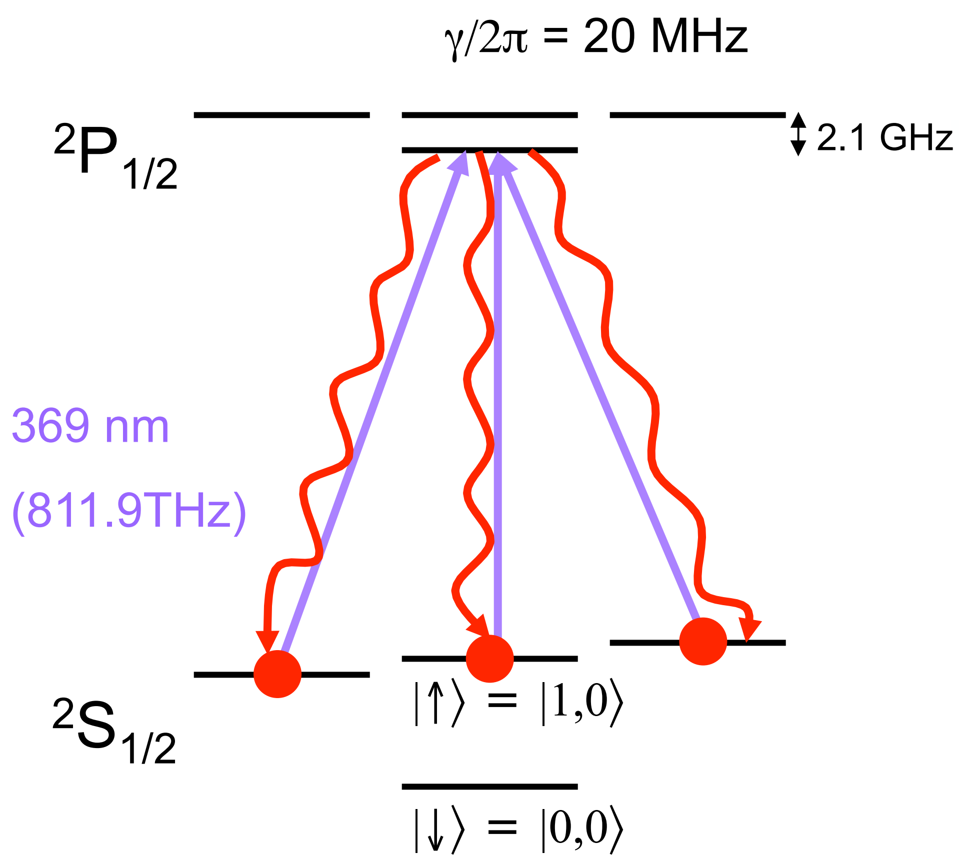
$\nu_{HF} = 12\,642\,812\,118 + 311B^2$ Hz

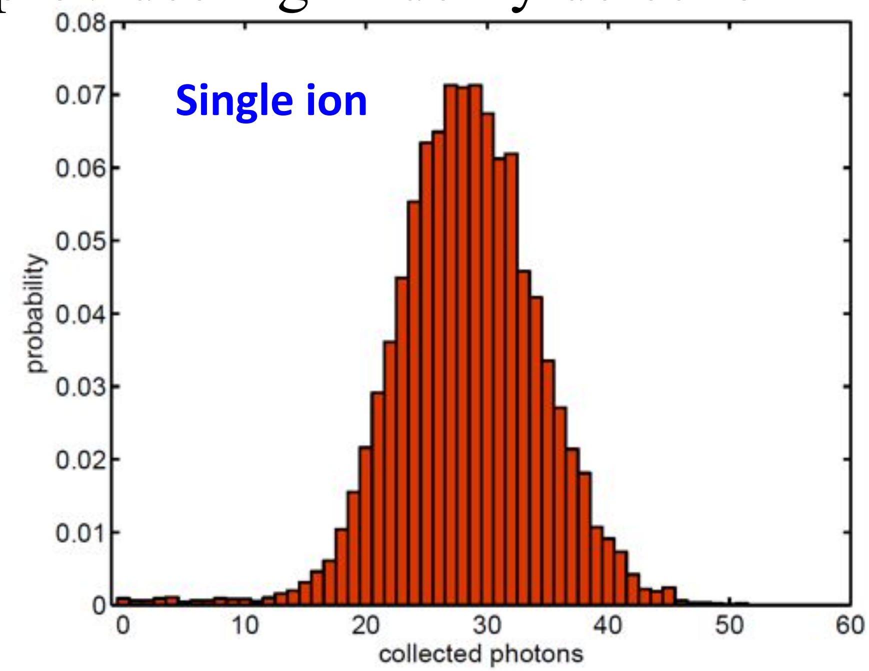
(600 Hz/G @ 1 G)

S. Olmschenk et al., PRA 76, 052314 (2007)

The $^{171}Yb^{+}$ Hyperfine Qubit: State Detection

- State-dependent fluorescence provides high fidelity detection





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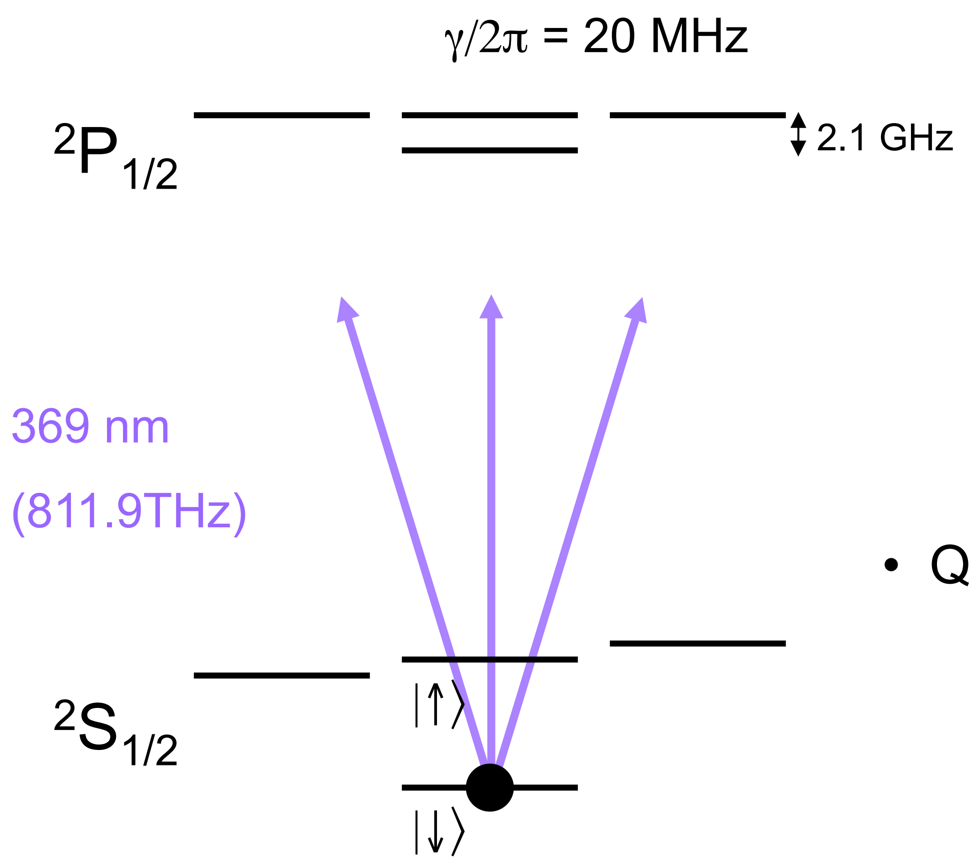
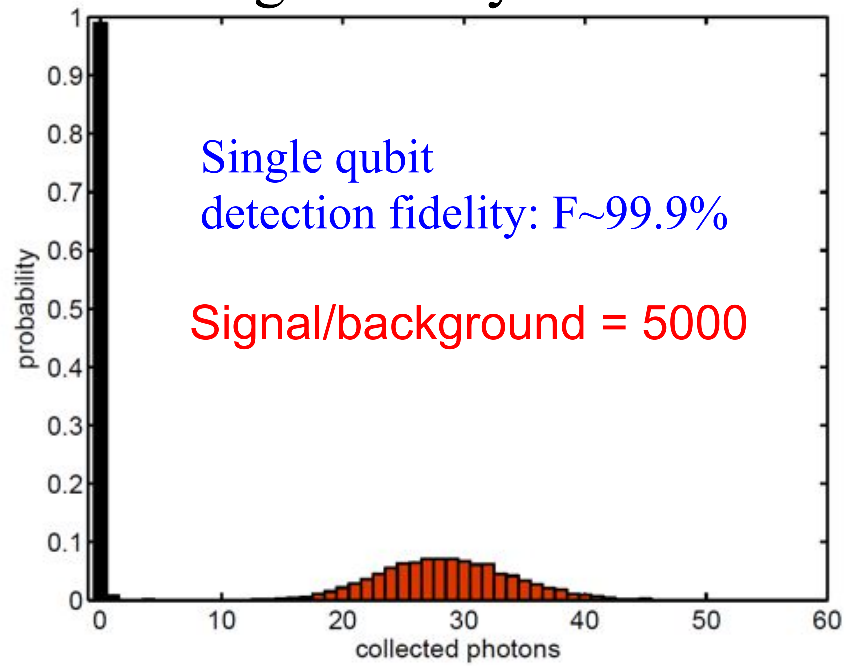




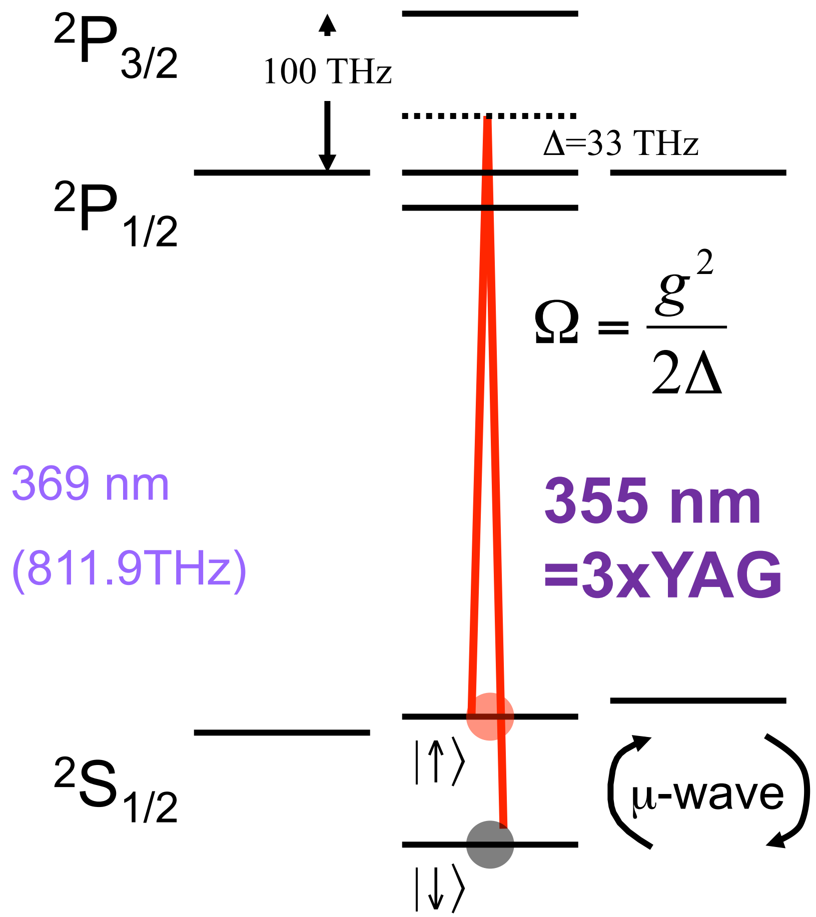
- Qubit state detection takes
  - < 30 us for ~99.9% fidelity
  - ~ 10 us for ~99% fidelity

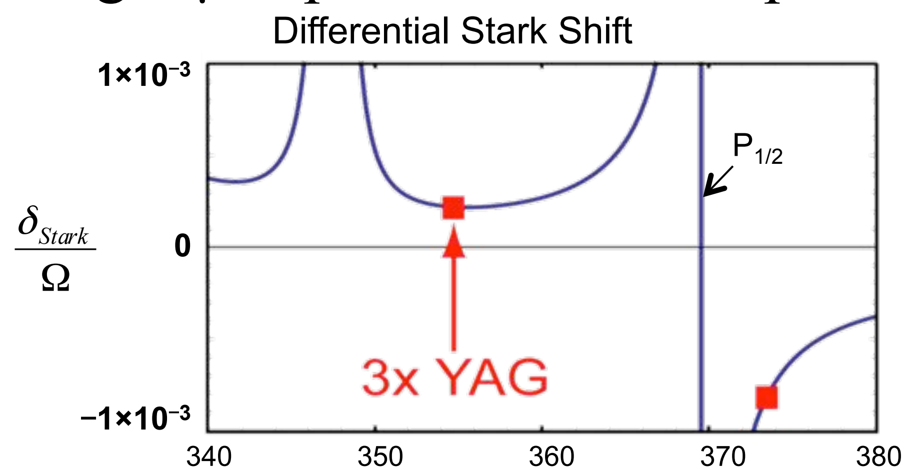
R. Noek et al., Opt. Lett. 38, 4735 (2013)

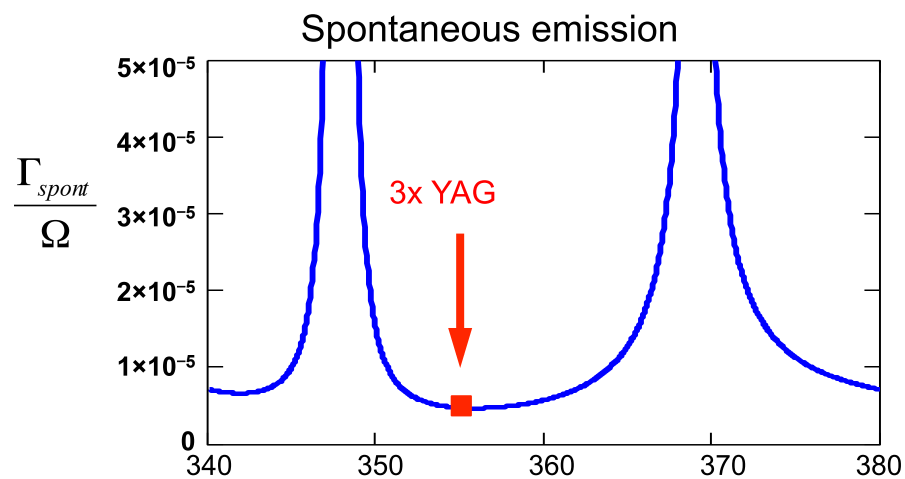
S. Olmschenk et al., PRA 76, 052314 (2007)

The $^{171}Yb^+$ Hyperfine Qubit: Single Qubit Gate

- High fidelity gates via Raman transition or microwave transition
- Single qubit fidelity over 99% using ~ μs optical/microwave pulse

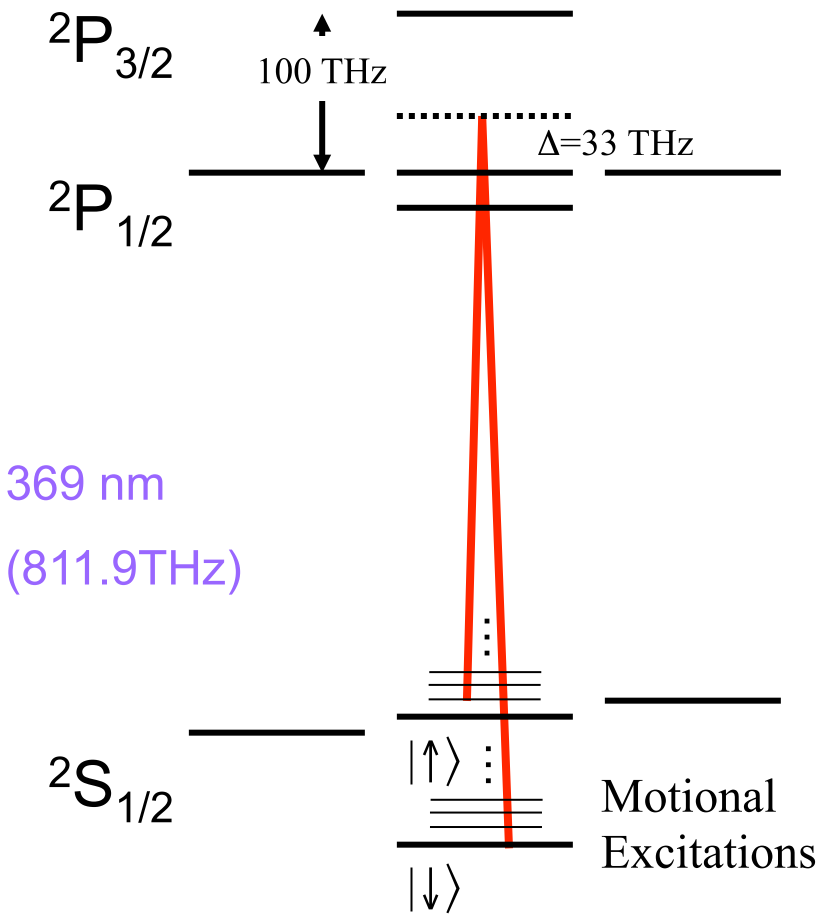


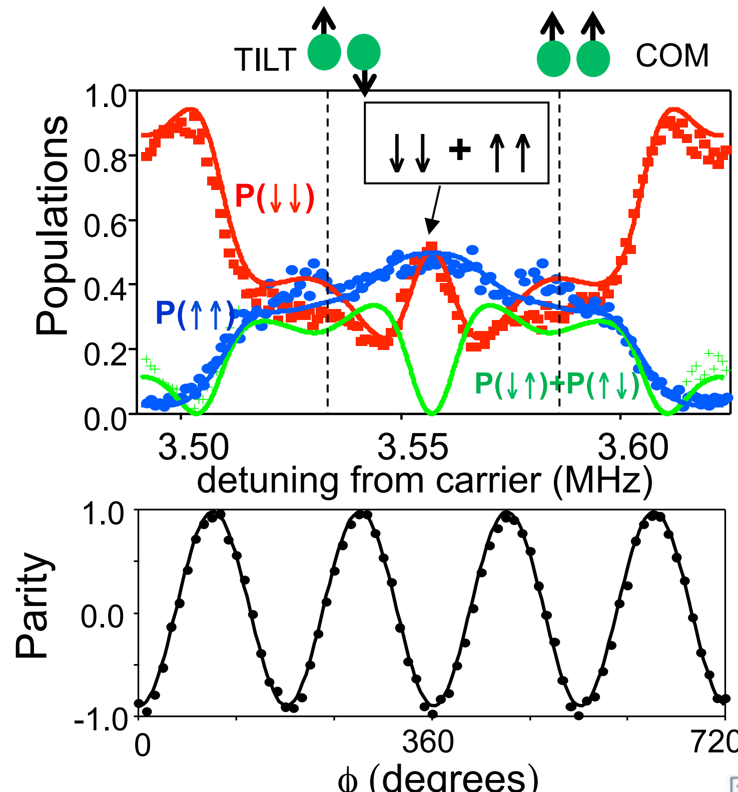




The $^{171}Yb^{+}$ Hyperfine Qubit: Multi-Qubit Gate

- Detuned Raman transition applies spin-dependent forces
- Can lead to robust spin-dependent phase shift (controlled-phase)





