Device and System Technologies for Quantum Information Processing

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- Rest of Wineland Group

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- Wolfgang Haensel (Innsbruck)
- David Weiss (Penn State University)
- Alex Kuzmich (Georgia Institute of Technology)

Goals of Quantum Computer Engineering

Goal	Description	Resources: qubits	Resources: gates	Are we there yet? (0-10)
Experimentally useful QC*	Explore and test fundamental quantum mechanics.	2	1	
Physically useful QC	Explore and test multi-system quantum physics.	$\gtrsim 10$	$\gtrsim 20$	
Computationally useful QC	Improve on classical computers.	$\gtrsim 10^2$	$\gtrsim 10^6$	
Realistically scalable QC	No engineering obstacles to boundless QC.	any	any	
Theoretically scalable QC	No fundamental obstacles to boundless QC.	any	any	

* Quantum Computing.

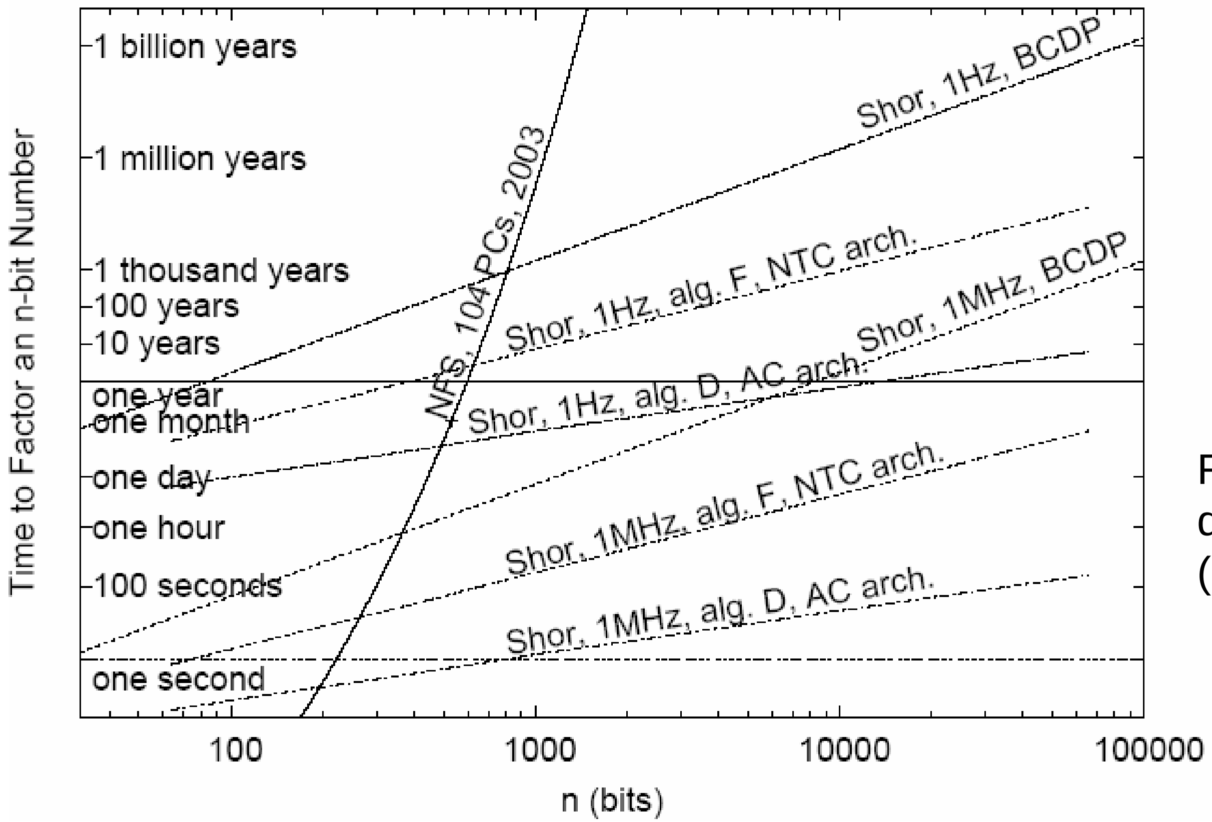
Slide from E. Knill, CLEO 2007 Invited Talk

The DiVincenzo Criteria (1995)

- Criteria required for scalable quantum computation
  - A scalable physical system with well-characterized qubits
  - Ability to initialize the state of the qubits to a simple fiducial state
  - Long decoherence times compared to gate operation time
  - Ability to perform universal set of quantum gates
  - Ability to perform qubit-specific measurement
- Is this enough?? – Quantum-Classical Interface
  - Quantum Wires
  - Quantum Communication
    - The ability to interconvert stationary and flying qubits
    - The ability to faithfully transmit flying qubits between specified locations
  - Other architectural issues??

The Factoring Problem

- Best known classical algorithm: Number Field Sieve
- RSA-640 (193 digits) factored with 30 2.2GHz-Opteron CPU years (5 calendar months) http://www.rsa.com/rsalabs/node.asp?id=2093
- Implementation architecture makes a big difference!!



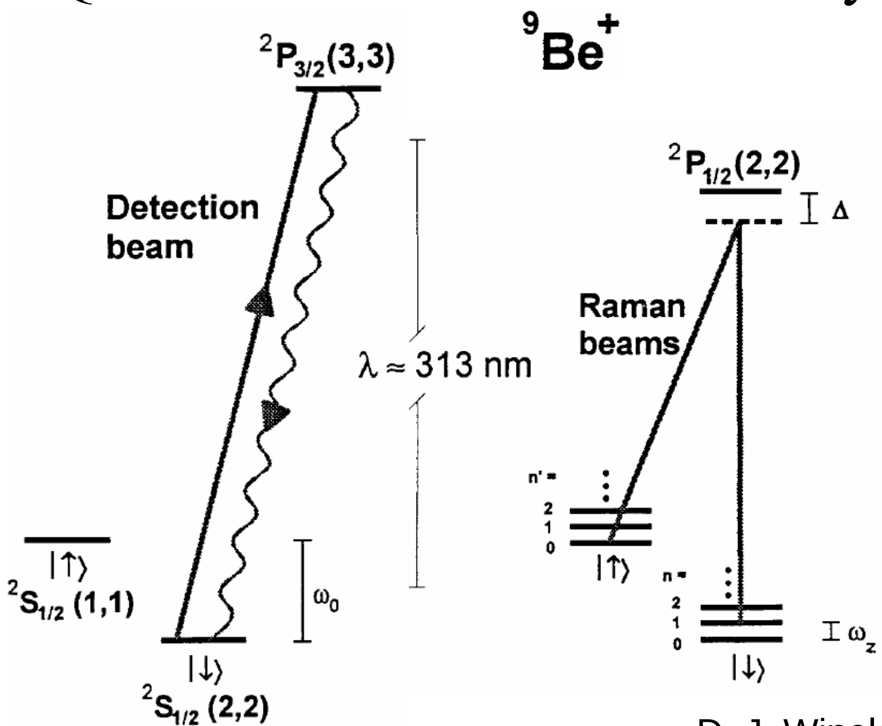
R. Van Meter et al., quant-ph/0507023 (2005)