$\tau_2 = 40\ \mu s$ $F_2 > 98\%$

K. Kim et al., Phys. Rev. Lett. **103**, 120502 (2009)

Ion Chain Quantum Register

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- Use transverse phonon mode for multi-qubit gates
- Design and control of laser pulses that apply spin-dependent forces at the heart of quantum register operation
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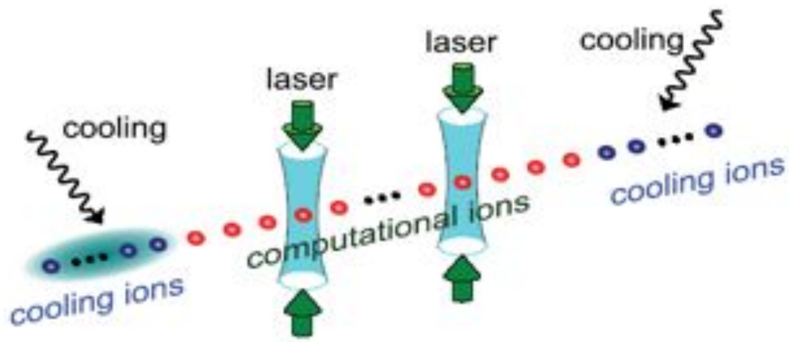
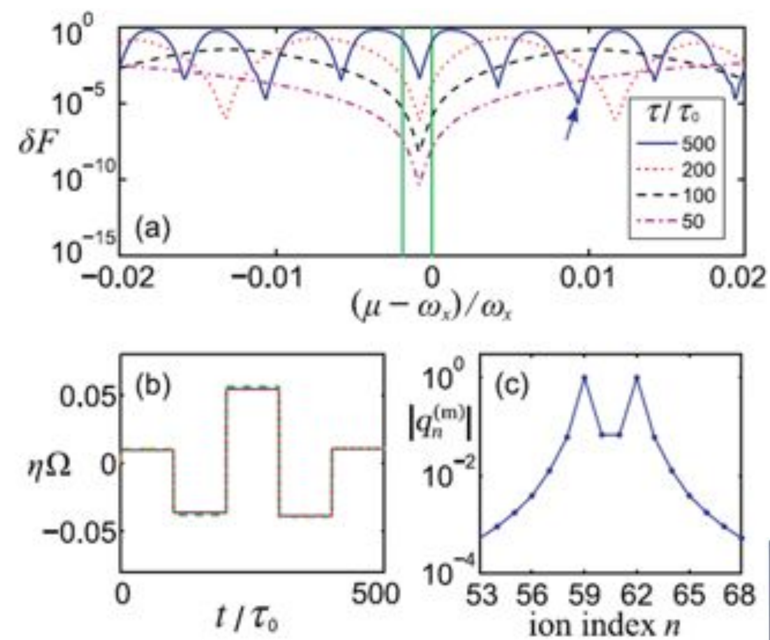


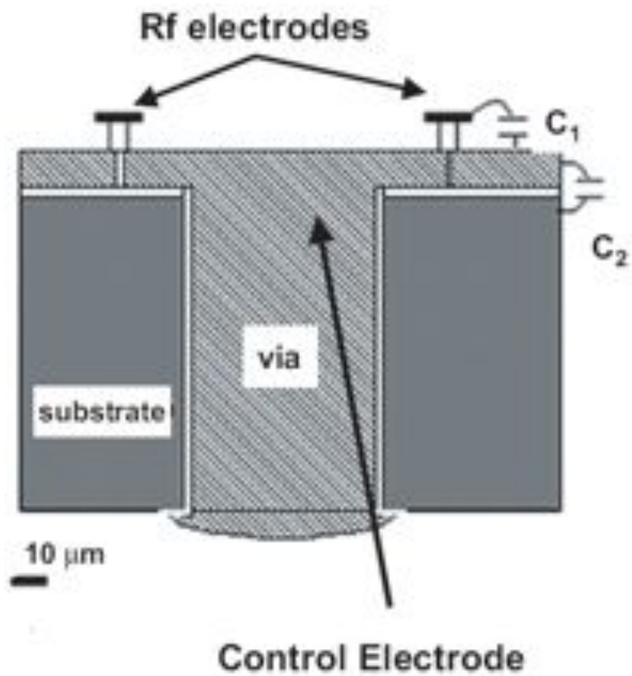


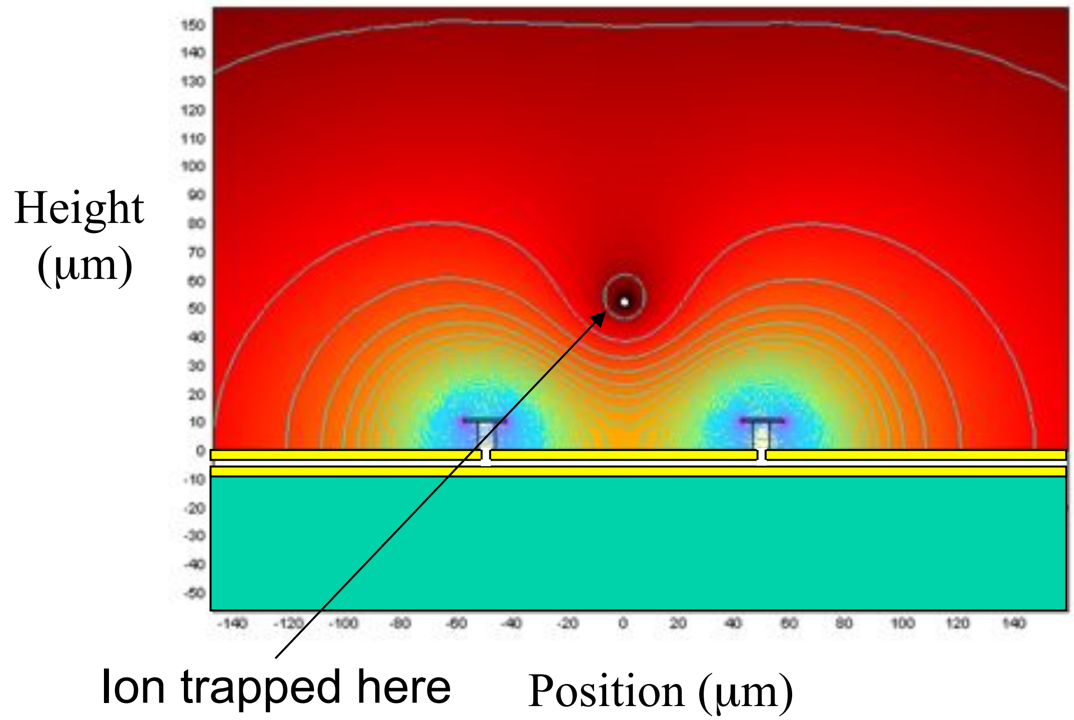
Zhu, Monroe and Duan, PRL 97, 050505 (2006); Europhys. Lett.73, 485 (2006)

Korenblit et al., New. J. Phys. 14, 095024 (2012)

Scalable Surface Ion Trap Chip

• **Design and Fabrication of Scalable Surface Ion Trap Chips**



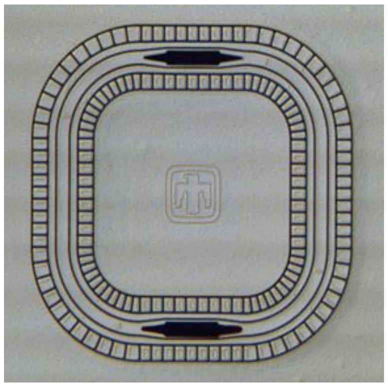


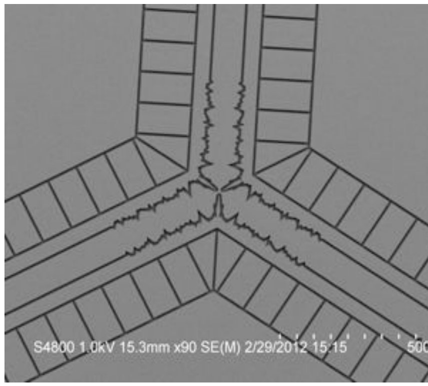
Surface Trap Fabrication: NIST, Georgia Tech, Sandia, MIT, Ulm, Mainz, …
Surface Trap Operation: NIST, Maryland, MIT, Duke, Innsbruck, Oxford, …

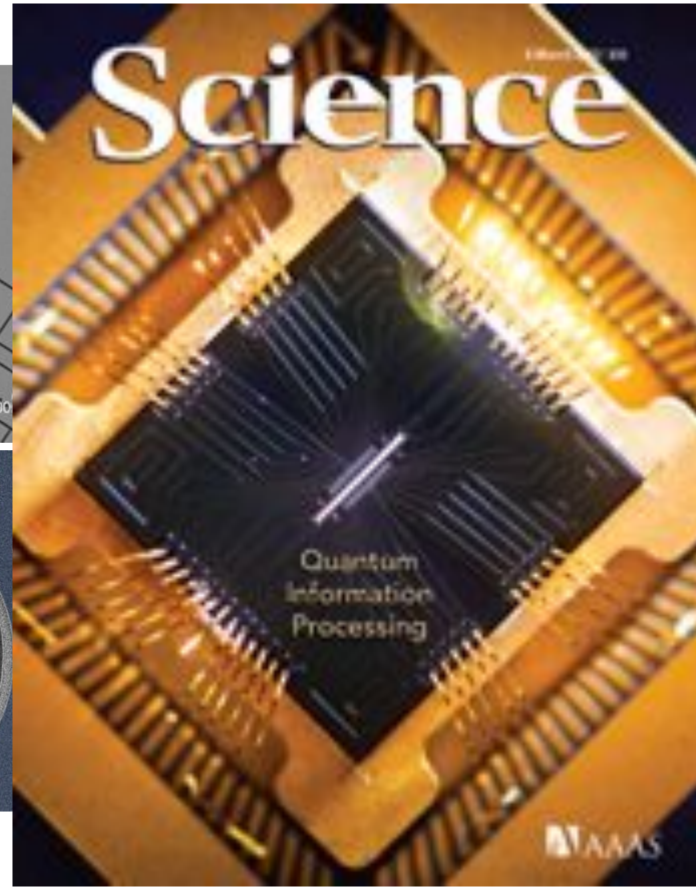
Chiaverini et al., Quant. Inf. Comput. 5, pp 419 (2005)
J. Kim et al., Quant. Inf. Comput. 5, pp 515 (2005)

New Trapping Technology in MUSIQC

- Microfabricated Ion Traps

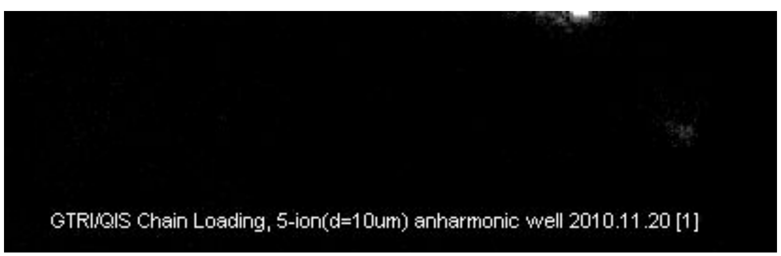






NJP 13, 075018 (2011)

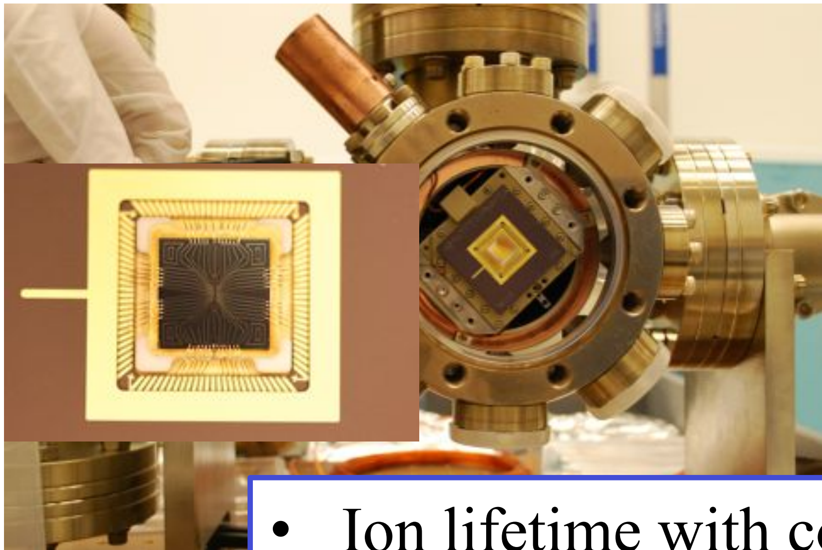
NJP 13, 103005 (2011)
NJP 14, 073012 (2012)
NJP 15, 033004 (2013)
NJP 15, 083053 (2013)

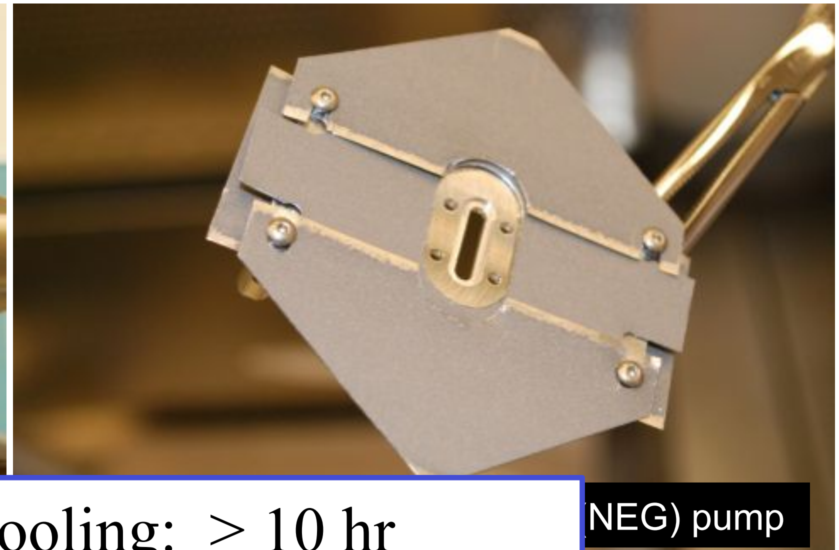


Advanced Trap Functionalities

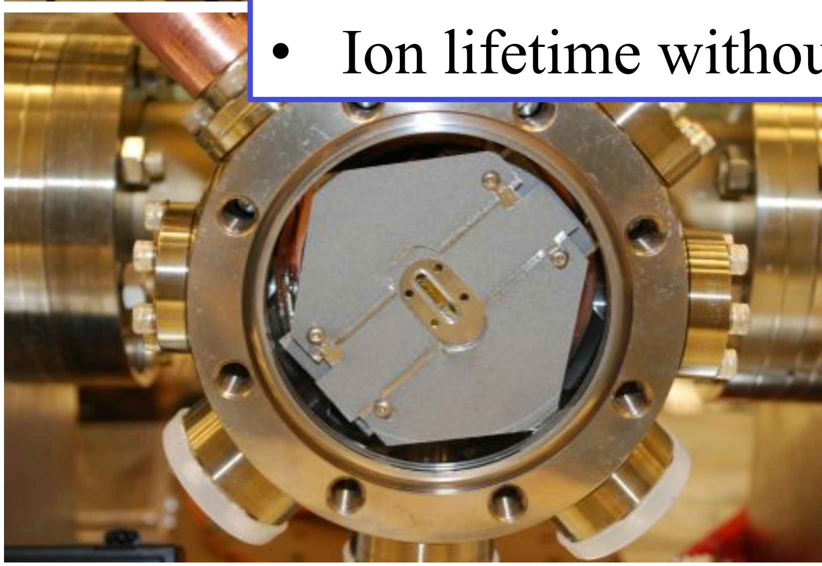
Jason Amini et al., GTRI (2011)

Sandia Thunderbird Traps at Duke

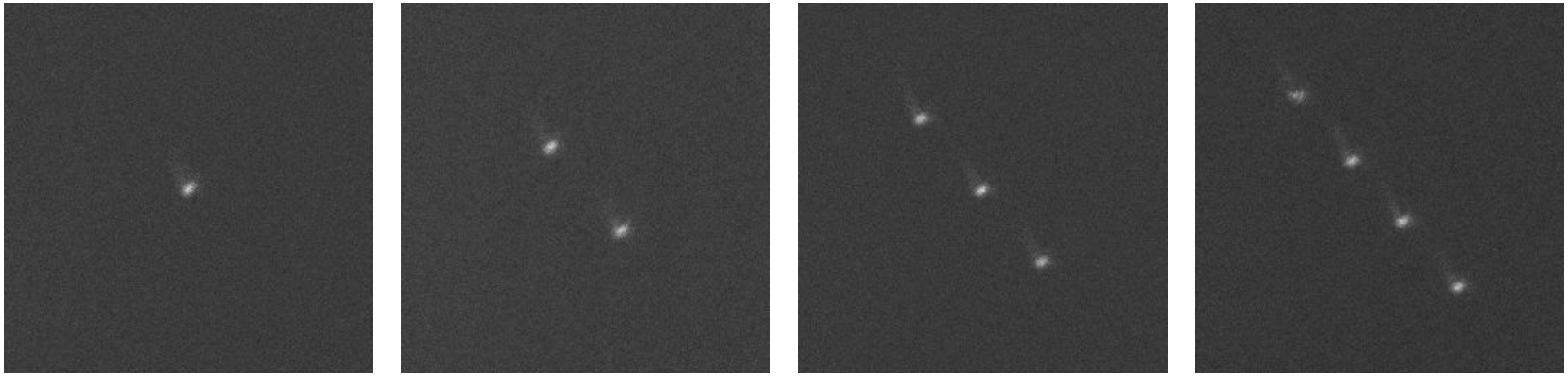




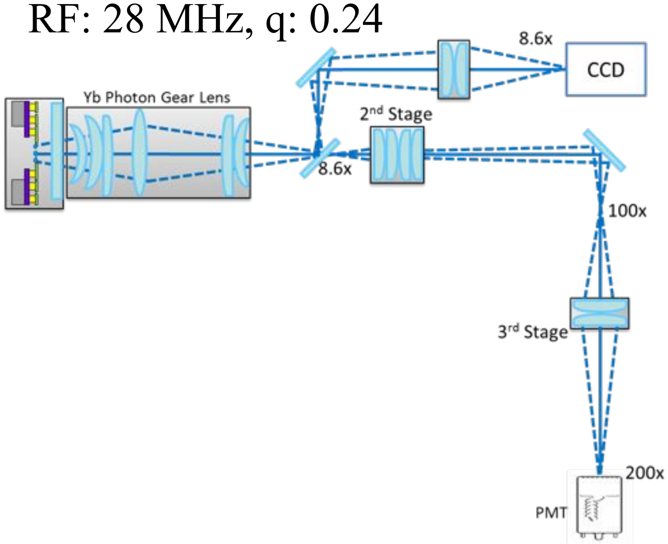
- Ion lifetime with cooling: > 10 hr
- Ion lifetime without cooling: > 20 min



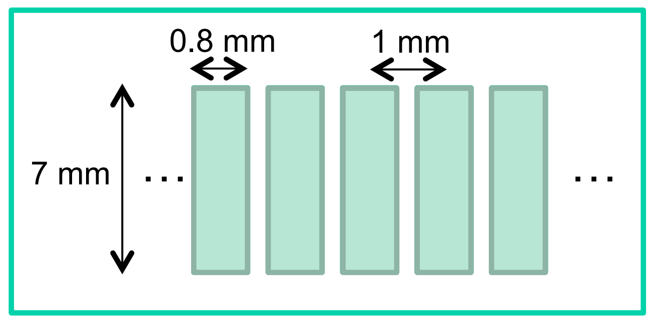
Ion chains in the Thunderbird



- Chains of two ions are held for up to 2 hours.
- RF: 28 MHz, q: 0.24

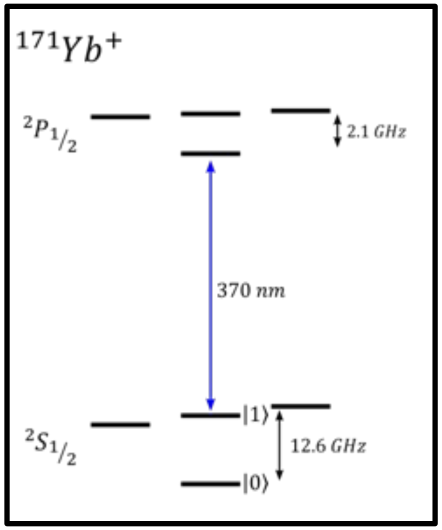


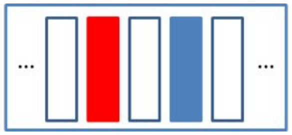
32-Channel PMT Array

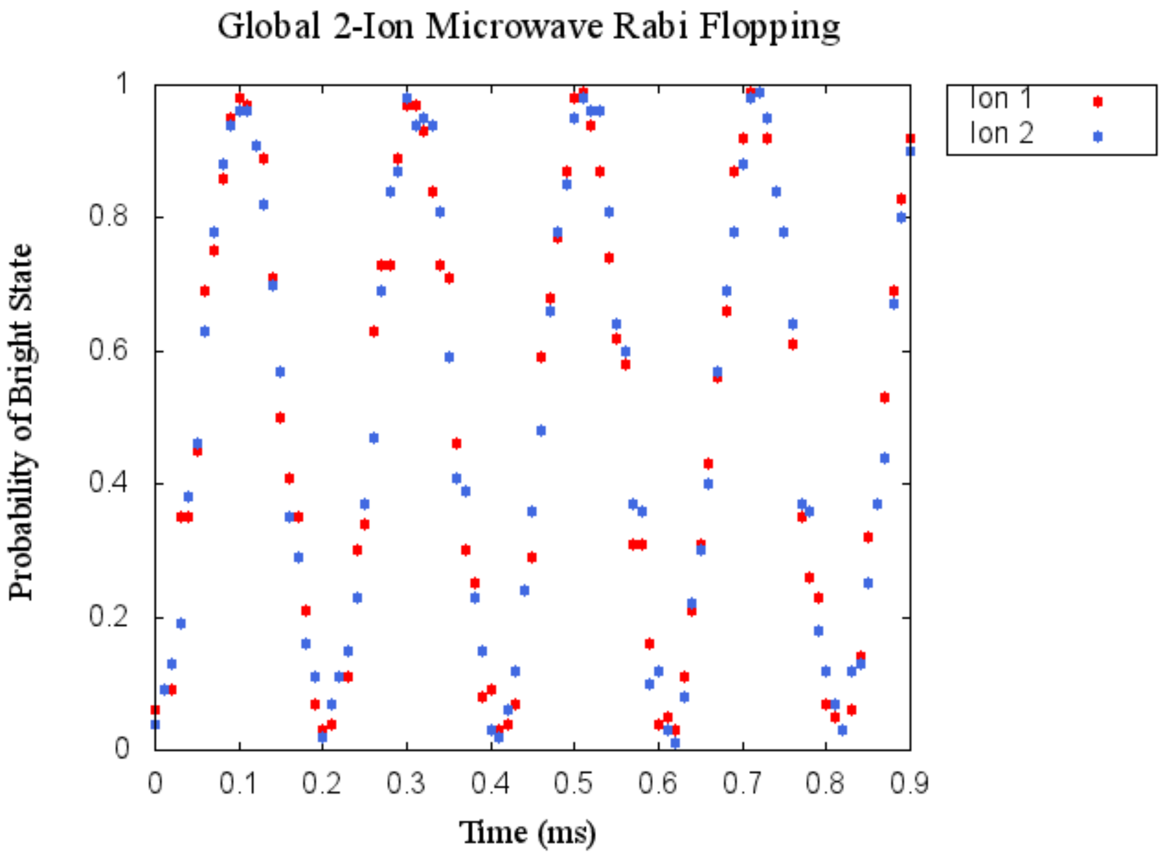


3 ions

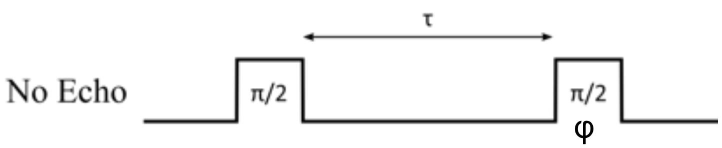
Global Microwave Single Qubit Gates

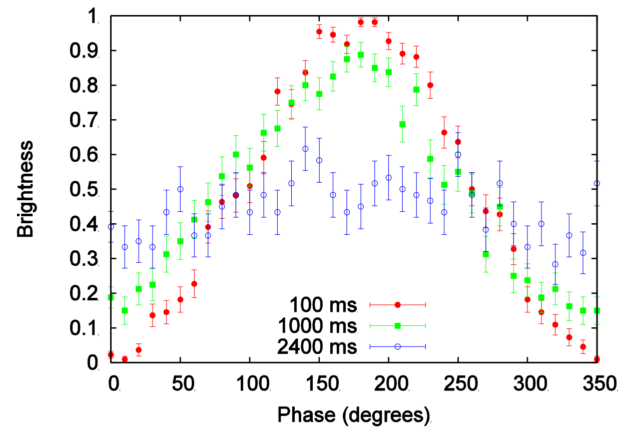




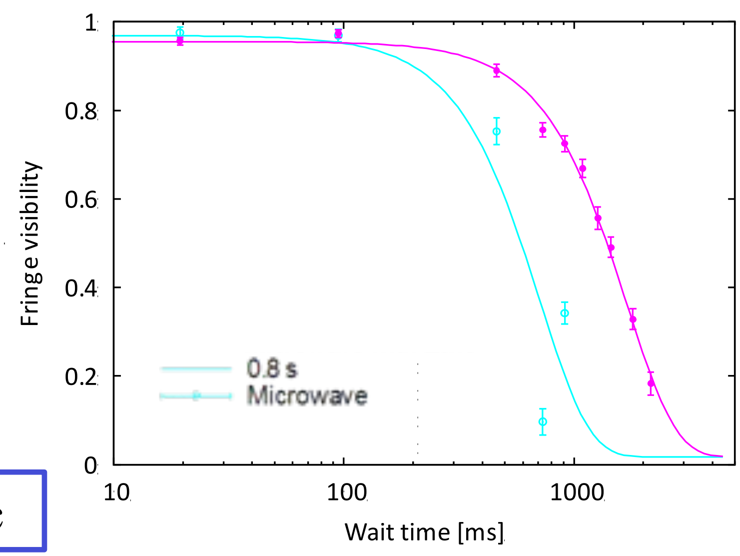


Qubit Coherence with Microwave Gates





- Microwave Ramsey experiment:
  - phase of 2nd pulse is incremented from 0 to 360deg.
  - Amount of time between pulses is varied
- Coherence time (no echo): 780 ms

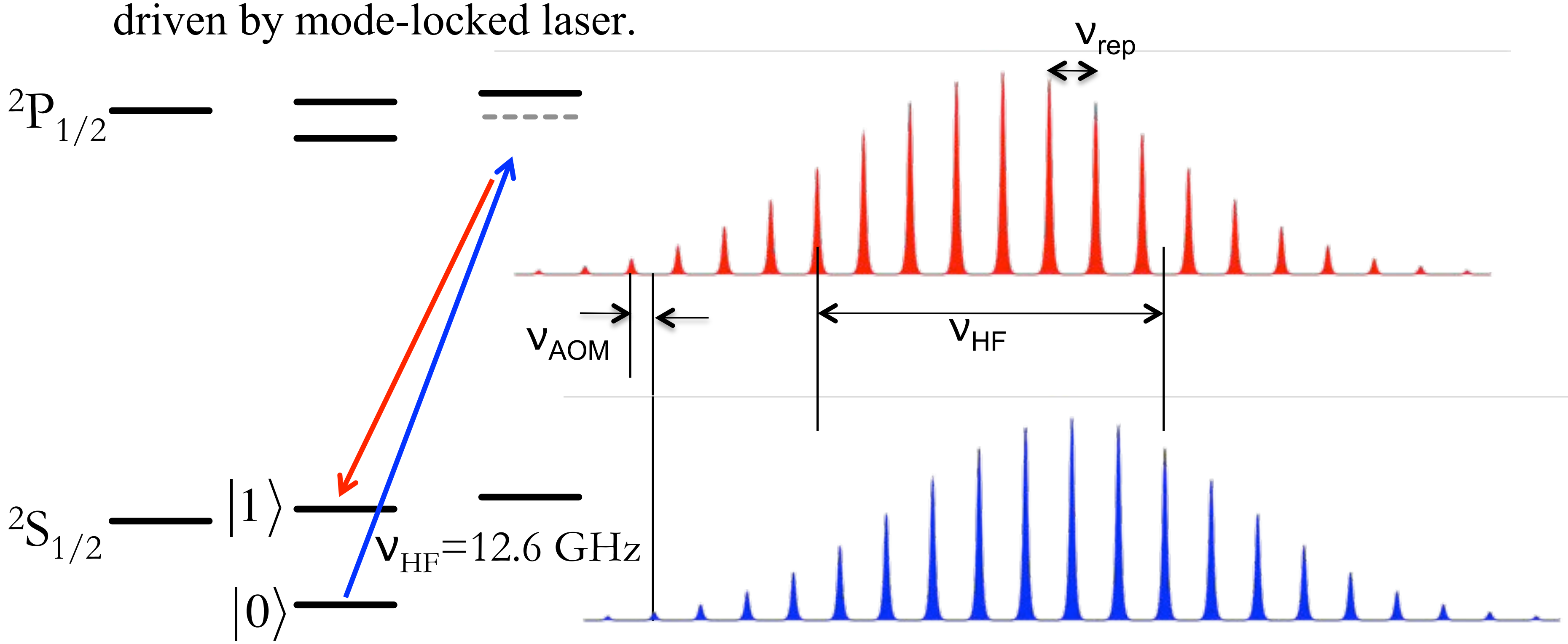


Coherence time with a single echo pulse: 1.9 sec

E. Mount *et al., New J. Phys.* **15** 093018 (2013)

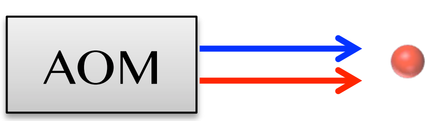
Raman Single Qubit Gates

- Global & Individual single qubit gates can be realized by Raman transition driven by mode-locked laser.



$$N \times \nu_{rep} + \nu_{AOM2} - \nu_{AOM1} = \nu_{HF}$$

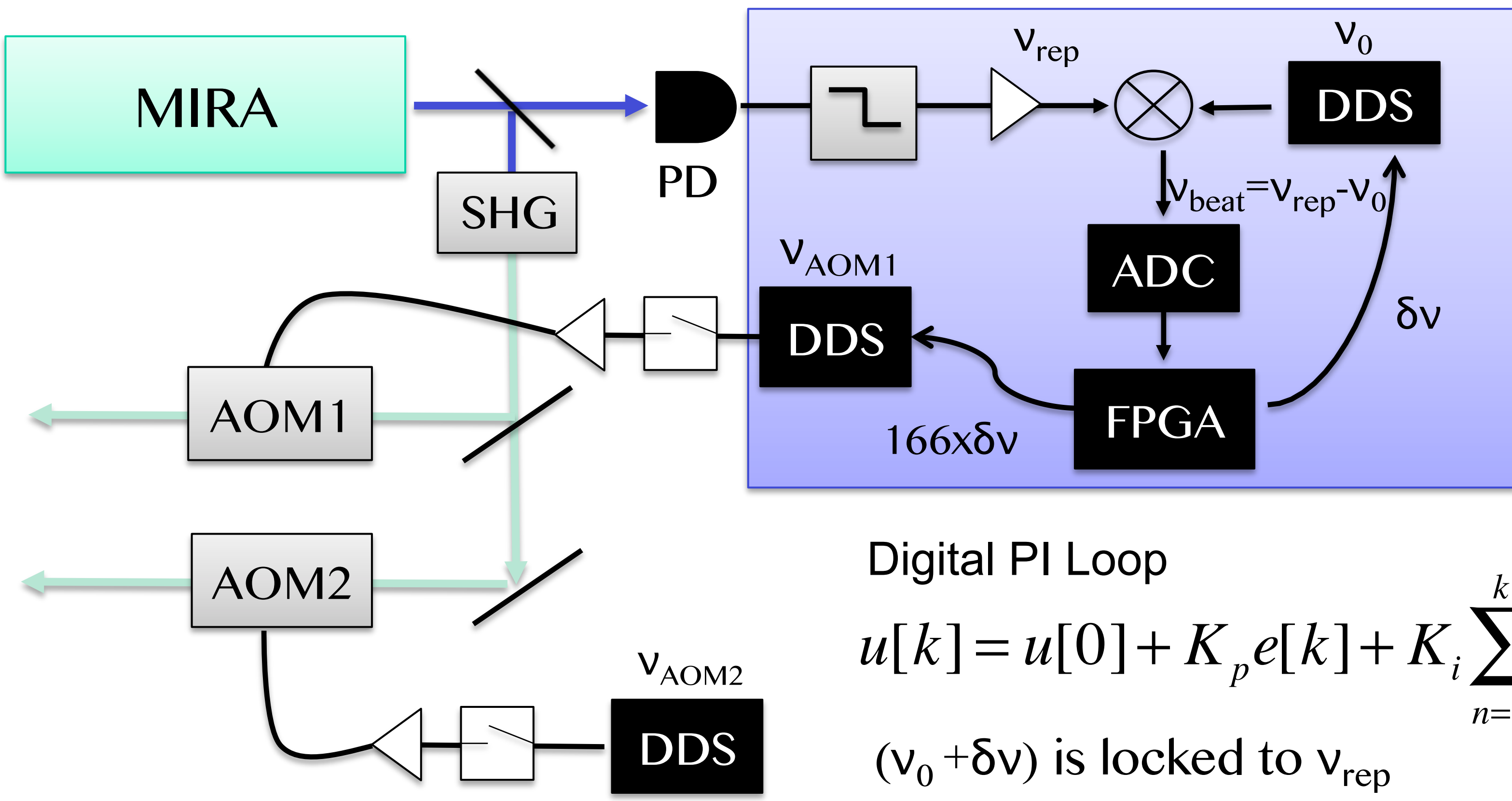
FIX!!



Co-propagating optical frequency combs

D. Hayes et al., PRL 104, 140501 (2010)

Digital PI Loop



Digital PI Loop

$$u[k] = u[0] + K_p e[k] + K_i \sum_{n=0}^{k} e[n]$$

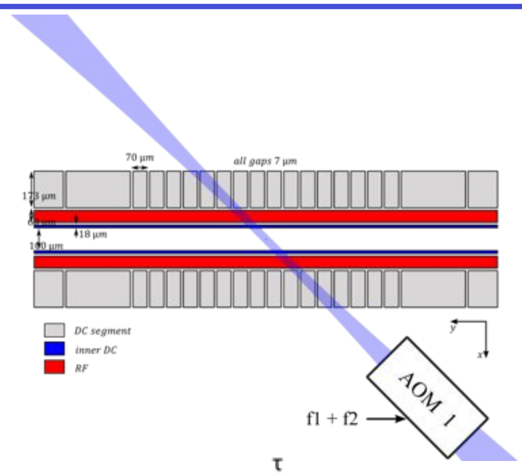
$(\nu_0 + \delta\nu)$ is locked to ν_{rep}

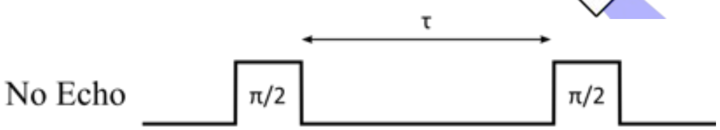
$\nu_{AOM1} = 210$ MHz $+ 166 \times \delta\nu$

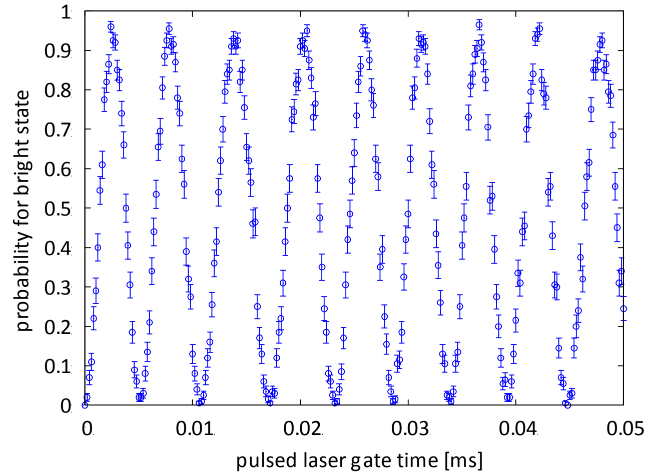
$\nu_{AOM2} = \nu_{HF} - 166 \times \nu_0 + \nu_{AOM1}$

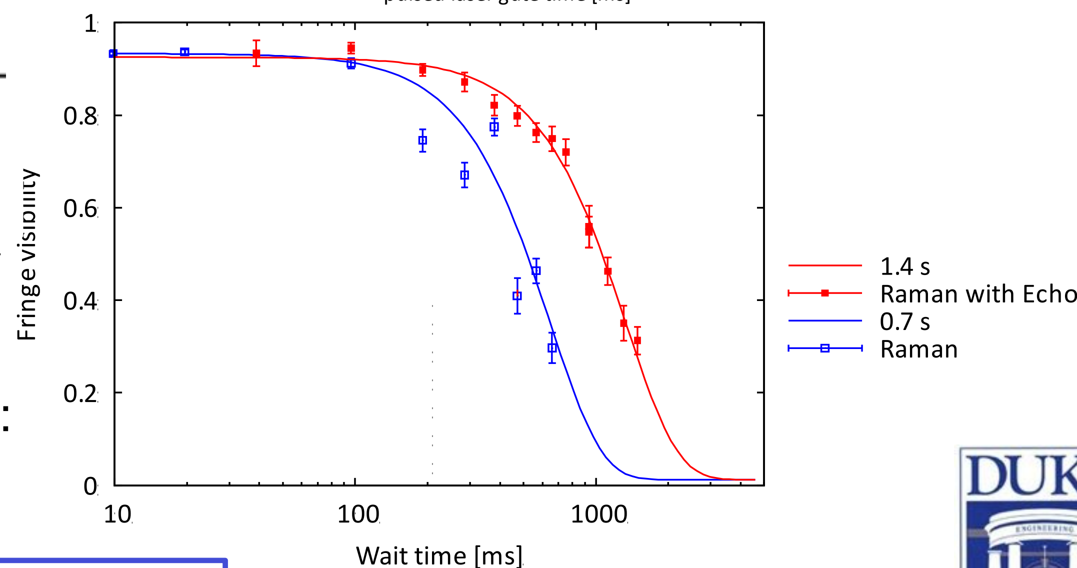
$(\nu_0 + \delta\nu) \times 166 + \nu_{AOM2} - \nu_{AOM1} = \nu_{HF}$

Qubit Manipulation with Raman Beams







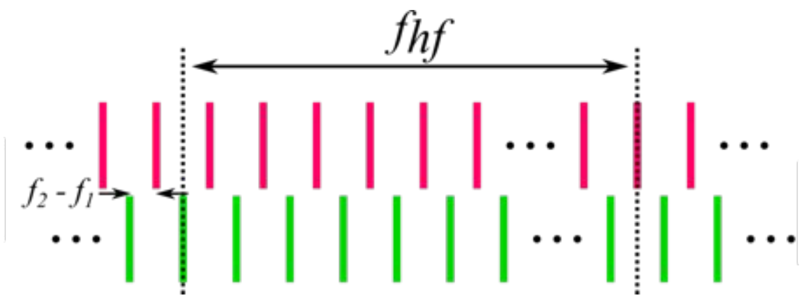


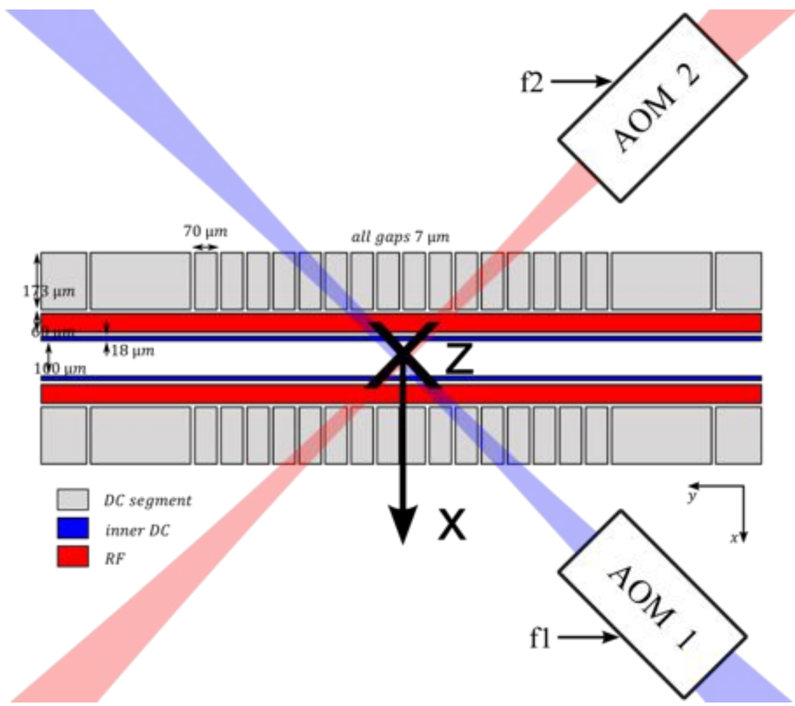
- Ramsey experiment with frequency combs:
- Coherence time without echo: 690 ms