Physical Systems for Implementation

- Trapped Ions
- Atoms in Optical Lattices
- Josephson superconducting circuits
- Nuclear spins/SET in Silicon
- Electron spins in semiconductors
- Quantum dot optical levels
- Solid state NMR – high field gradients
- Linear optics

The Atomic Qubit

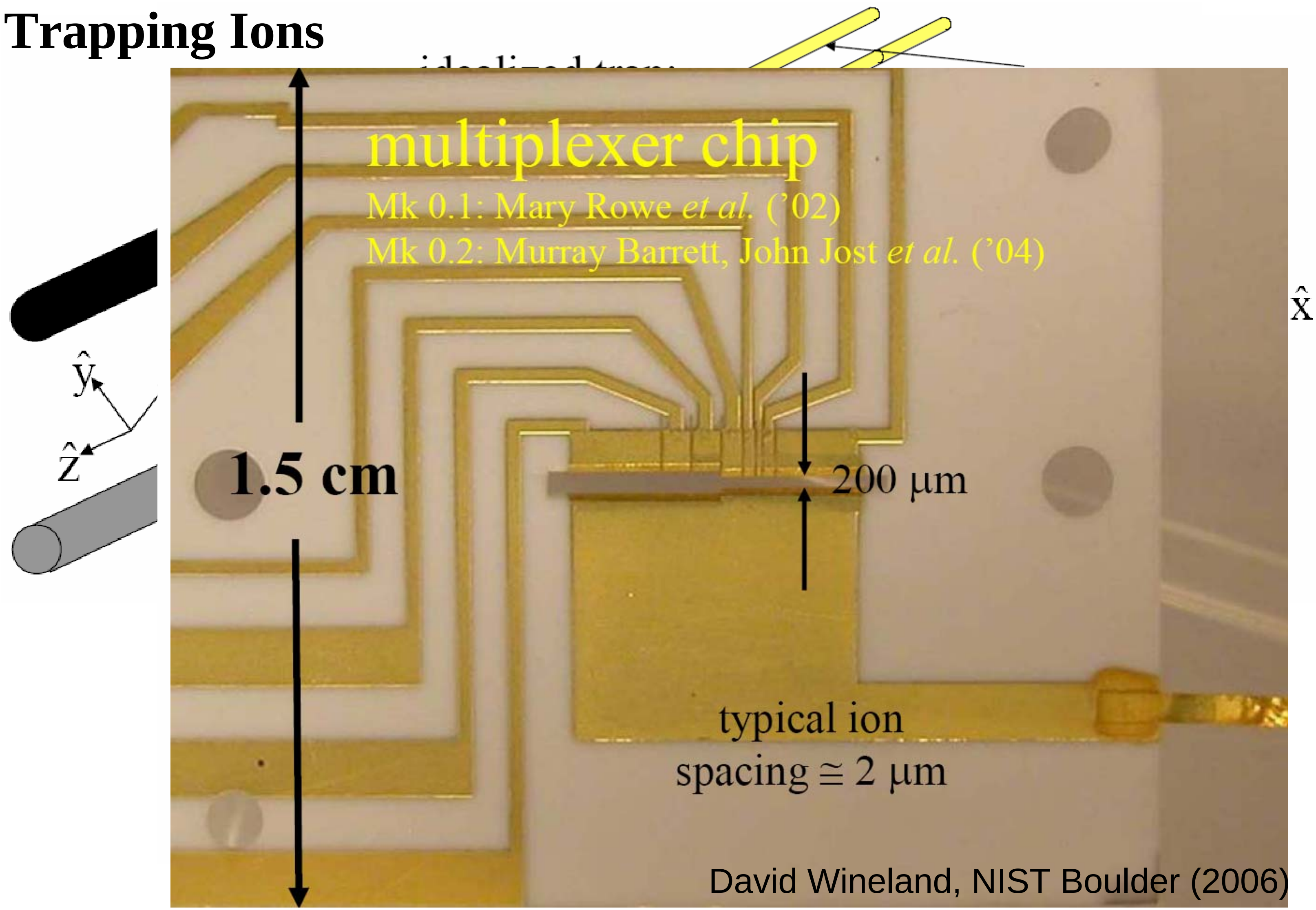
- Qubit states are two internal states of the atom/ion
- Initialization can be performed by optical pumping
- Carefully chosen states have long coherence times (~15sec)
- Quantum Logic Gates by laser beam manipulation
- Quantum State Measurement by state-dependent scattering



Two-qubit gates performed by
- Coulomb interaction in ions
- Dipole-dipole interaction in neutral atoms