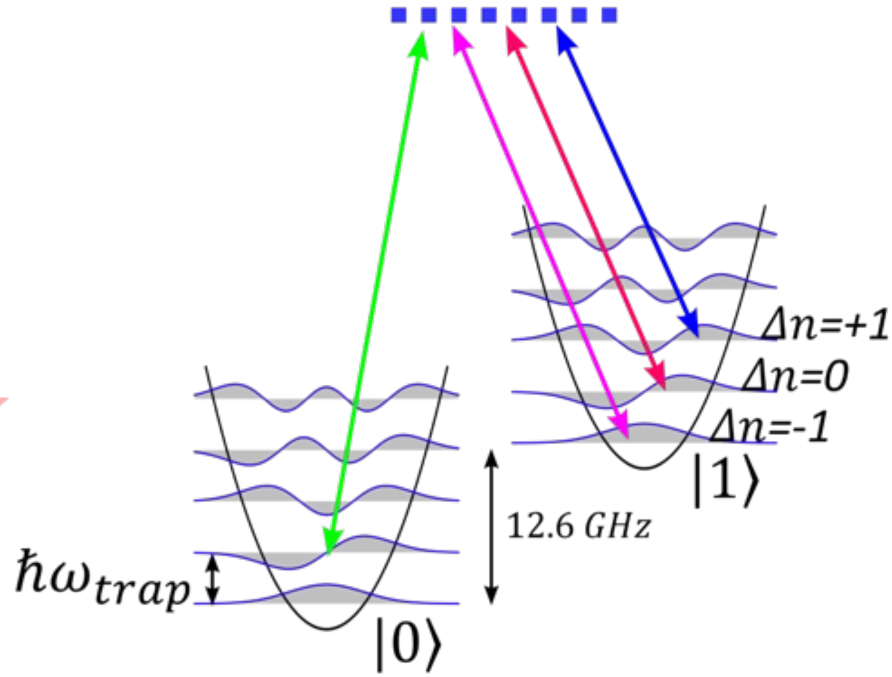
Coherence time with a single echo pulse: 1.4 sec

E. Mount *et al, NJP* **15** 093018 (2013)

Motional Raman transitions



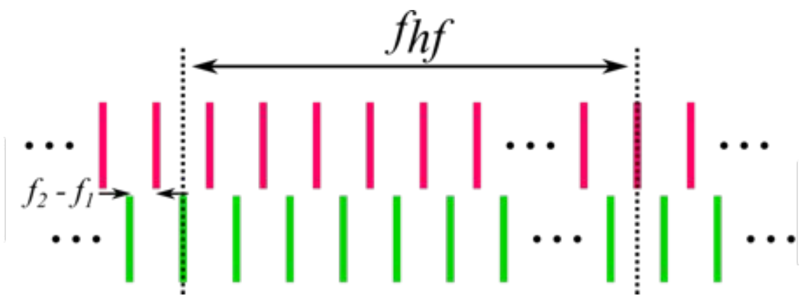


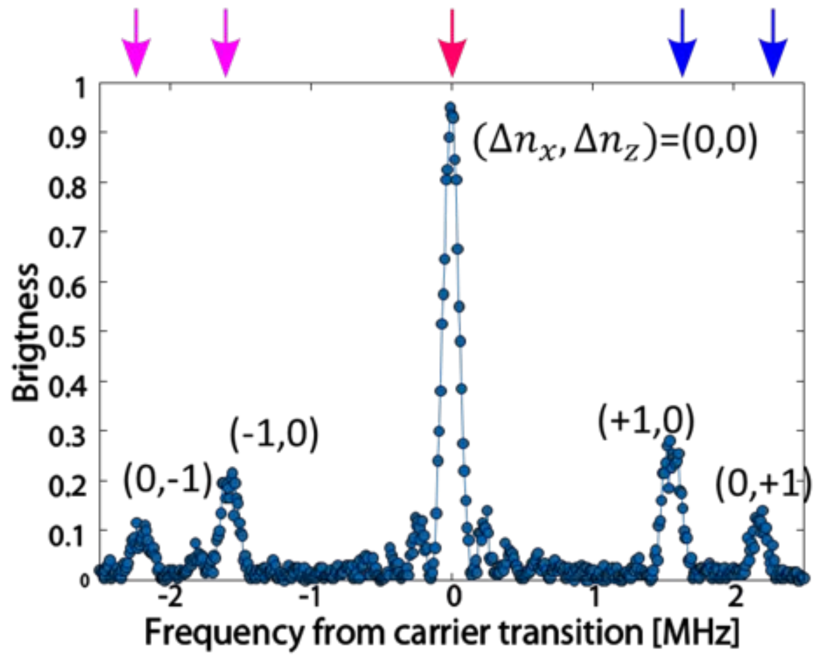


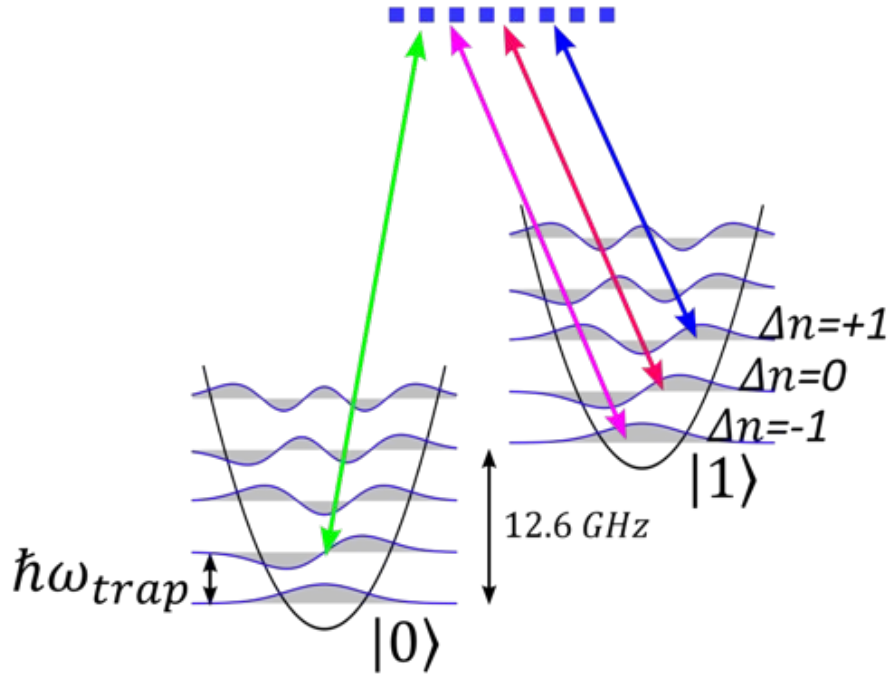
$$n * f_{rep} + (f_2 - f_1) = f_{hf} \pm f_{trap}$$

E. Mount *et al, NJP* **15** 093018 (2013)

Motional Raman transitions



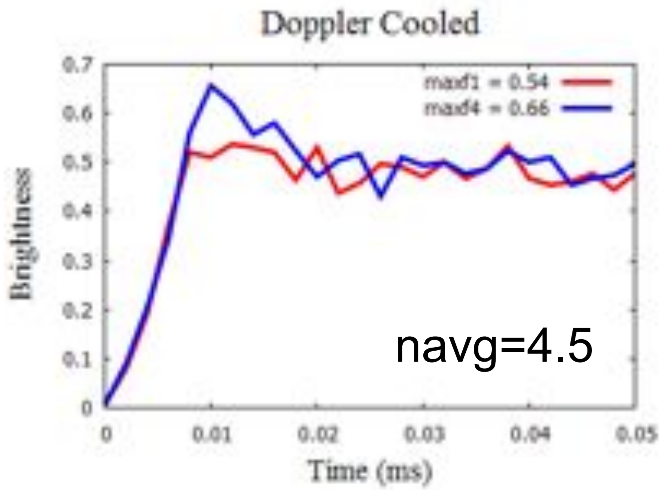


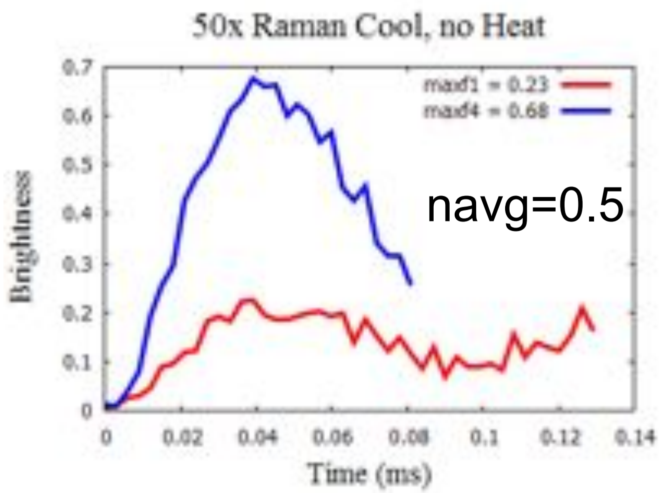


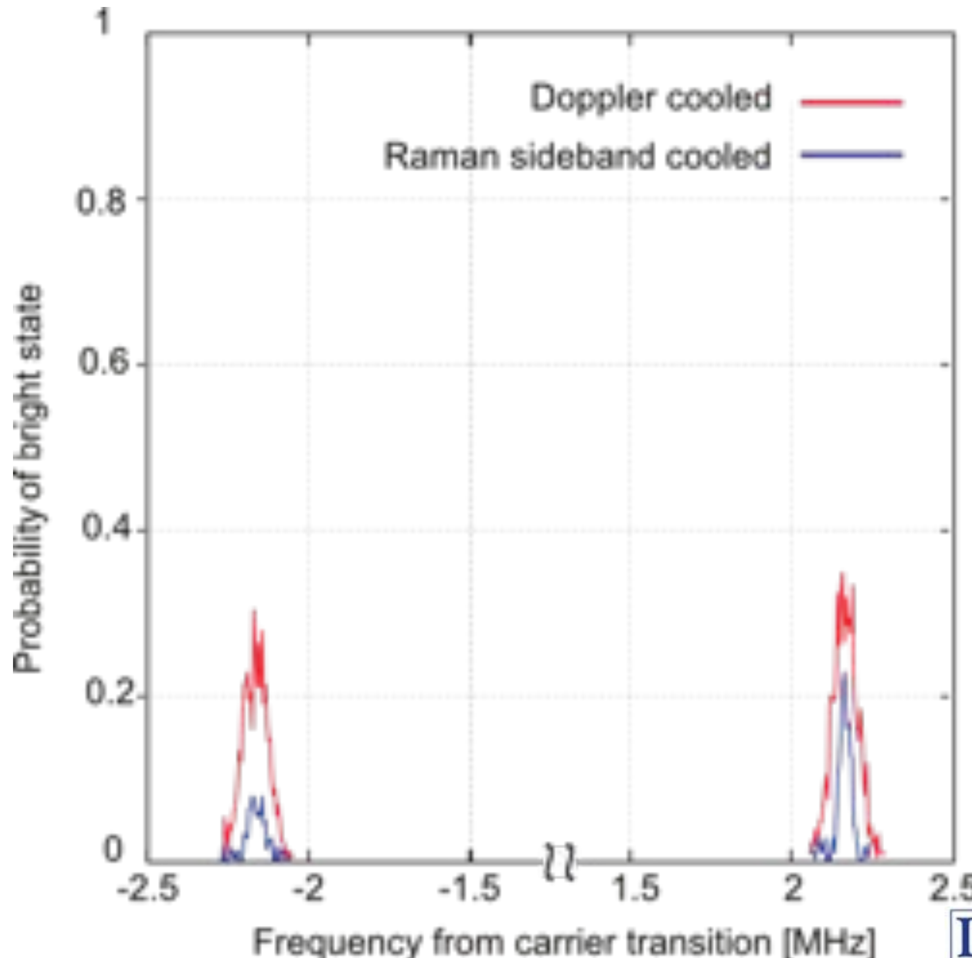
$$n * f_{rep} + (f_2 - f_1) = f_{hf} \pm f_{trap}$$

E. Mount *et al, NJP* **15** 093018 (2013)

Ground state cooling

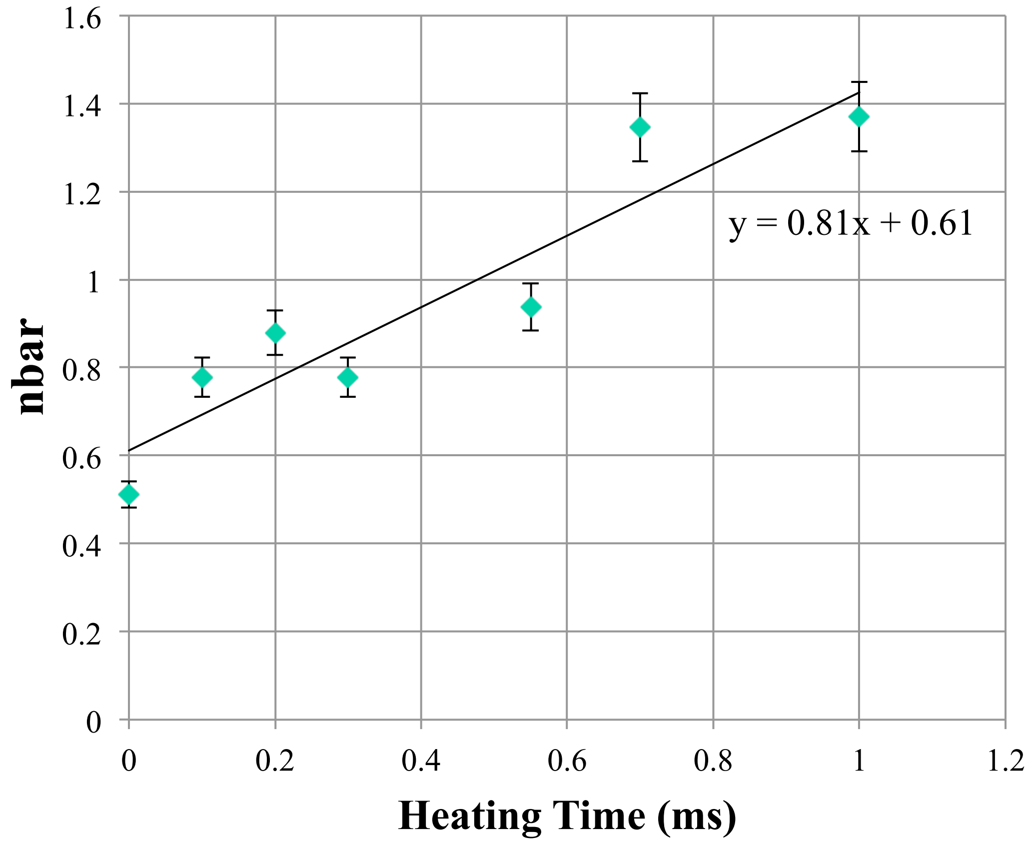






E. Mount *et al, NJP* **15** 093018 (2013)

Heating rate

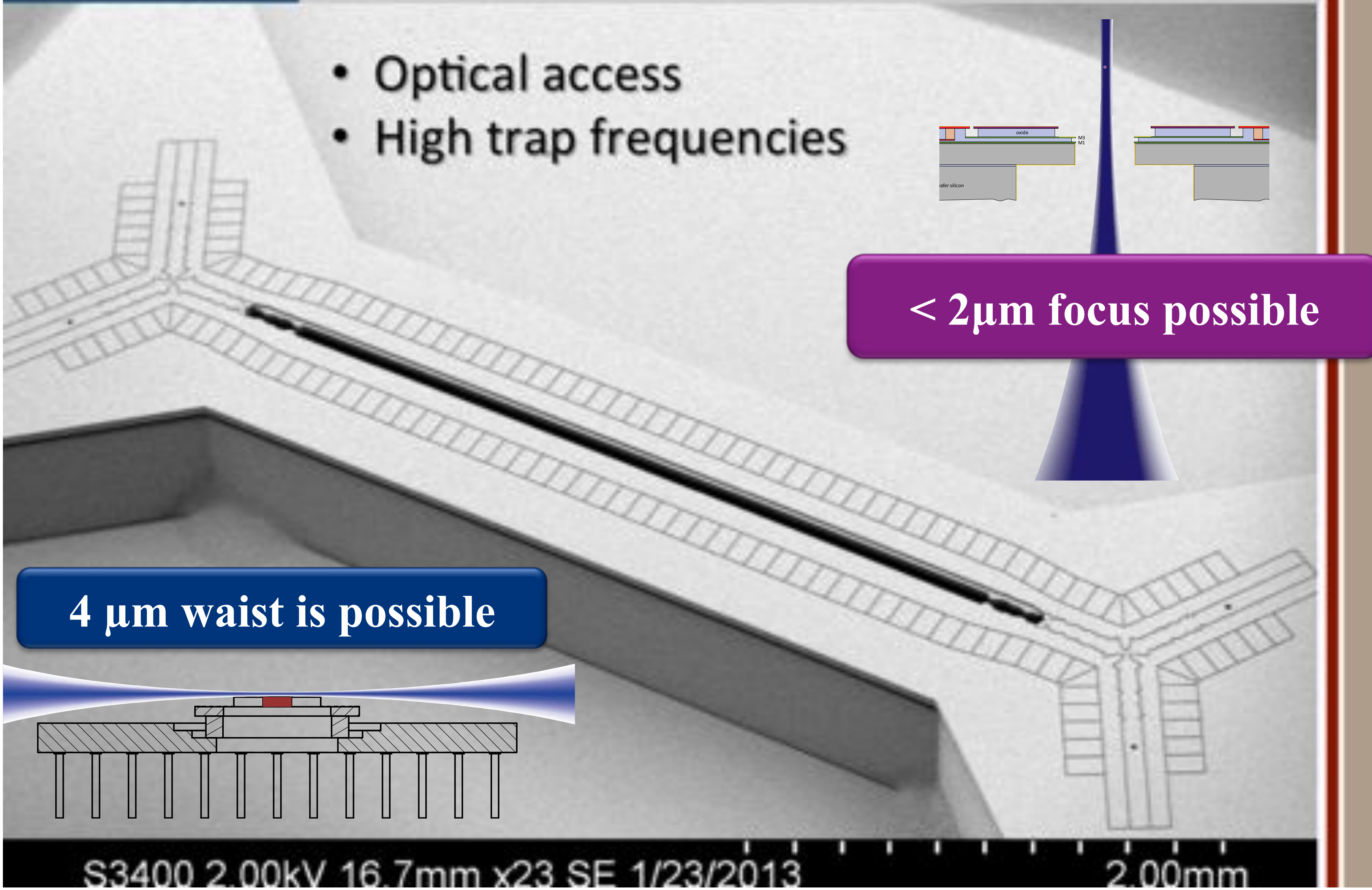


Heating Rate (transverse mode):
~1 quantum/ms

E. Mount *et al, NJP* **15** 093018 (2013)

HOA 1

- Optical access
- High trap frequencies



Large NA Lens for Better Photon Collection

- High NA lens was designed for ion emission into a single mode fiber
- Useful for state detection!!

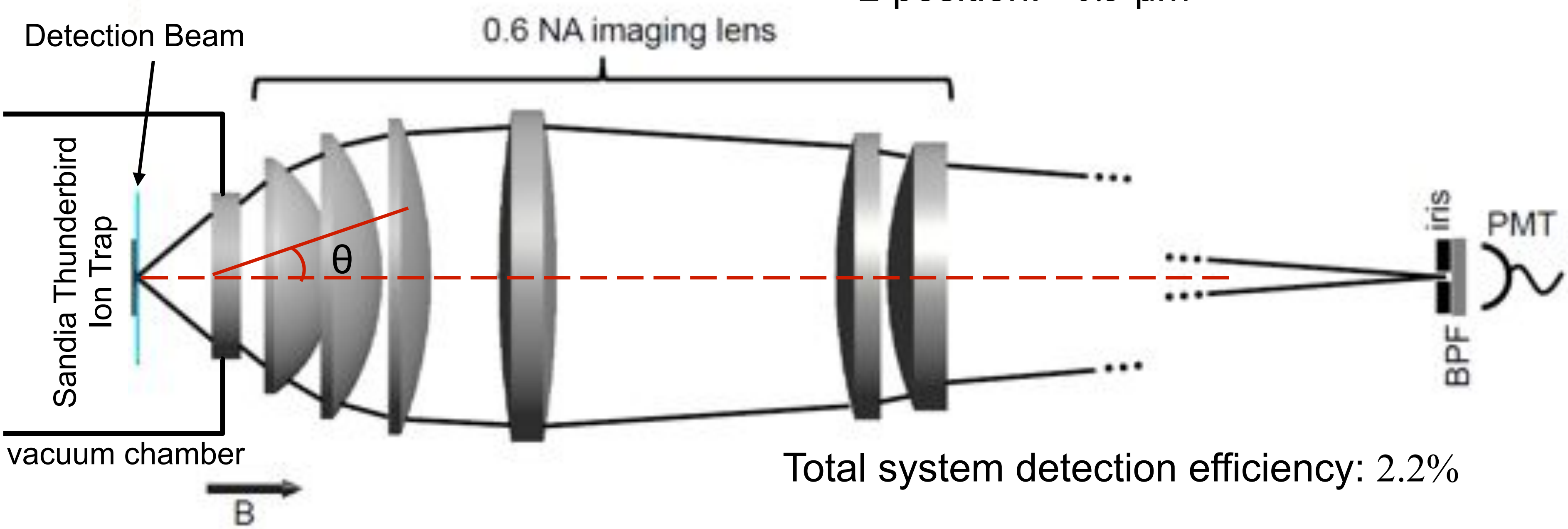
Diffraction limited field of view: 440 μm

Maximum fiber coupling efficiency: 80%

Lens tilt θ: ±0.027°

z-position: ±0.5 μm

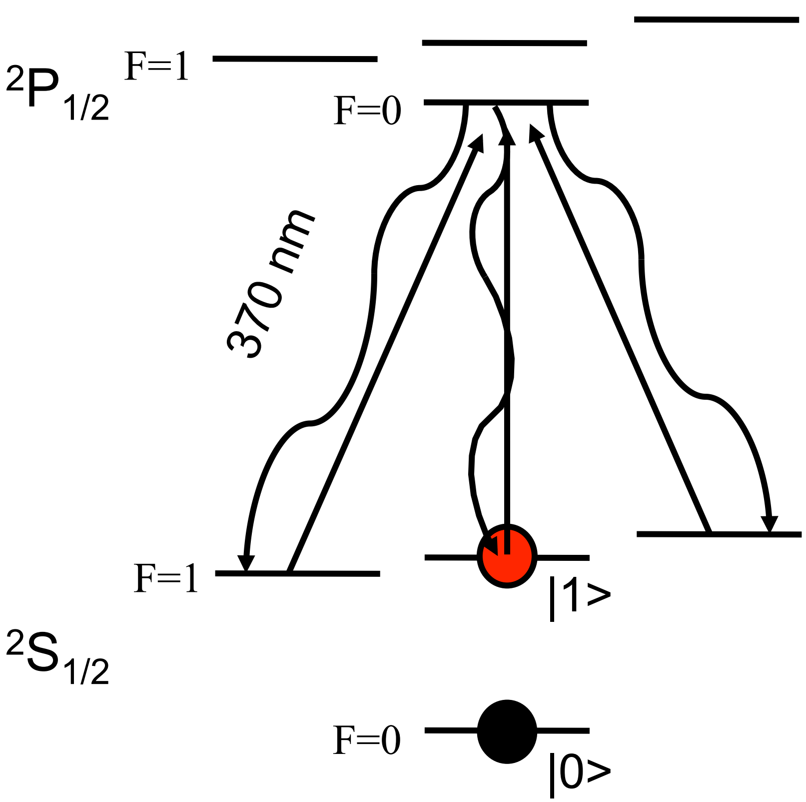
10% collection from the ion

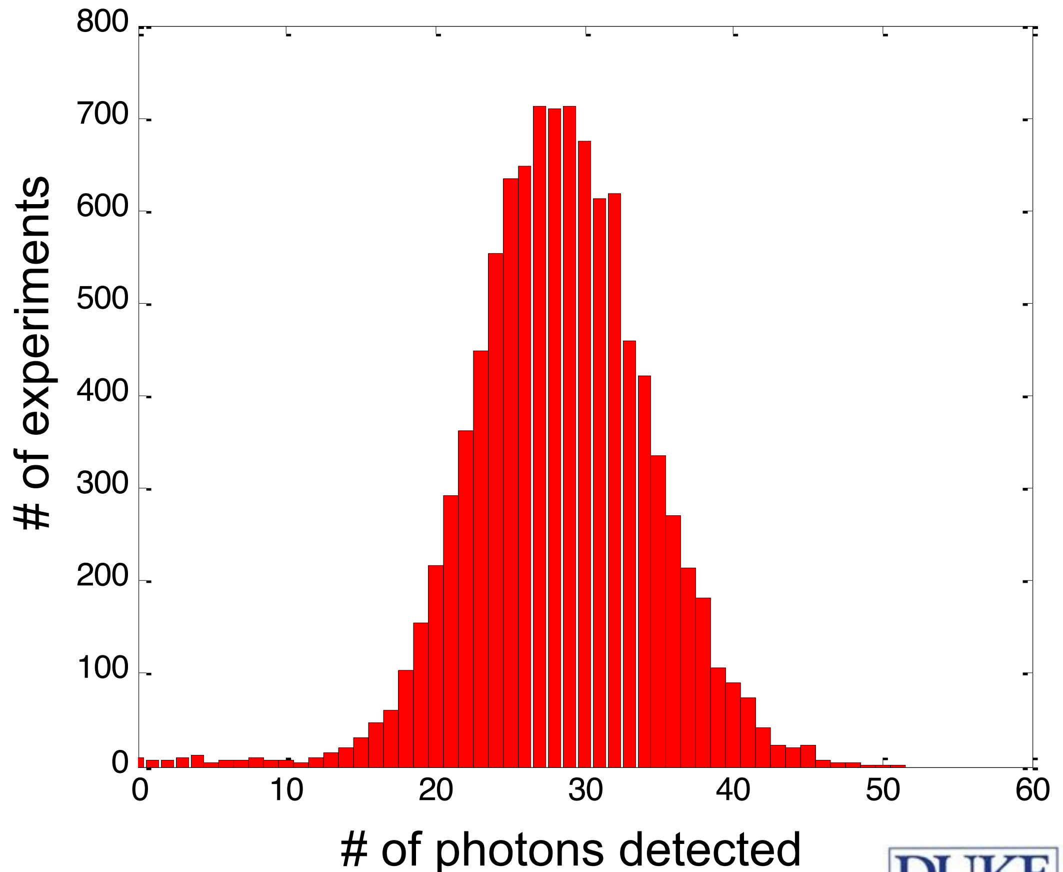


Total system detection efficiency: 2.2%

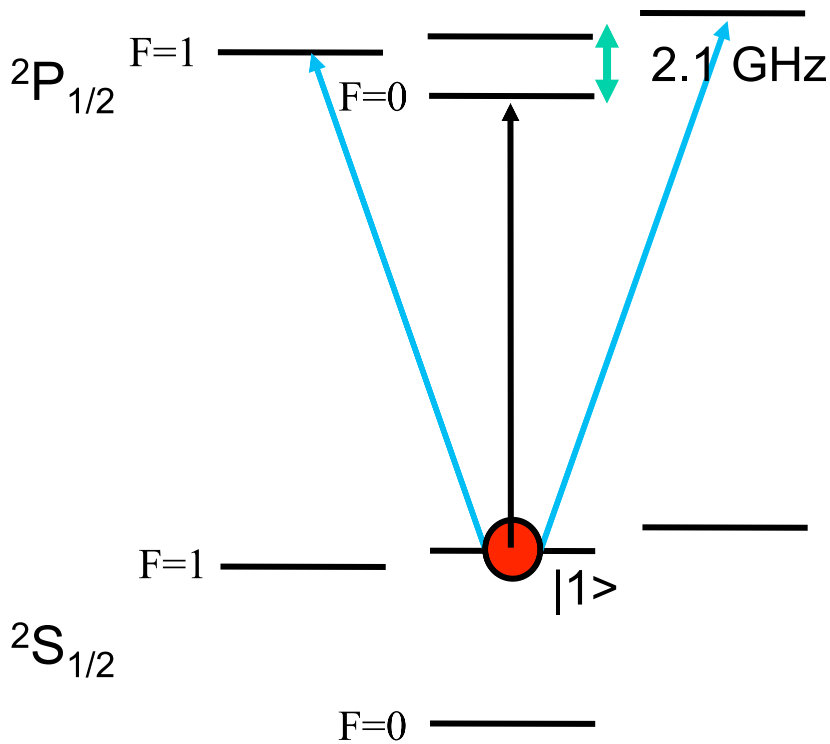
Dark counts: 6Hz+32Hz/μW

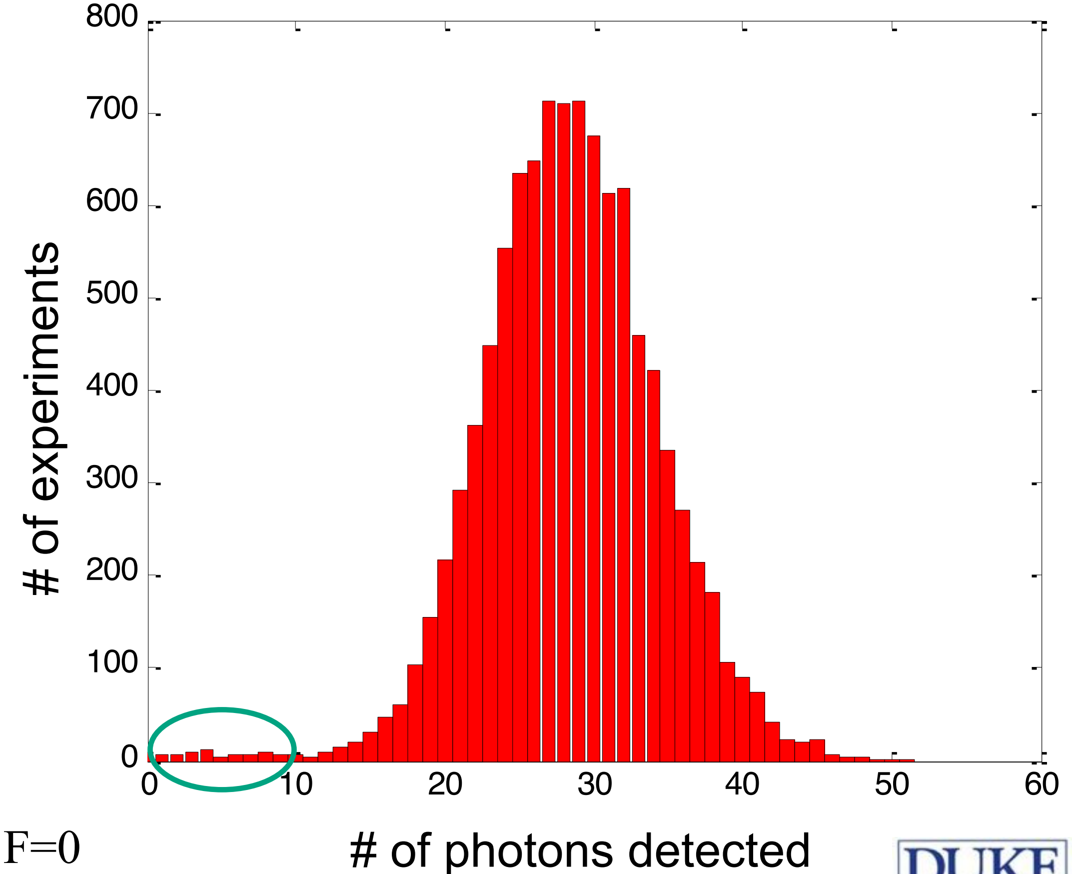
$^{171}Yb^{+}$ Hyperfine State Detection





Dark Pumping





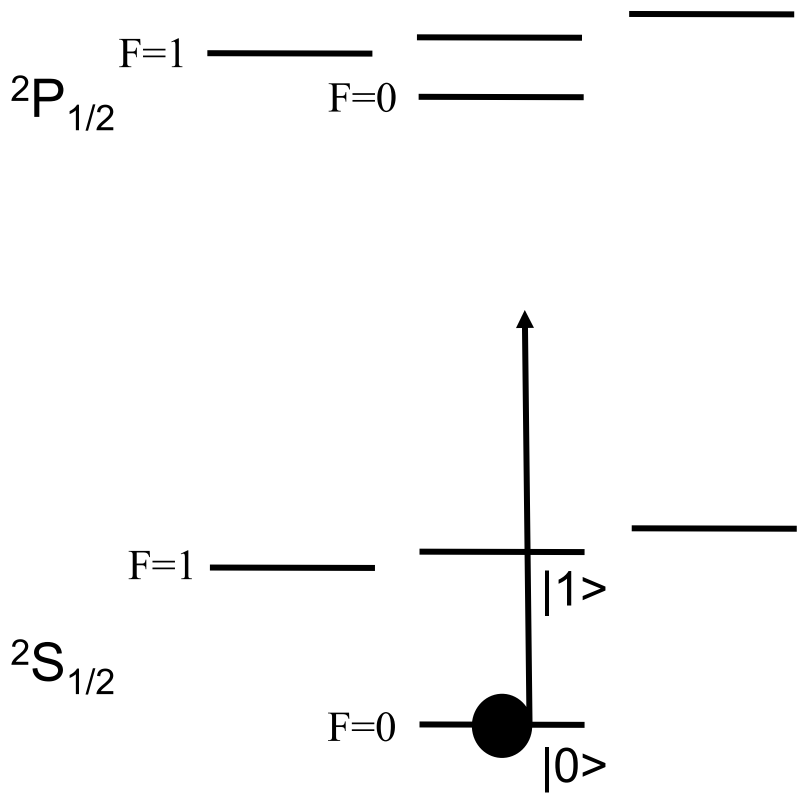
Coherent dark states

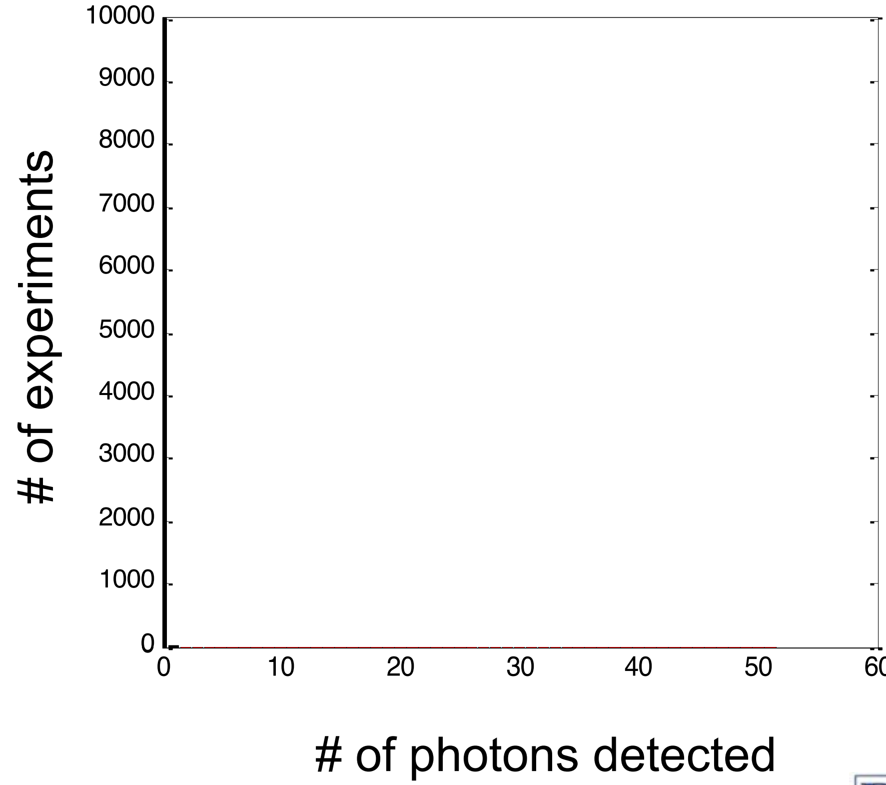
Probability to decay to F=0

$$R_{\mathrm{d}} \approx \left(\frac{2}{3}\right)\left(\frac{1}{3}\right)\left(\frac{\Gamma}{2}\right)\left(\frac{2\Omega^2}{\Gamma^2}\right)\left(\frac{\Gamma}{2\Delta_{\mathrm{HFP}}}\right)^2$$