D. J. Wineland et al., Fortschr. Phys. 46, p 363 (1998)

Trapping Ions : Example

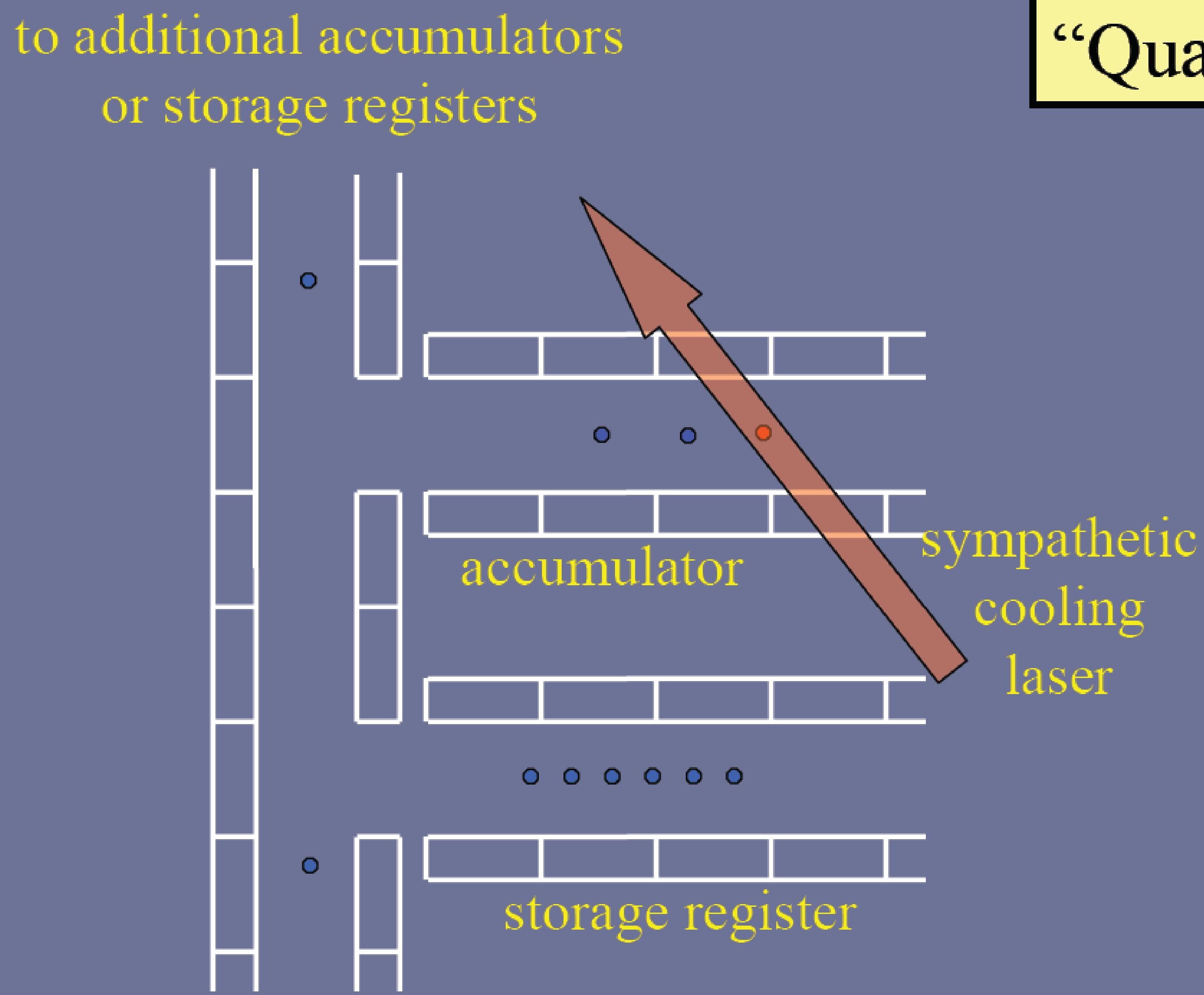


State-of-the-Art in Quantum Computation

- Using similar approaches, basic demonstrations
  - Long coherence times
    - C. Langer et al., Phys. Rev. Lett. 95, 060502 (2005)
  - State Initialization
    - B. E. King et al., Phys. Rev. Lett 81, 1525 (1998)
  - Robust two-qubit logic gates
    - F. Schmidt-Kaler et al., Nature 422, 408 (2003)
    - D. Leibfried et al., Nature 422, 412 (2003)
    - P. Haljan et al., Phys. Rev. Lett. 94, 153602 (2005)
  - State-dependent measurement
    - W. Nagourney et al., Phys. Rev. Lett. 56, 2797 (1986)
- Advanced Experiments
  - Quantum teleportation
    - M. Reibe et al., Nature 429, 734 (2004)
    - M. Barrett et al., Nature 429, 737 (2004)
  - Quantum error correction
    - J. Chiaverini et al., Nature 432, 602 (2004)
  - Simple quantum algorithm
    - S. Gulde et al., Nature 421, 48 (2003)

Limited to 3-8 ions!!!

“Quantum CCD”

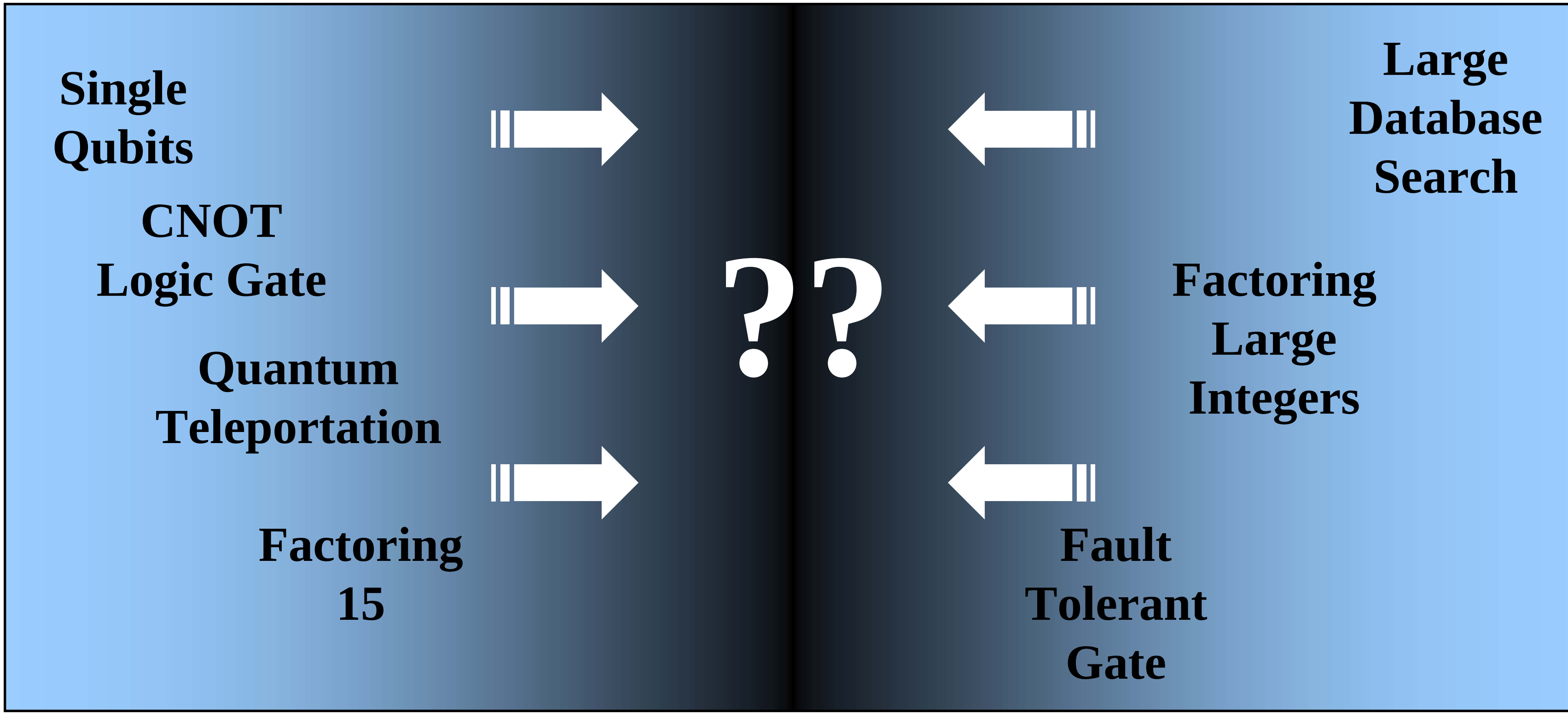


Slide from
Dave Wineland
Ion Trap QC Workshop
Feb 2006

D. J. W. *et al.*, J. Res. Nat. Inst. Stand. Technol. **103**, 259 (1998).
D. Kielpinski, C. Monroe, and D. J. Wineland, Nature **417**, 709 (2002).
Other proposals: DeVoe, Phys. Rev. A **58**, 910 (1998); Cirac & Zoller, Nature **404**, 579 (2000);
L.-M. Duan, B. Blinov, D. Moehring, C. Monroe, Quant. Inf. Comp. **4**, 165 (2004).