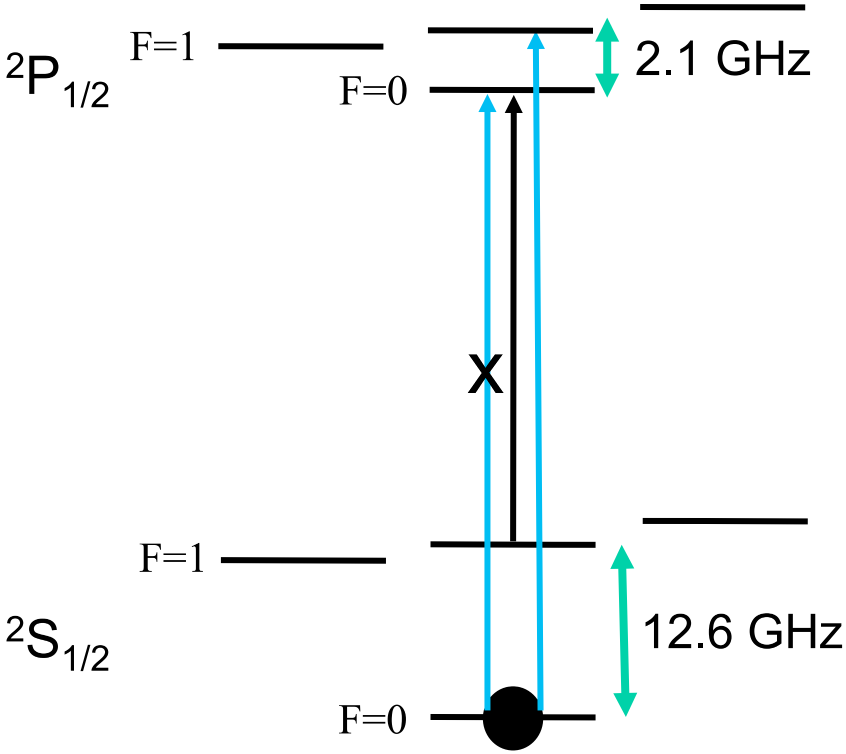
Off-resonant two level scattering

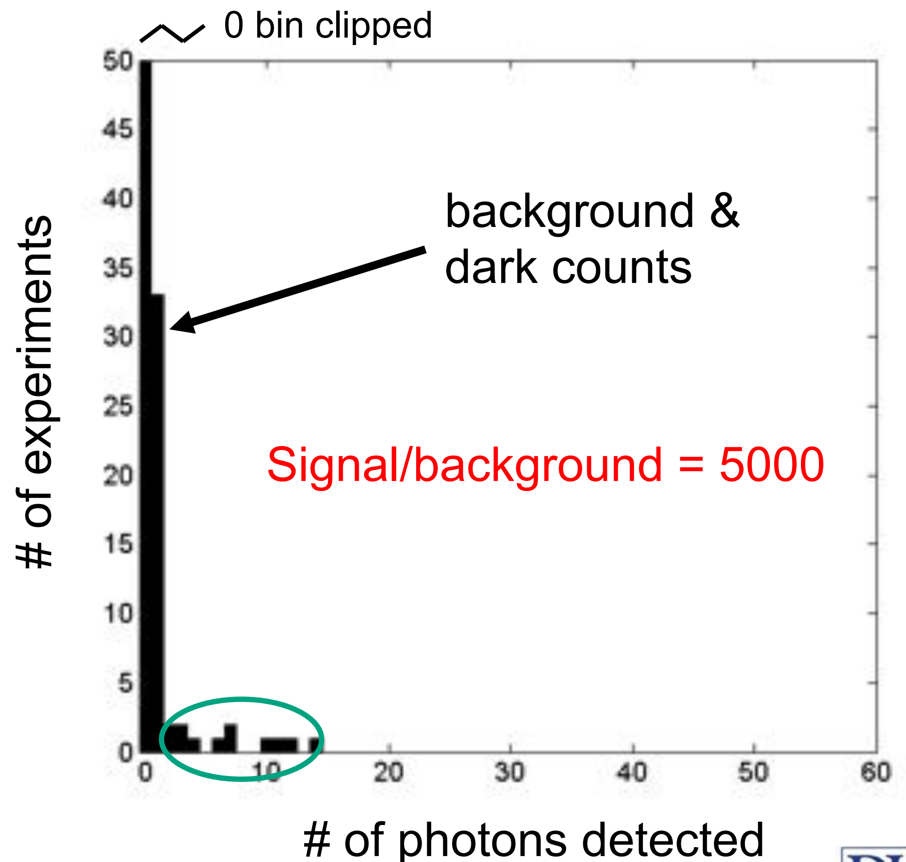
$^{171}Yb^+$ Hyperfine State Detection





Bright Pumping



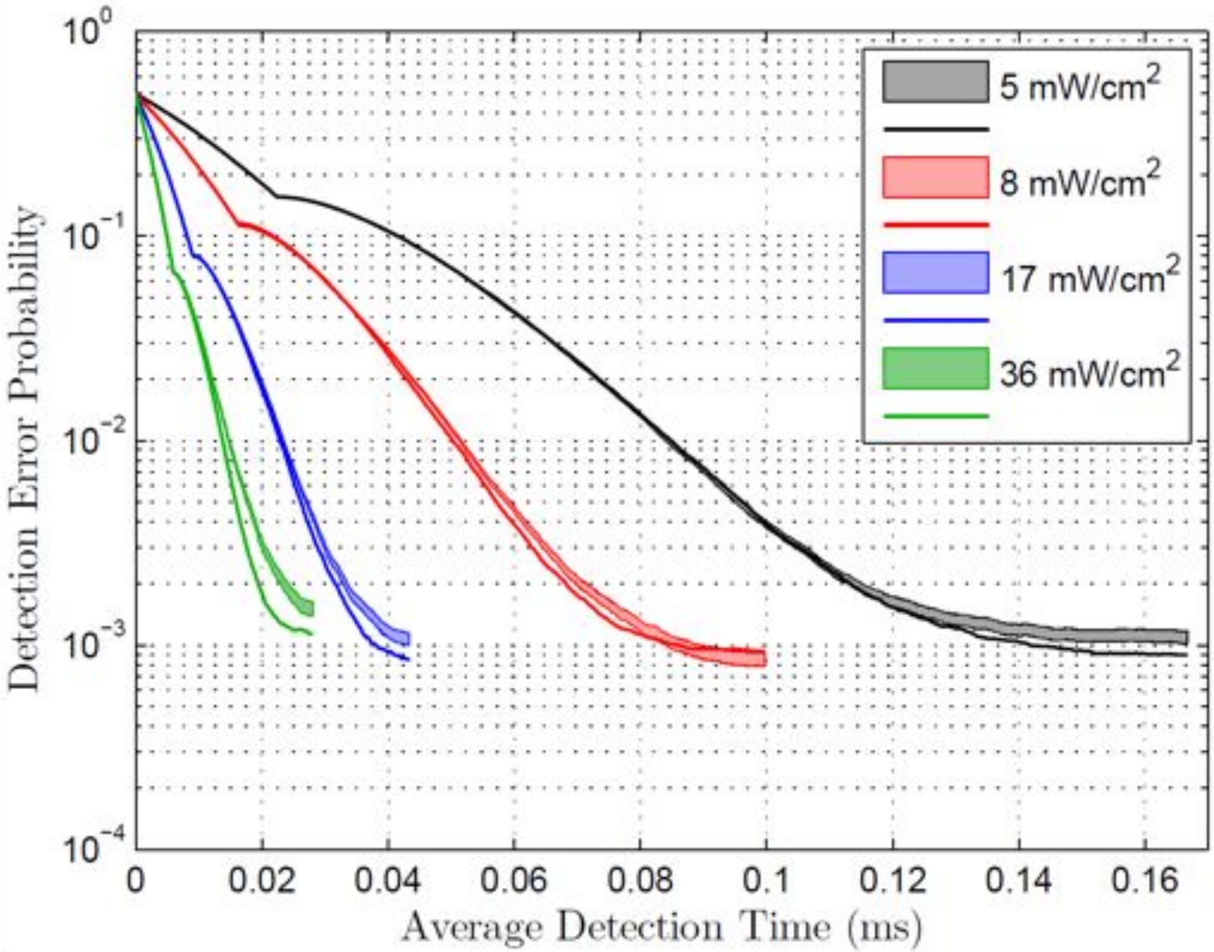


Probability to decay to F=1

$$R_b \approx \left(\frac{2}{3}\right)\left(\frac{\Gamma}{2}\right)\left(\frac{2\Omega^2}{\Gamma^2}\right)\left(\frac{\Gamma}{2\left(\Delta_{\mathrm{HFP}}+\Delta_{\mathrm{HFS}}\right)}\right)^2$$

Off-resonant two level scattering

Large NA State Detection Results



- High fidelity: 99.915(7)% in 99.8 μs (181.6μs max)
- High speed: 99.85% in 28.1 μs (51.4μs max)
- Ultra high speed: 99% in 10.5 μs (17μs max)

Noek, R; Vrijsen, G.; Gaultney, D.; Mount, E.; Kim, T.; Maunz, P.; Kim, J., Optics Letters, accepted October 2013.

Improved State Detection with High NA Optics

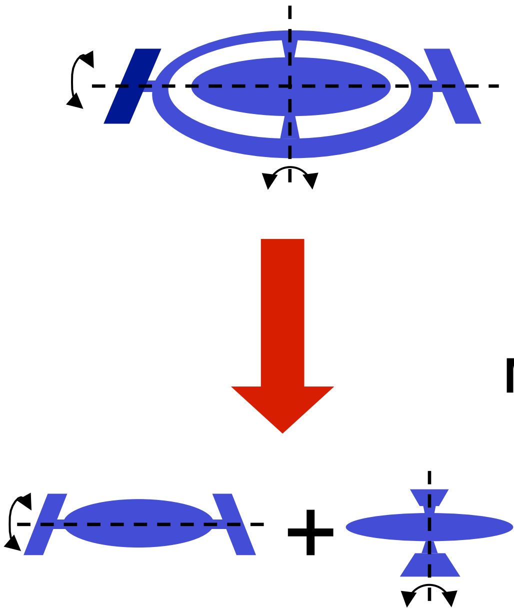
Qubit type	Average Detection Time	Fidelity	Method
$^{40}Ca^{+}$ Optical*	145 μs	99.99%	Adaptive time-resolved photon counting (distribution comparison)
$^{43}Ca^{+}$ Hyperfine*	400 μs (shelving) + ≥145 μs	99.77%	Shelving + above
$^{171}Yb^{+}$ Hyperfine (Duke)	28.1 μs	99.85(1)%	2 event discrimination
$^{171}Yb^{+}$ Hyperfine (Duke)	10.5 μs	99%	2 event discrimination

*Myerson, A. H., Szwer, D. J., Webster, S. C., Allcock, D. T. C., Curtis, M. J., Imreh, G., Sherman, J. A., Stacey, D. N., Steane, A. M. and Lucas, D. M. High-Fidelity readout of trapped-ion qubits. Phys. Rev. Lett. 100, 200502 (2008).

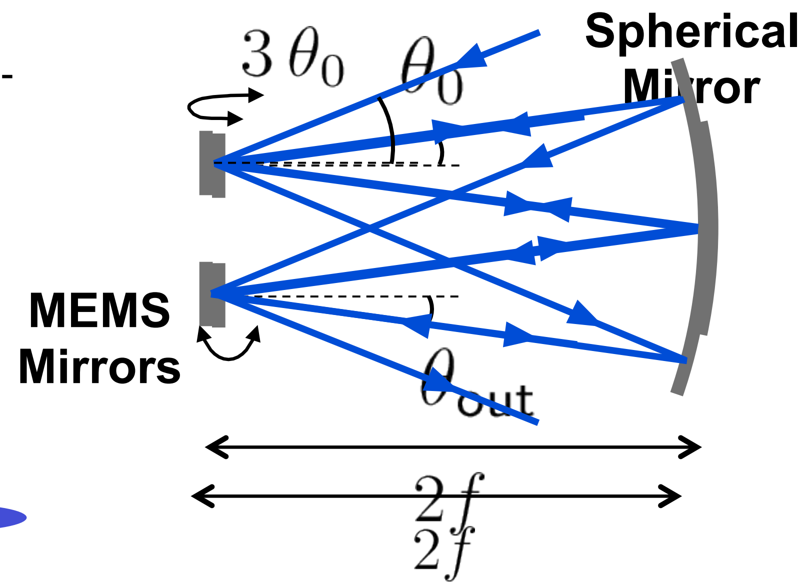
Individual Addressing Strategies

- Options for Individual Addressing of Atoms
  - Frequency discrimination: Siegen (Wunderlich), Penn State (Weiss)
  - Beam Steering: Wisconsin (Saffman, AO), Innsbruck (Blatt, EO)
  - Difficult to scale to parallel Operations
- Scalable MEMS beam steering
  - Scalable fabrication technology
  - Low optical loss over broadband
  - Provide Optical Multiplexing
    - Addressing locations
    - Beam paths
    - Operating wavelengths
- MEMS challenges
  - Speed – 10^3 speedup
  - Stability, reliability and optical performance

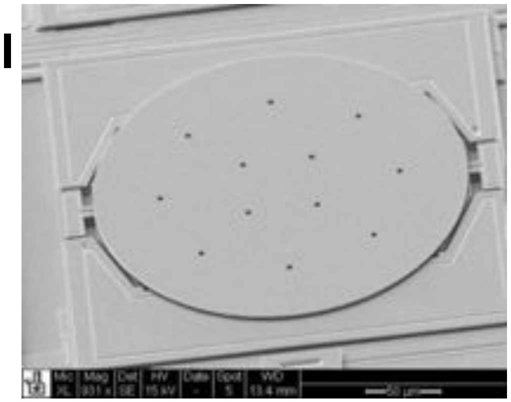
2D Tilt with MEMS Micromirrors

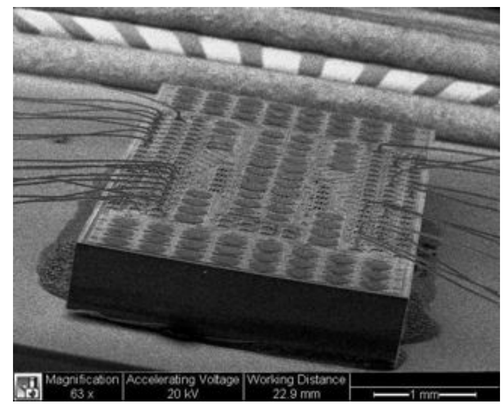


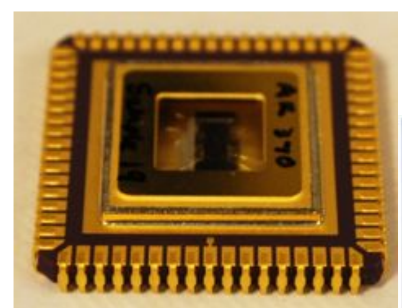
2D decoupled tilt



Double-bounce System





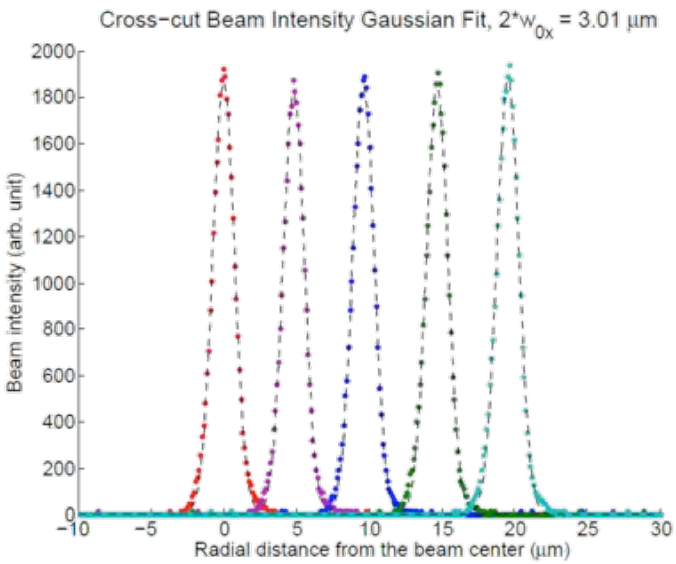


$$\Delta\theta_{\text{out}} = 4\,\alpha$$

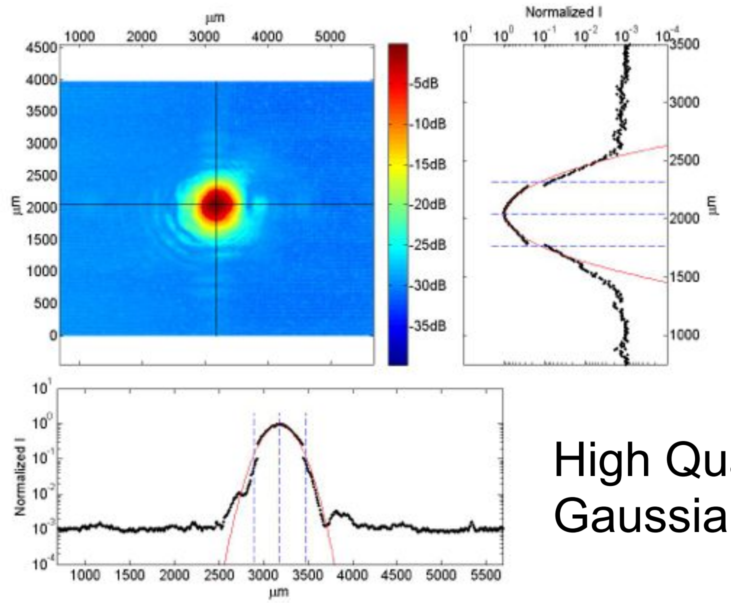
α: MEMS mechanical tilt angle

$\Delta\theta_{\text{out}}$: change in beam tilt angle

Beam Steering Capability

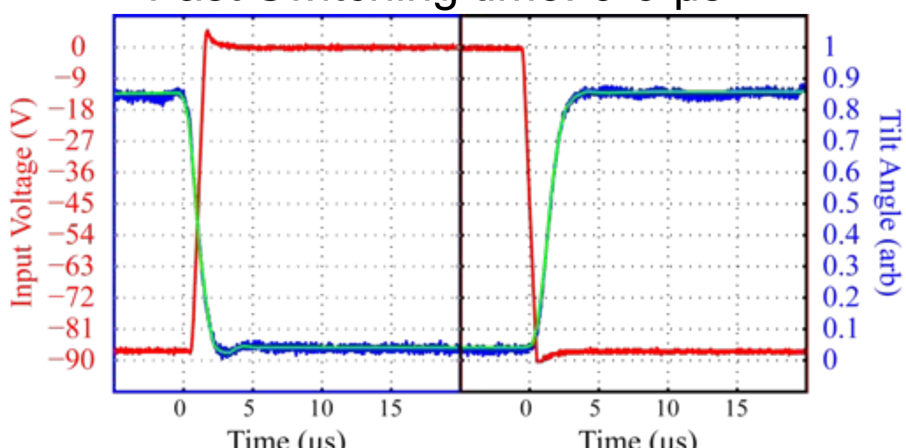


Knoernschild et al.,
Optics Express 17, 7233 (2009)