“Transistor to Processor”

- ***Quantum Abyss (Dave Wineland, NIST)***

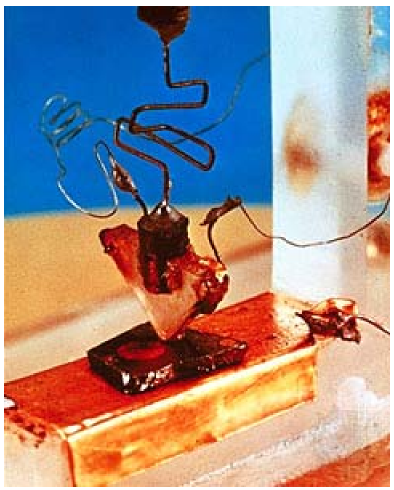


1 2 3 7 10^2 10^3 10^5 10^7

Complexity (# Qubits)

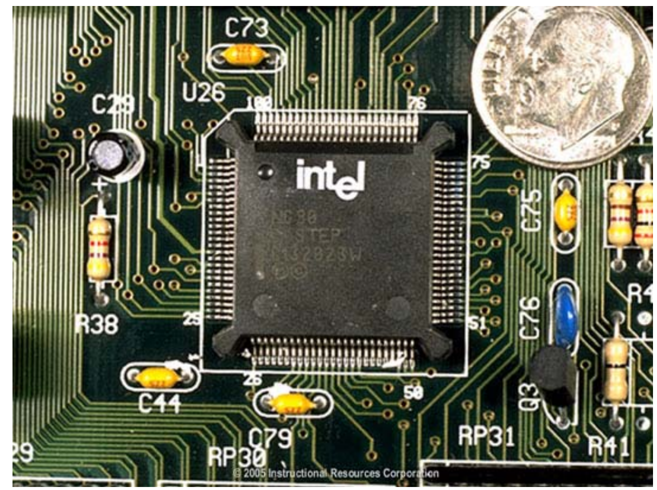
Classical Analog: Microprocessors

- ***Integrated Circuits Technology (Kilby & Noyce, 1958)***
  - ***Scalable technology platform*** **for creating functional circuits**
  - **Reduced the cost and increased the functionality of electronic functions by a factor of a million in last 30 years**



The First Transistor

AT&T Bell Lavs (http://www.britannica.com)



Intel® Microprocessor

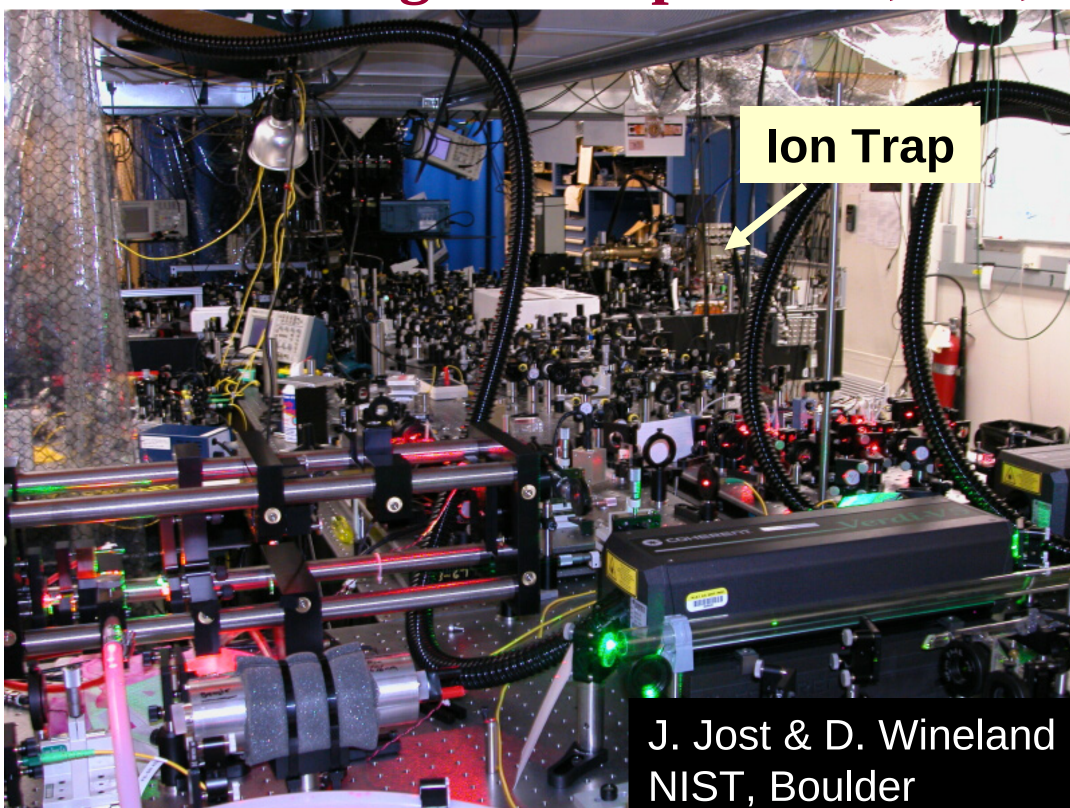
http://education.discovery.com/

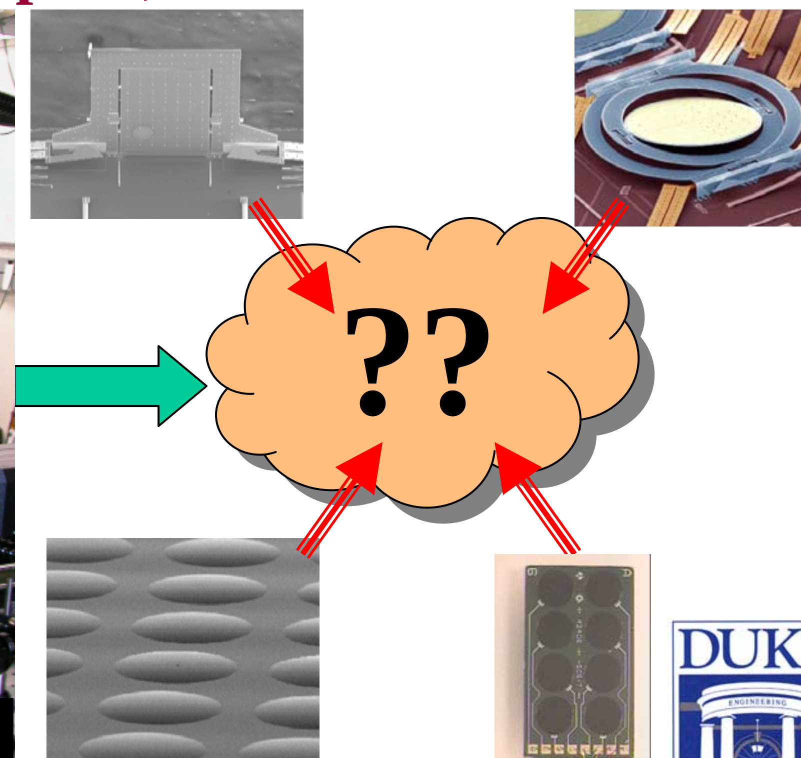
Technology to integrate ALL components needed for computation
Ability to control each and every transistor in the processor at will!!

Quantum Version of "IC" Technology

- Physical system dependent
- Capability to integrate ALL ELEMENTS required
- Quantum-classical boundary between the qubits and controller

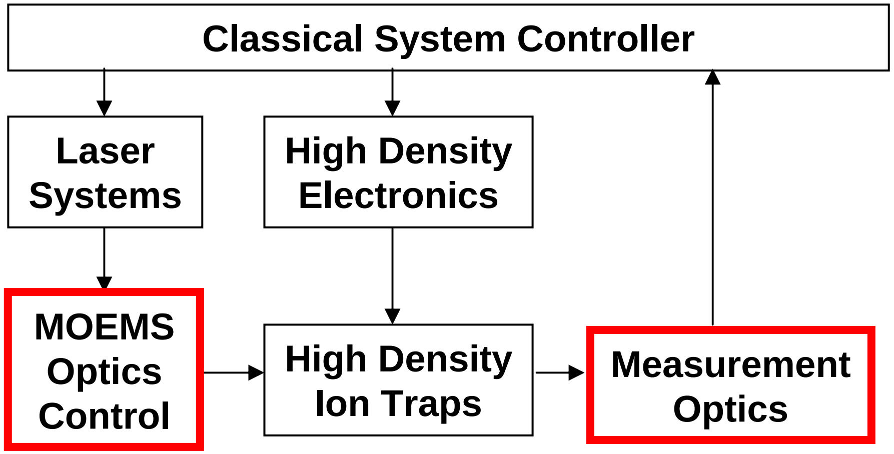
  Matching the temperature, size, speed, etc. is critical!!!