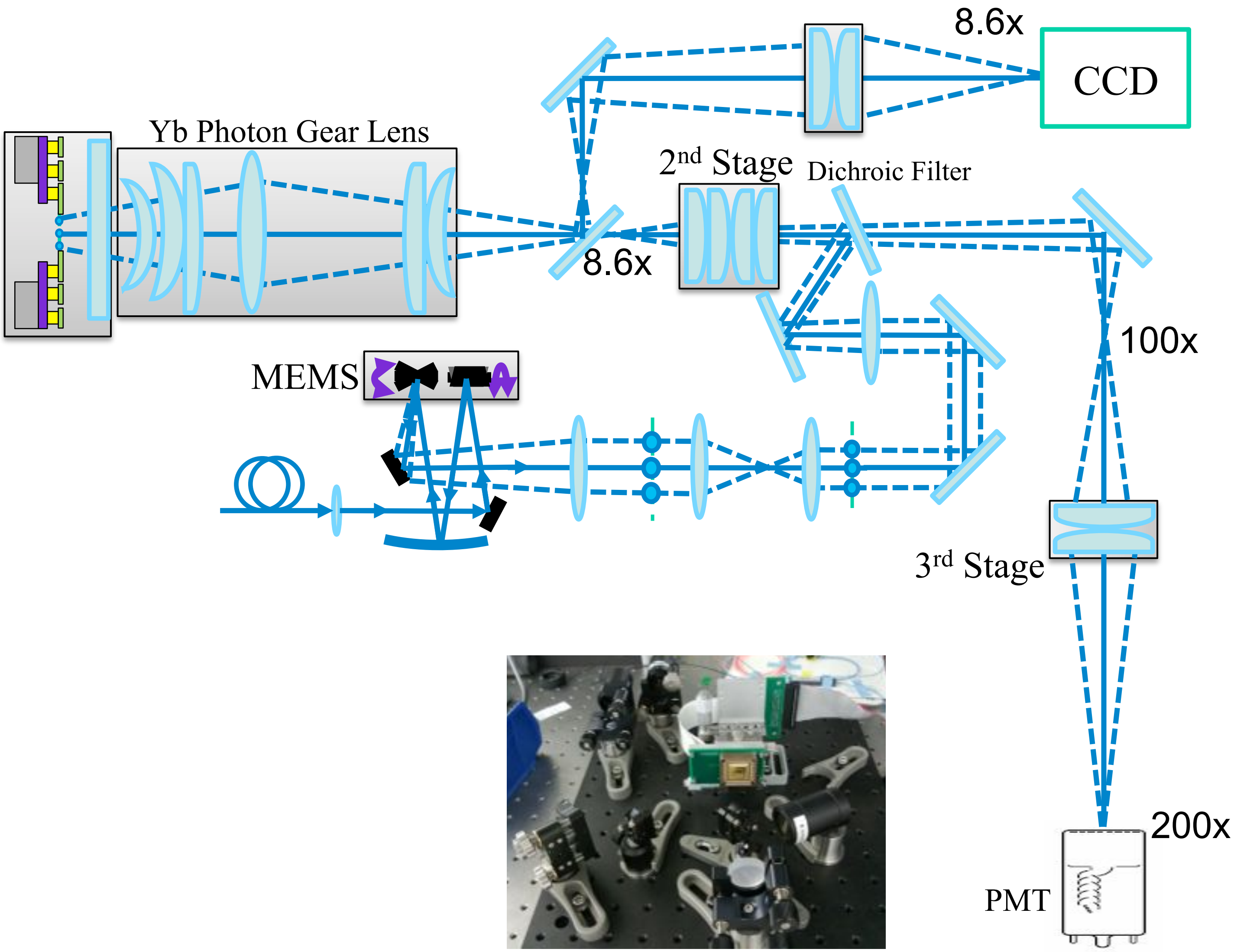


High Quality Beams
Gaussian down to < -30dB

Fast Switching time: 3-5 μs

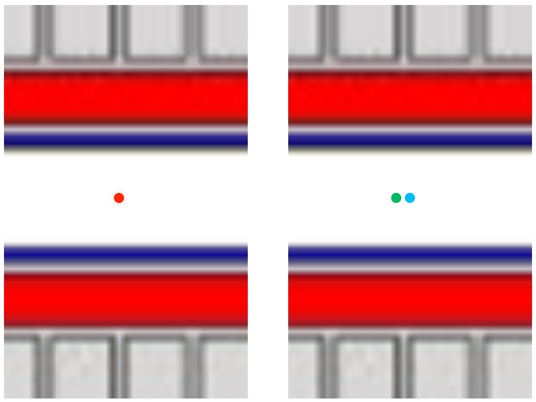


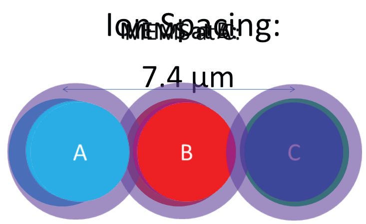
MEMS integration

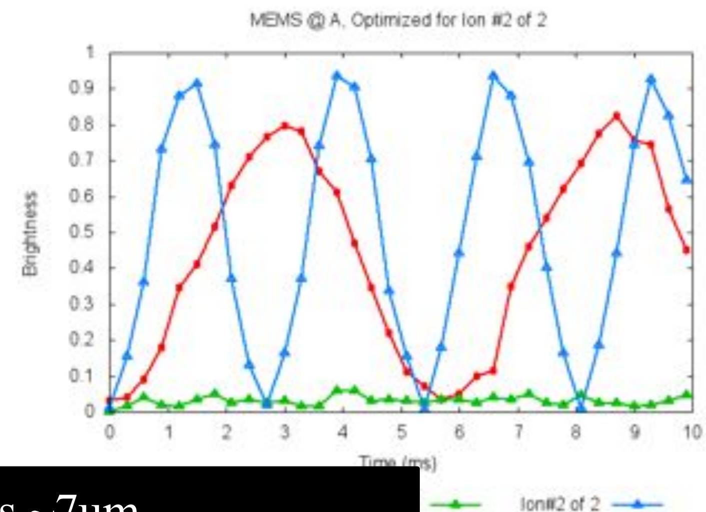


Single ion addressing (preliminary results)

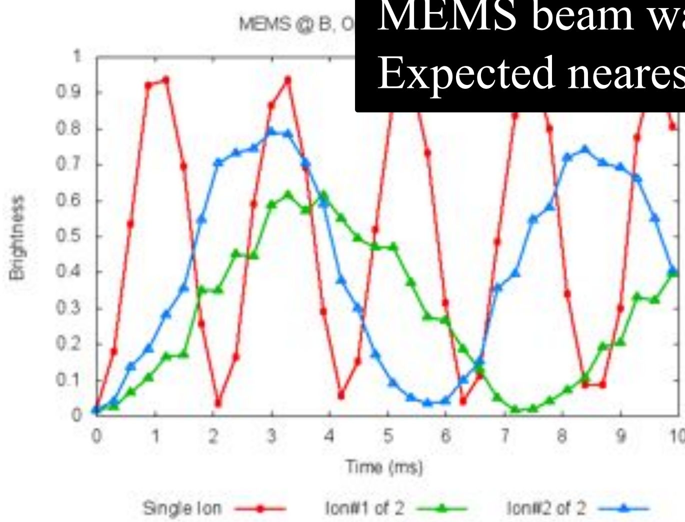
No MEMS Beam

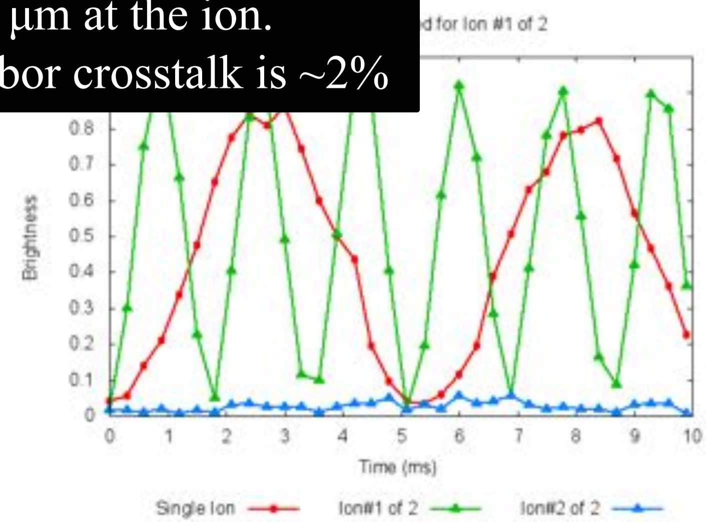






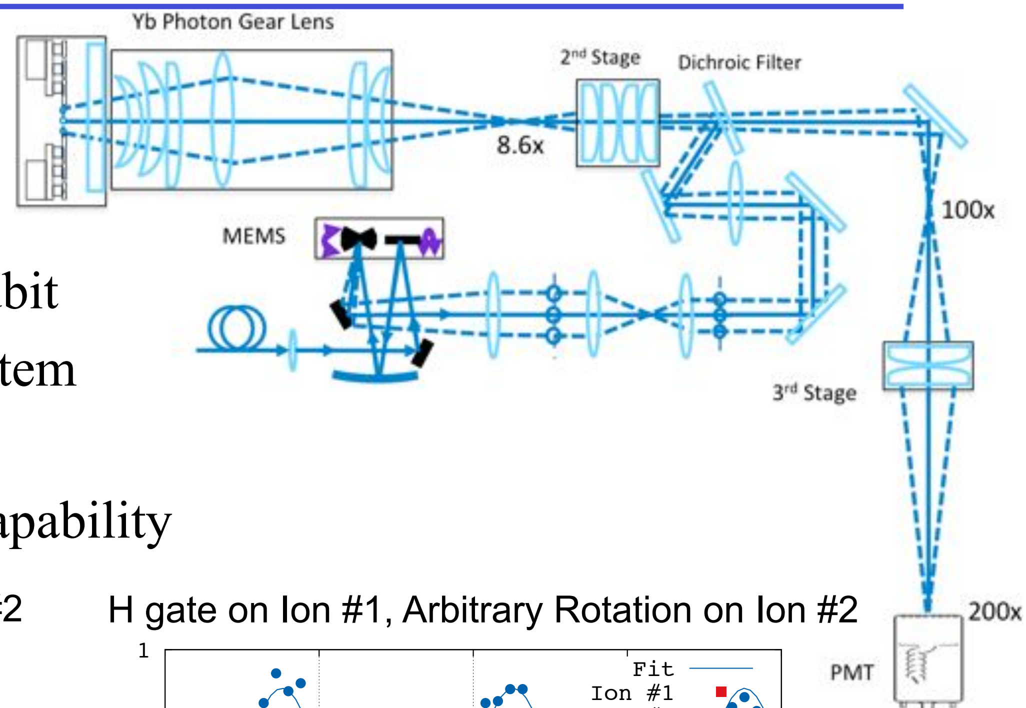
Measured ion spacing is ~7um
MEMS beam waist ~ 5 µm at the ion.
Expected nearest neighbor crosstalk is ~2%



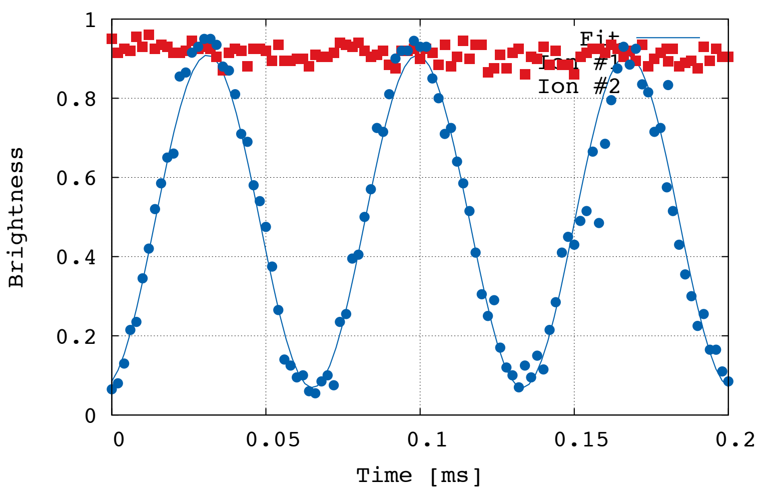


Individually Addressed Single Qubit Gates

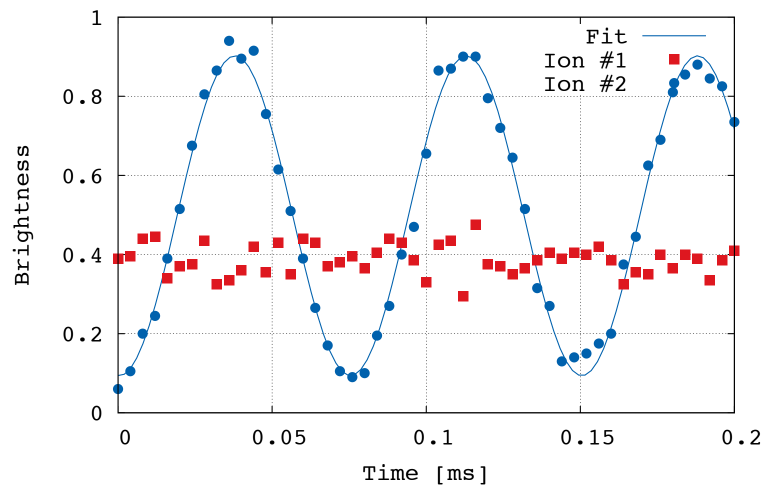
- New experimental capability
  - State preparation in parallel
  - Individual state detection
  - Individually-addressed single qubit
    Raman gates using MEMS system
  - Simultaneous single-qubit gates
  - Full state/process tomography capability



X gate on Ion #1, Arbitrary Rotation on Ion #2

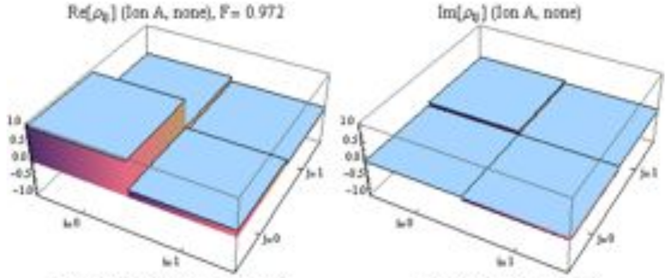


H gate on Ion #1, Arbitrary Rotation on Ion #2

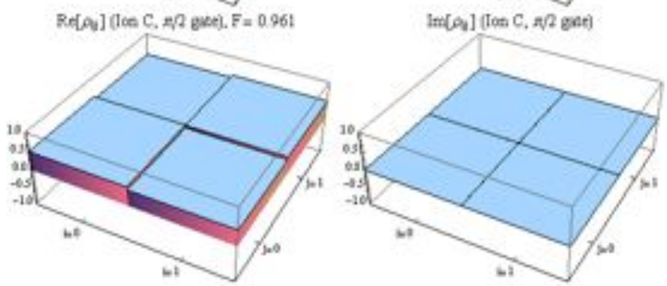


Multi-Qubit State Tomography

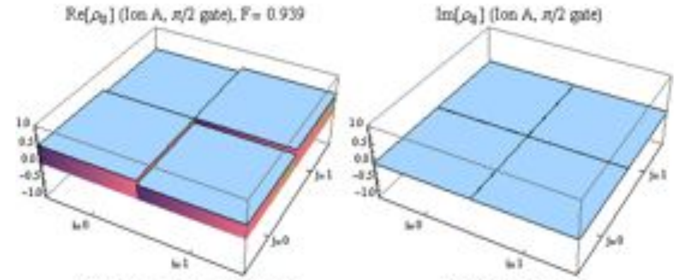
I_A
F=97%



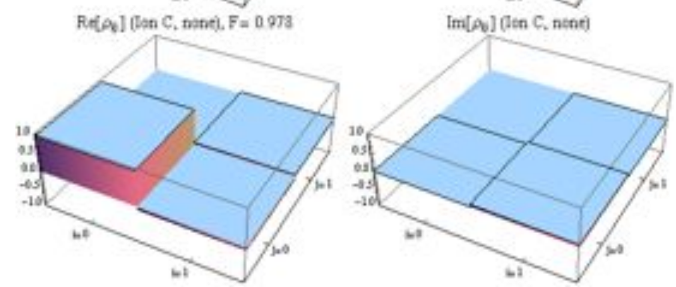
$R_X(\pi/2)$
F=96%



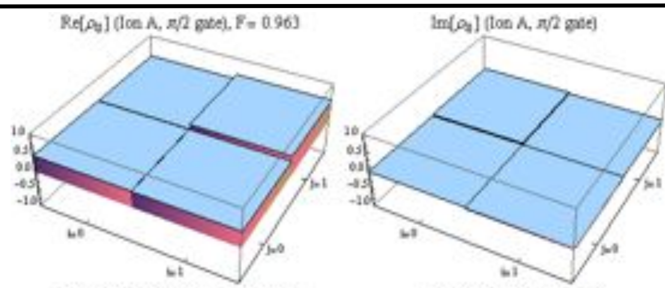
$R_X(\pi/2)$
F=94%



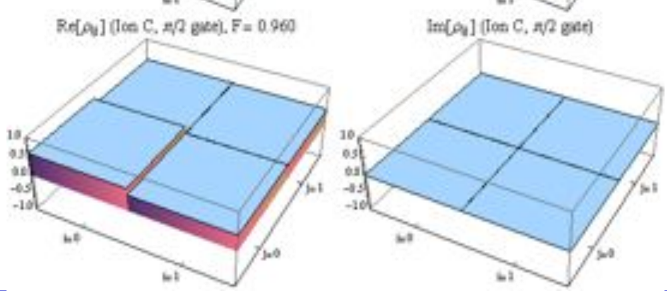
I_C
F=98%



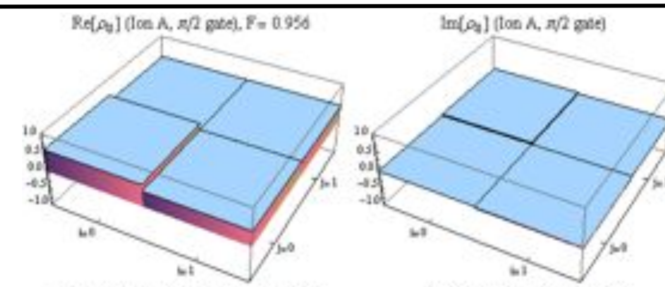
$R_X(\pi/2)$
F=96%



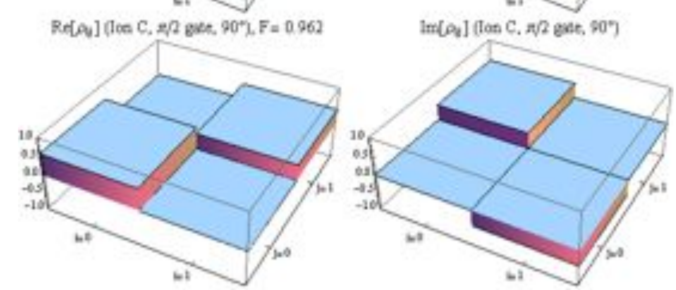
$R_X(\pi/2)$
F=96%



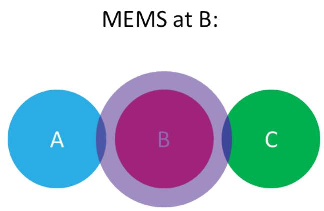
$R_X(\pi/2)$
F=96%

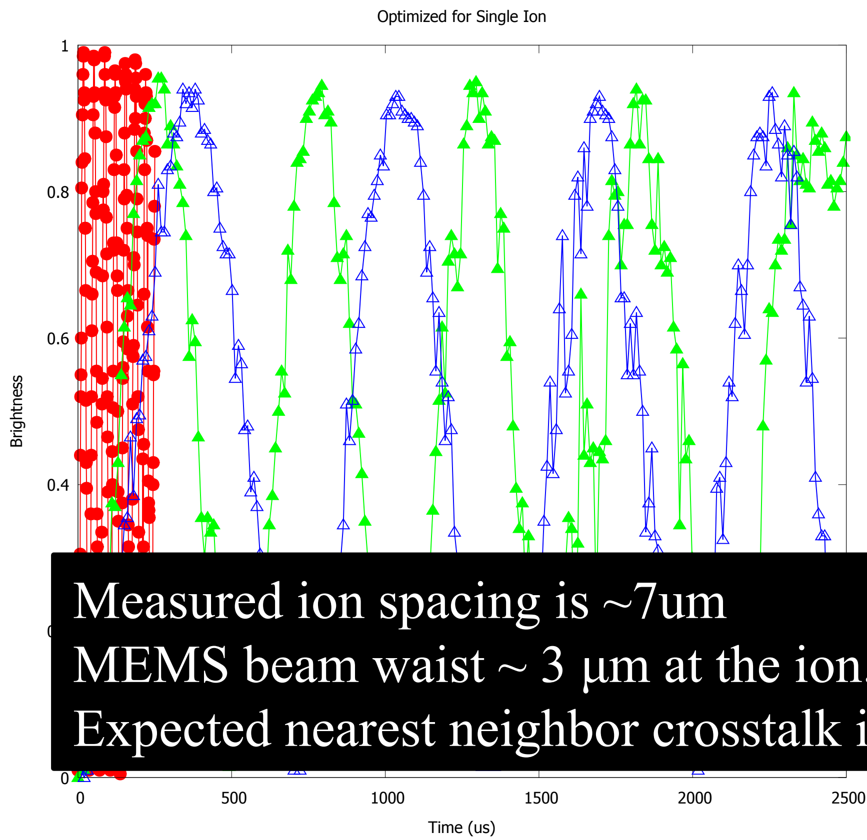


$R_y(\pi/2)$
F=96%



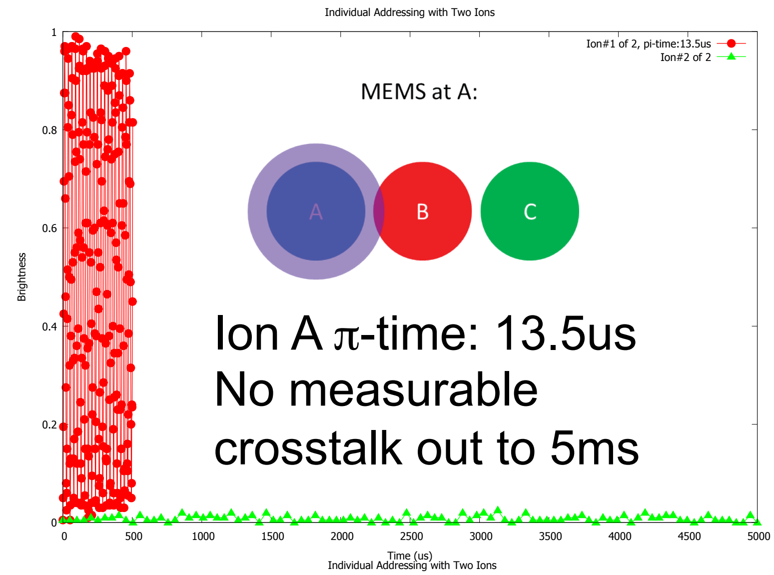
Improved Crosstalk (Preliminary)

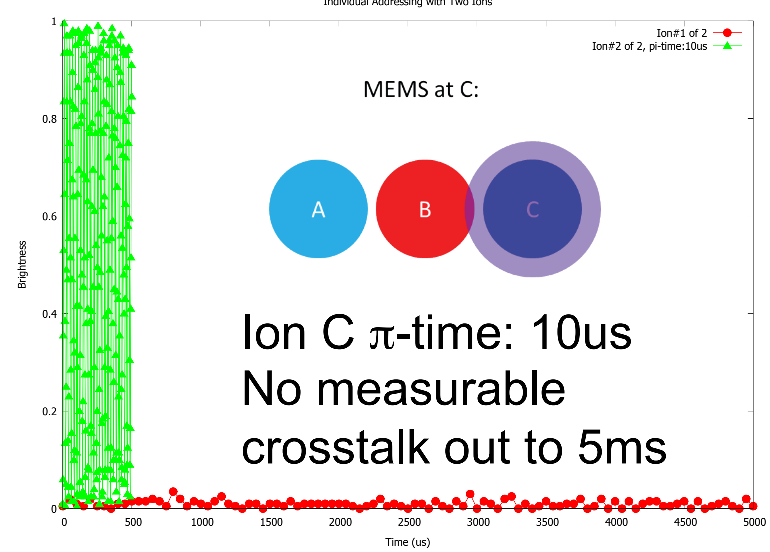




π-times
Ion B: 17us
Ion A: 250us
Ion C: 315us

Measured ion spacing is ~7um
MEMS beam waist ~ 3 µm at the ion.
Expected nearest neighbor crosstalk is ~2×10^{-5}



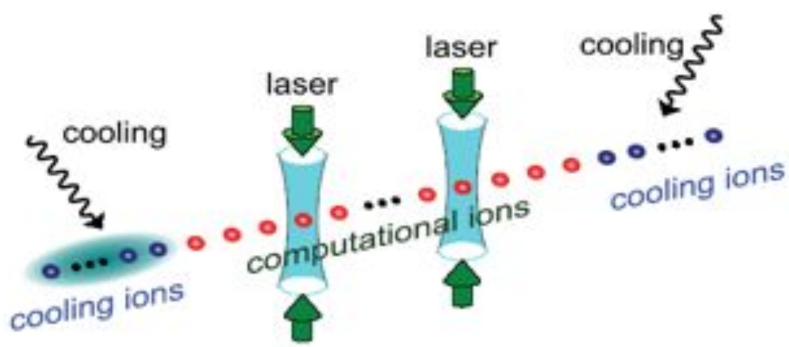


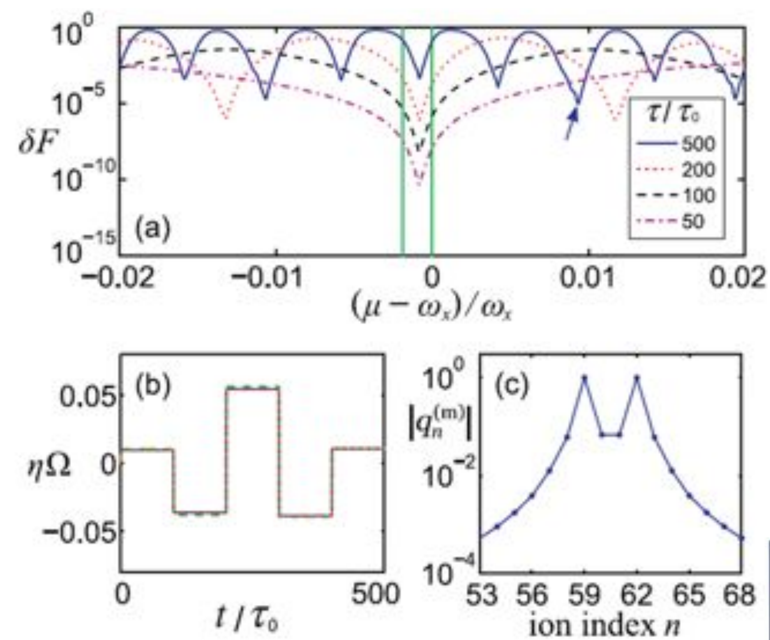
Outline

- Introduction
  - Quantum Computers and Quantum Simulators
  - Quantum "IC": Enabling Hardware Technology
- New Technologies for Trapped Ion Experiments
  - Physical System: Atomic Ions
  - Qubits Manipulation in Surface Traps
  - Better Optics: Fast Qubit State Detection
  - Adapting MEMS and Microsystems Technology
- Summary and Outlook

Ion Chain Quantum Register

- Equally spaced long ion chain
- Use transverse phonon mode for multi-qubit gates
- Design and control of laser pulses that apply spin-dependent forces at the heart of quantum register operation
- Forms Elementary Logic Unit (ELU) in MUSIQC architecture

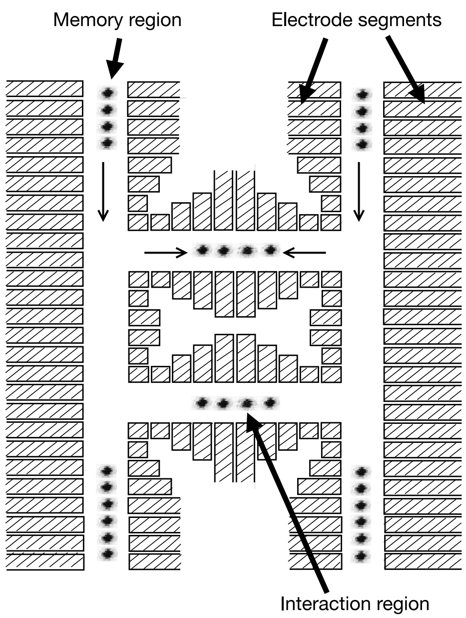




Zhu, Monroe and Duan, PRL 97, 050505 (2006); Europhys. Lett.73, 485 (2006)

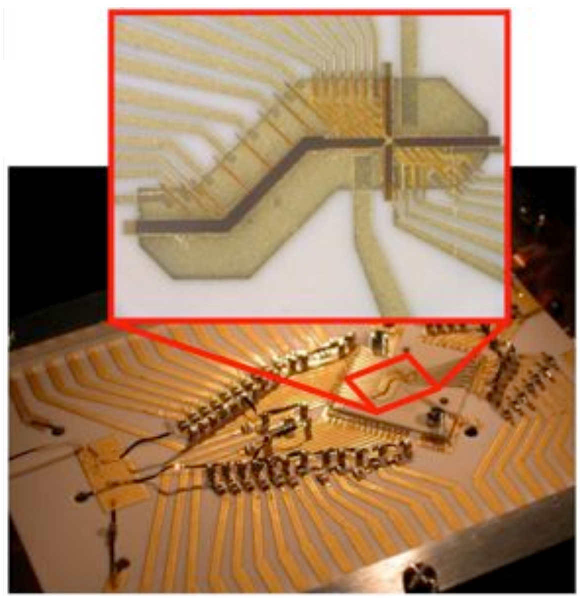
Shuttling of Ions on a Chip Trap

- Changing voltages can move the center of the trap
- Qubit state remain undisturbed through shuttling
- Sympathetic cooling necessary to perform motional gates after ion shuttling
- Noise-free qubit transport performed at NIST-Boulder



Kielpinski, Monroe and Wineland
Nature 417, 709 (2002)

D. Leibfried et al. NIST

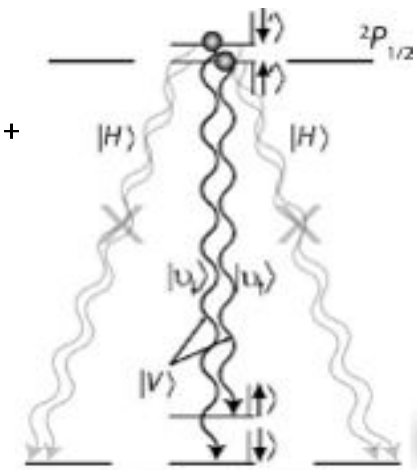


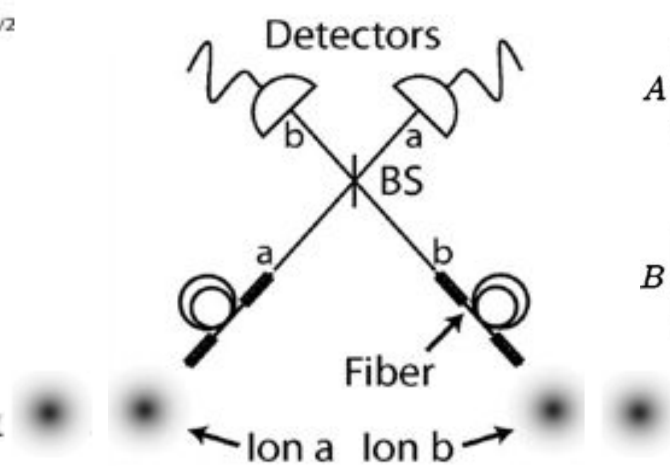
R. B. Blakestad, et al.,
Phys. Rev. Lett. 102, 153002 (2009)

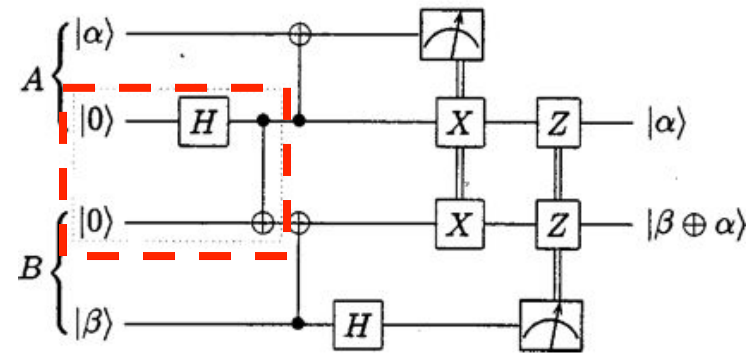
Entangling Ions using Photons

- Remote Entanglement Generation
  - Entanglement of internal atomic state and photon (e.g., color)
  - From a pair of such systems, interfere the photons
  - Based on measurement, entanglement is generated probabilistically between ions through entanglement swapping
  - Use the entanglement for logic operation

$^{171}Yb^{+}$







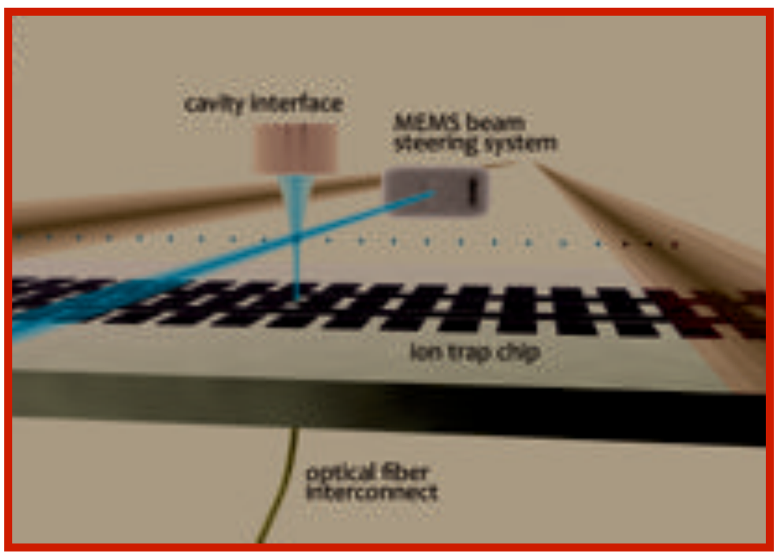
Ion-Photon (2004)
NV-Photon (2010)
QD-Photon (2012)

Ion-Ion (2007)
NV-NV (2013)

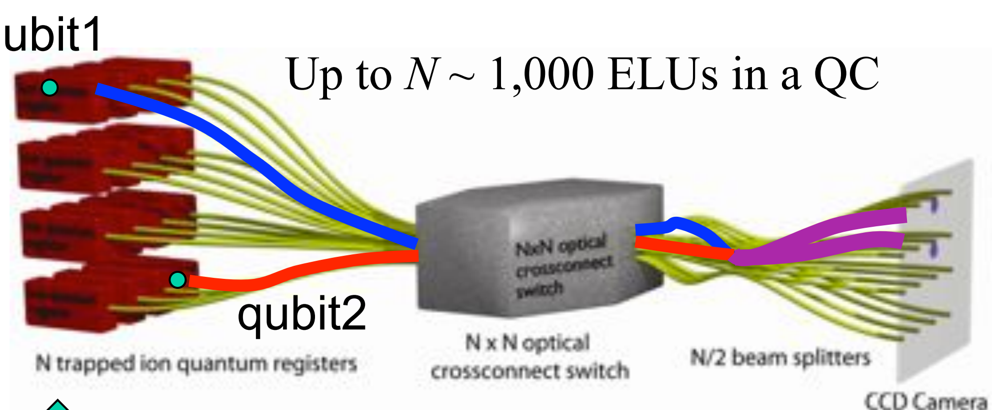
Duan et al., Quant. Inf. Comput. 4, 165 (2004)
Experiments from C. Monroe group
Gottesman and Chuang, Nature 402, 390 (1999)

MUSIQC: Multi-Tier Approach to Scalability

- Quantum Computation in Small Coulomb Crystals
  - Linear ion chain with 20-100 ions (Elementary Logic Unit, or ELU)
  - Arbitrary quantum logic operation among the qubits in the chain
- Interconnect of Multiple Coulomb Crystals via Photonic Channel
  - Reconfigurable interconnect using optical crossconnect (OXC) switches
  - Efficient optical interface for remote entanglement generation



m ~ 10-100 qubits / ELU



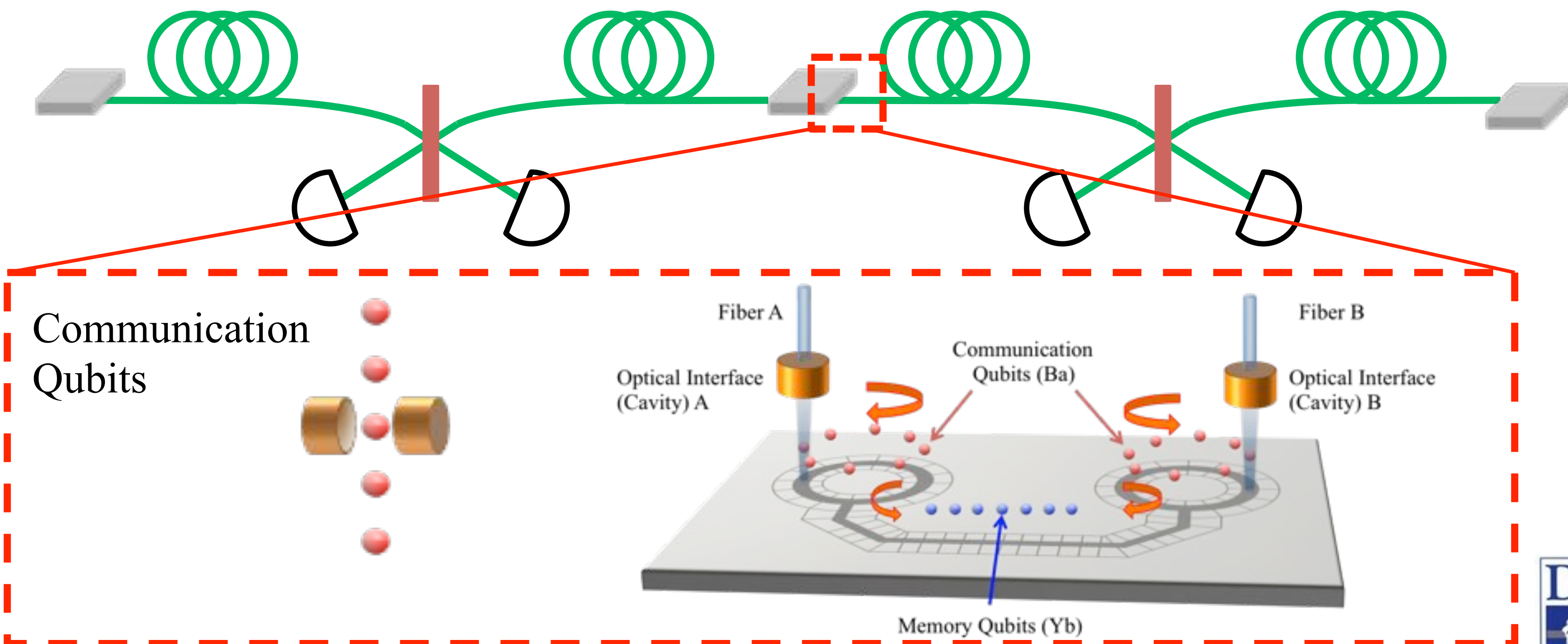
Up to N ~ 1,000 ELUs in a QC

Up to mN qubits in a QC

Monroe, Kim, Duan (2009)
Luo et al., Fortschr. Phys. 57, 1133 (2009)

SPARQC: Quantum Repeater Platform

- Strategy for Quantum Repeater Realization
  - Trapped-ion quantum information processor with two optical ports can function as a quantum repeater node



Monroe and Kim, Science 399, 1164 (2013)

Conclusions

- ***New Technologies for Trapped Ion Experiments***
  - Surface trap works very well (2-qubit gate TBD)!
  - Good optics makes huge difference
  - MEMS is adequate for individual addressing
- ***Importance of Integrated Systems Approach***
  - Larger system needed to answer some fundamental questions on quantum computing at the next level
    - Controlling large quantum entanglement?
    - Can quantum fault tolerance be implemented?
    - Flexible quantum simulator
  - Take us to frontiers of complex quantum system

Team and Collaboration

- Duke Team

  Peter Maunz, Taehyun Kim[1], So-Young Baek, Byung-Soo Choi, Seo Ho Youn, Jinhyun Cho, Rachel Noek, Emily Mount, Hui Son, Daniel Gaultney, Ryan Clark, Andre van Rynbach, Stephen Crain, Seongphill Moon, Muhammed Ahsan, Caleb Knoernschild[2], Kyle McKay[3]

- MUSIQC Collaborators

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  Luming Duan (U. Michigan)
  Ken Brown (Georgia Tech)
  Boris Blinov (U. Washington)
  Michael Biercuk (U. Sydney)
  Steve Flammia (U. Sydney)
  Robert Raussendorf (UBC)
  Steven Naboicheck (MagiQ)
  Jason Amini et al. (GTRI)
  Peter Maunz et al. (Sandia)

- SPARQC Collaborators

  Chris Monroe (U. Maryland)
  Daniel Gauthier (Duke)
  Mikhail Lukin, Marko Loncar, Hongkun Park (Harvard)
  Matthew Markham, Daniel Twitchen (E6)
  Liang Jiang (Yale)
  Norbert Lutkenhaus (U. Waterloo)
  Peter Maunz (Sandia)
  Marty Fejer (Stanford)

- Quantum Circuits MURI

  Paul Kwiat (UIUC)
  Ben Lev (Stanford)
  Edo Waks (U. Maryland)
  Duncan Steel (U. Michigan)
  Lu Sham (UCSD)
  Dan Gauthier (Duke)
  Dan Gammon (NRL)
  Jake Taylor (NIST/JQI)

- Other Collaborators

  Felix Lu (AQT)
  Mark Saffman (U. Wisconsin)
  Dave Weiss (Penn State)
  David Scherer (PSI)
  Jaewan Kim (KIAS)

- [1] SK Telecom, Korea
- [2] Raytheon Corporation
- [3] NIST, Boulder CO

http://mist.ee.duke.edu