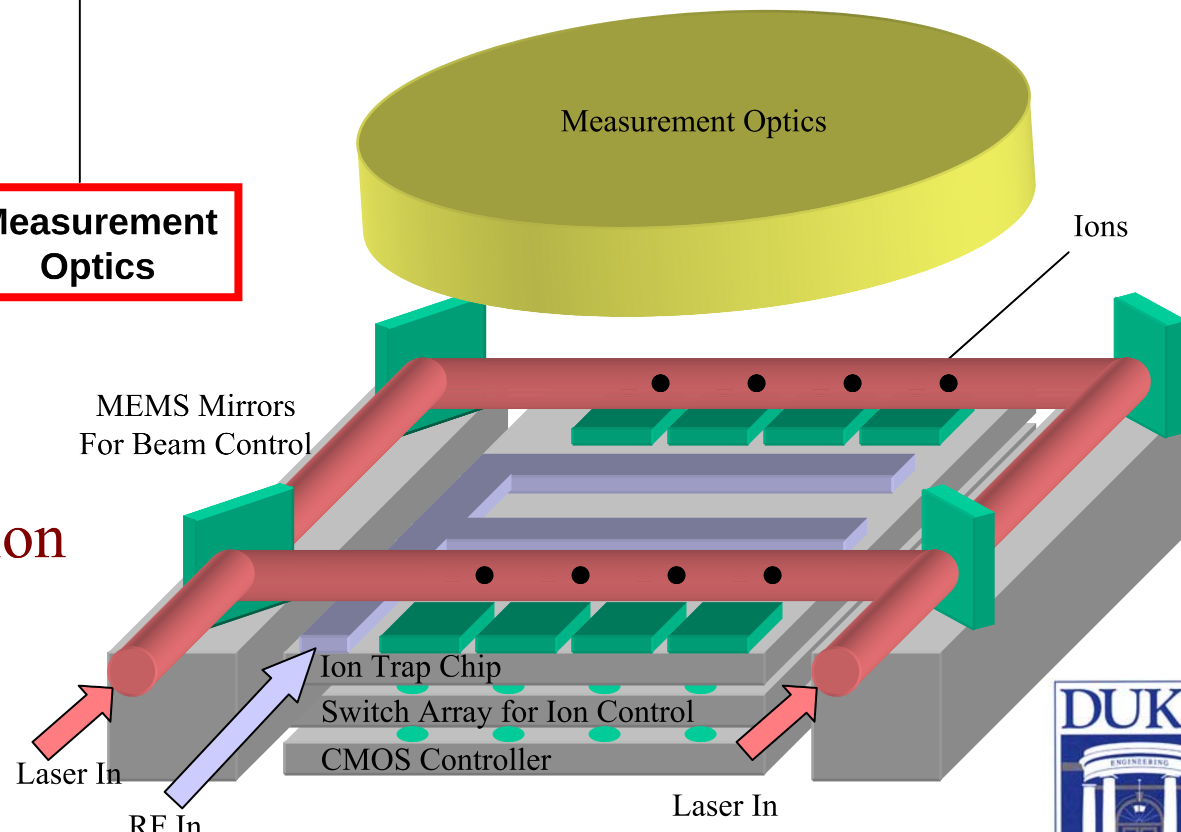


Technology for Scaling Ion Traps

Elements of Ion Trap Quantum Computer



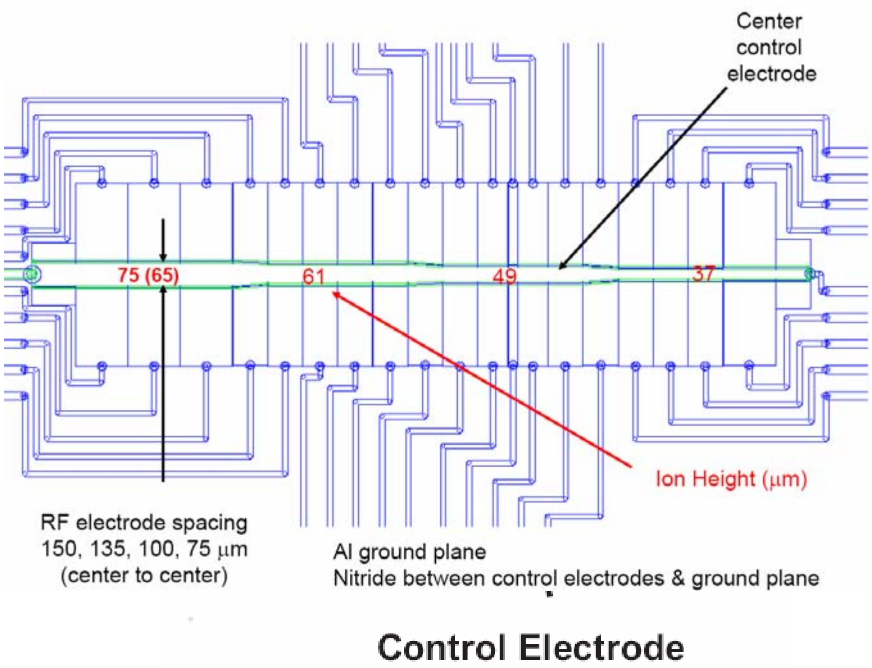
Technology for Realization

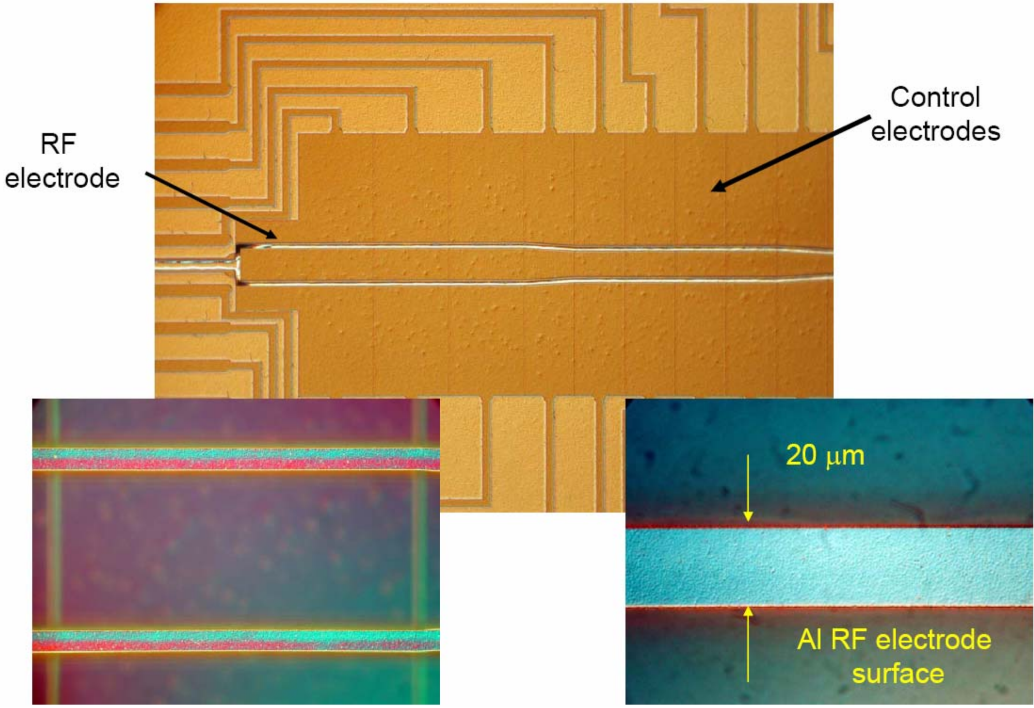


Kim et al., Quant. Inf. Comp. 5, 515 (2005)

Scalable Ion Trap Chip

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





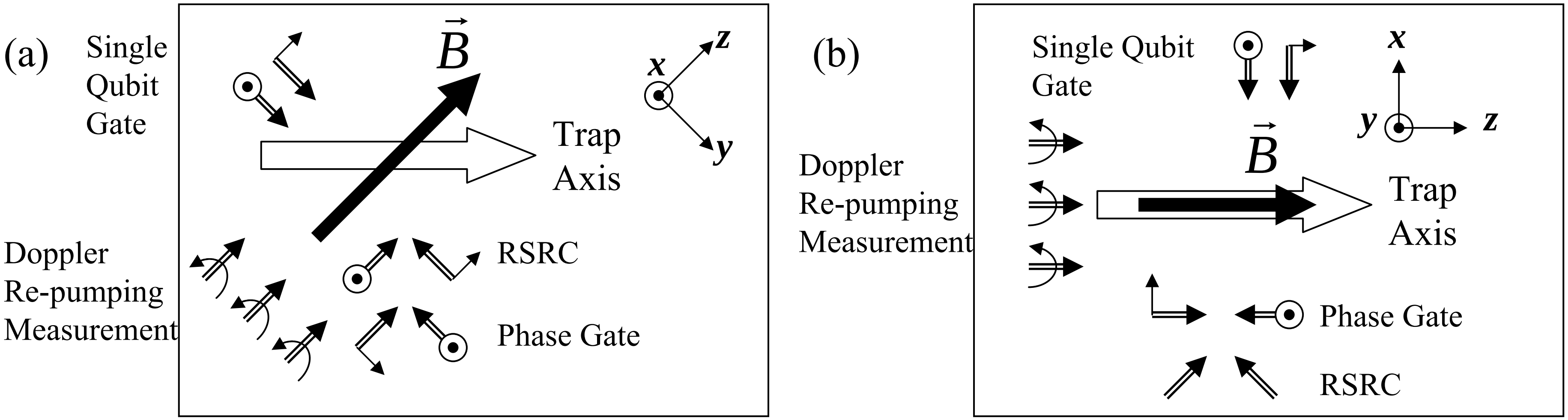
Design: Kim et al., Quant. Inf. Comp. 5, 515 (2005)

Fabrication: R. Slusher et al., Bell Labs (2006)

Integration Requirements for Optics

Function	Polarization	Target Ion	Raman Detuning	Momentum Difference	Intensity	Location
RSRC	π, σ^+ or σ^-	$^{24}Mg^+$	$\omega_0' - \omega_z$ [a]	Large Δk	Modest	All Gate Regions
Re-pumping	σ^+ or σ^-	$^{24}Mg^+$	-	-	Mild	All Gate Regions
Single qubit	π, σ^+ or σ^-	$^9Be^+$	ω_0	Small Δk	Modest	Single Qubit Gate Regions
Two qubit	σ^++σ^-, σ^+-σ^-	$^9Be^+$	$\sqrt{3}\omega_z + \delta$	Large Δk	Extreme	Two Qubit Gate Regions
Measurement	σ^-	$^9Be^+$	-	-	Modest	Measurement Regions
Doppler	σ^-	$^9Be^+$	-	-	Mild	$^9Be^+$ Loading Zone, Measurement Regions
Depopulation	σ^-	$^9Be^+$	-	-	Mild	$^9Be^+$ Loading Zone, Measurement Regions
Doppler	Any	$^{24}Mg^+$	-	-	Mild	$^{24}Mg^+$ Loading Zone

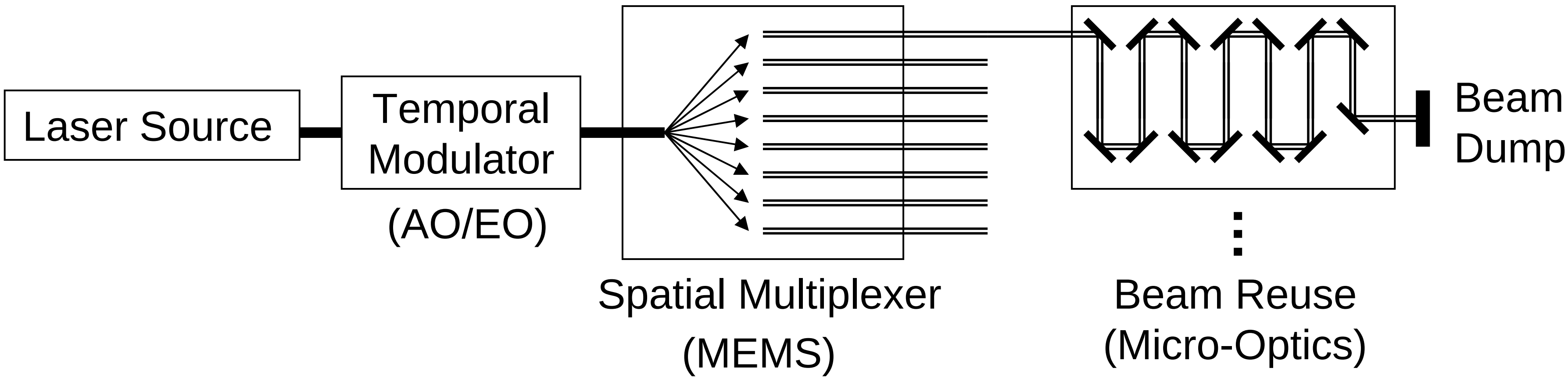
[a] ω_0' is hyperfine ground state splitting of $^{24}Mg^+$.



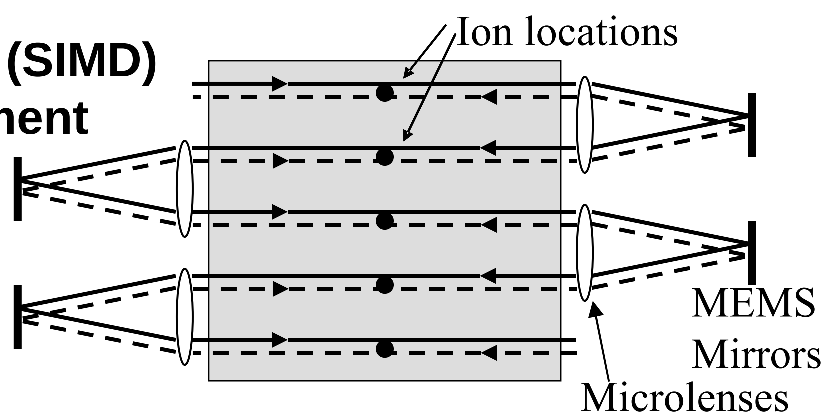
J. Kim and C. Kim, work in progress

Requirements for Flexible Optics

- ***Tailored photons are scarce resource (2-qubit gates)!!***
  - **Frequency, polarization and intensity stability**
  - ***Two stage, diffraction limited free-space optics***

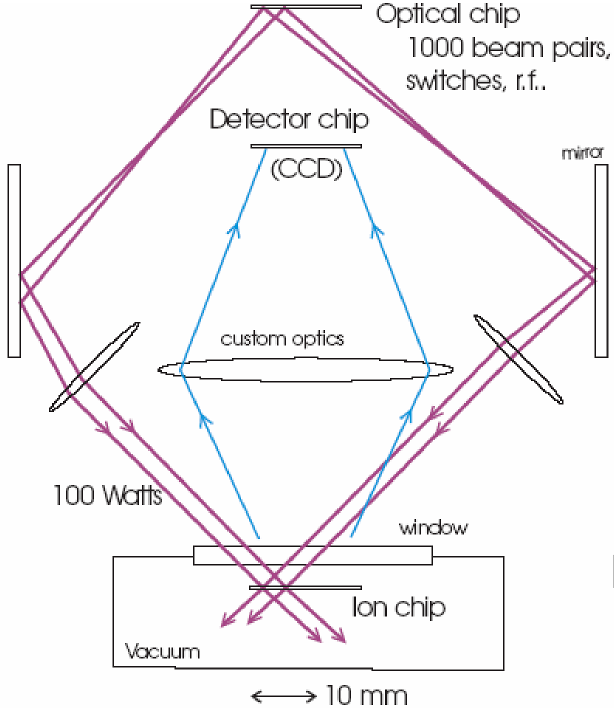


Single Instruction on Multiple Data (SIMD)
Reduces total laser power requirement

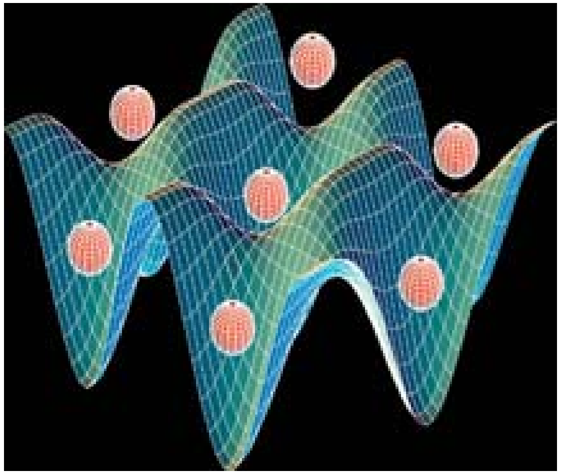


MEMS Technology Adaptation for QIP

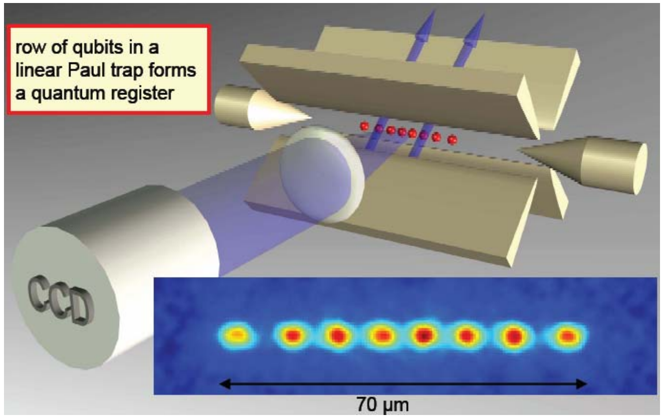
- ***MEMS-based integrated optics in quantum computation***
  - **Ion and Atom based QIPs require delivery of laser beams for state preparation, manipulation and detection**



A. Steane Scheme
Quant-ph/0412165

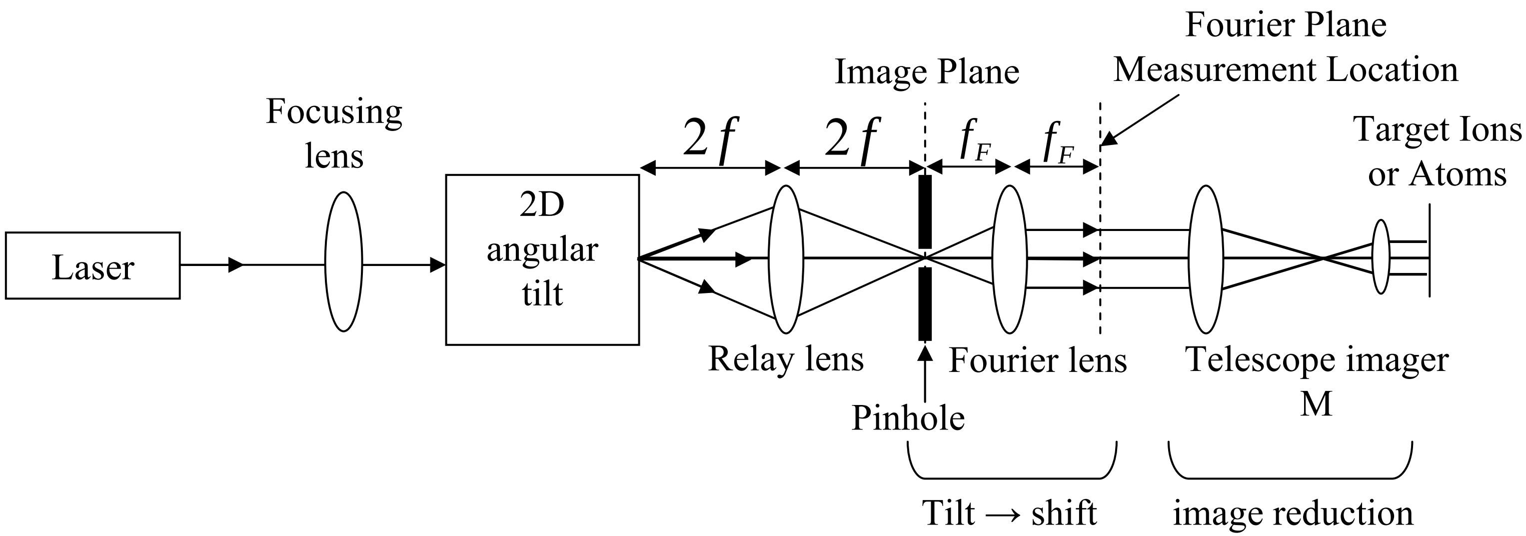


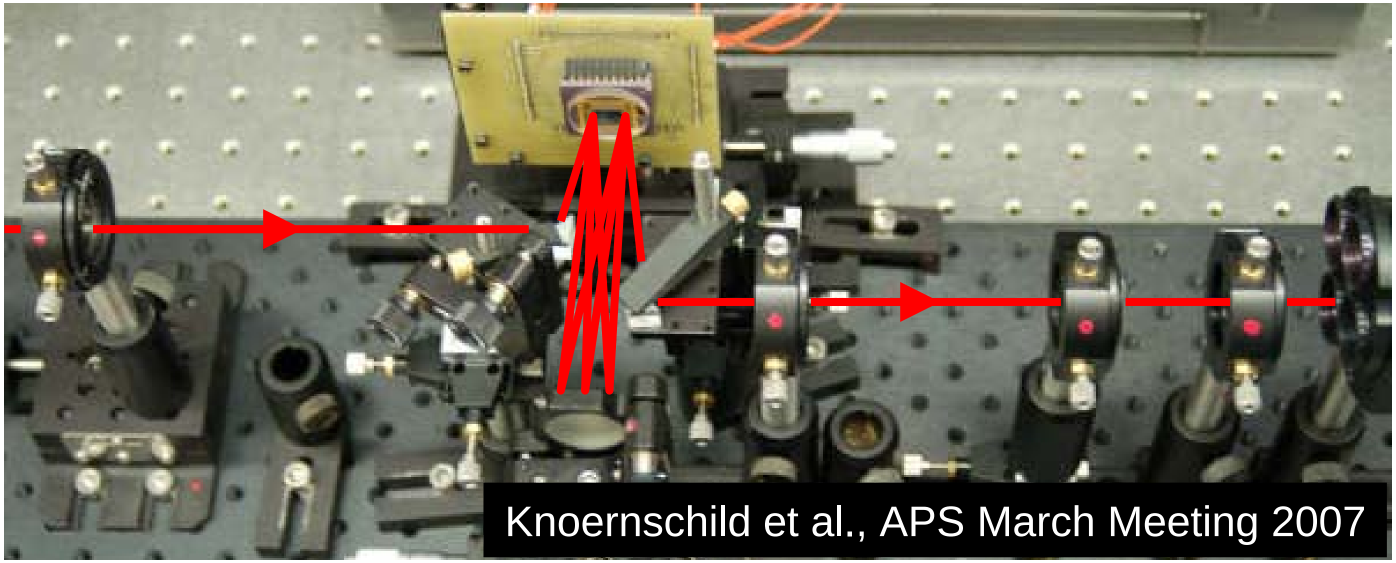
Neutral Atoms trapped
In Optical Lattice
Individual qubit addressing
(NIST, Wisconsin, etc.)



Linear ion traps
Simultaneous addressing
Of two arbitrary ions
(Innsbruck Group)

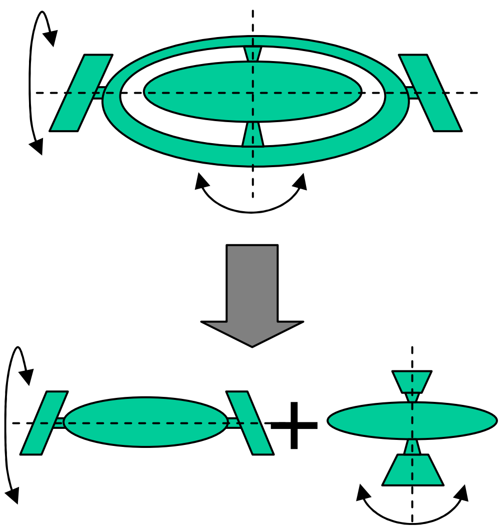
MEMS-based Beam Steering System

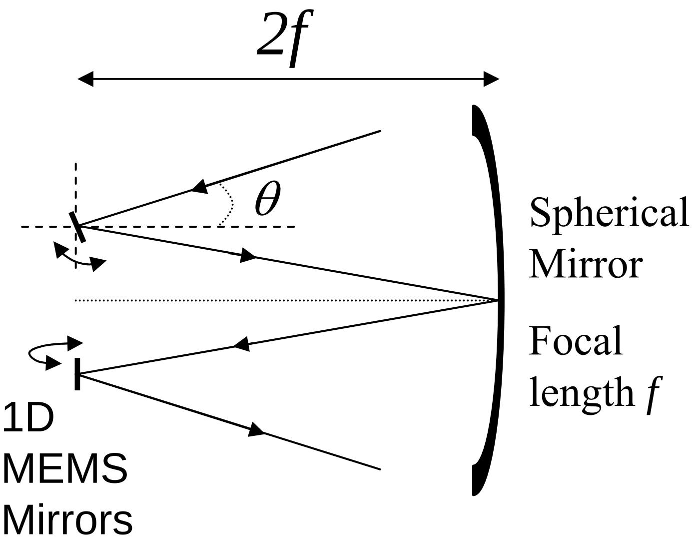


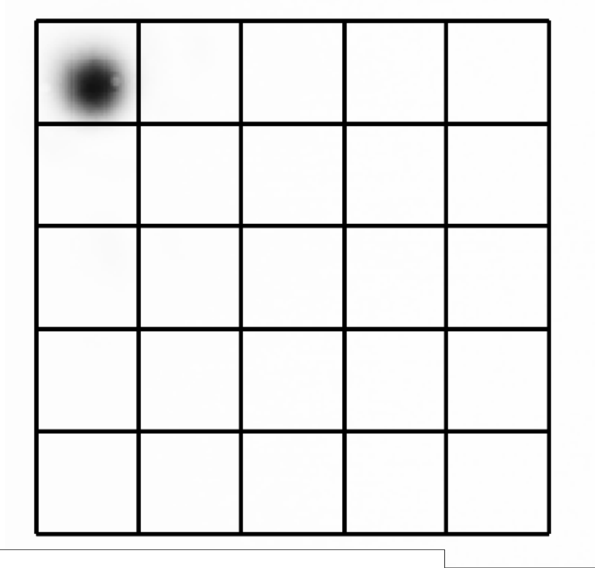


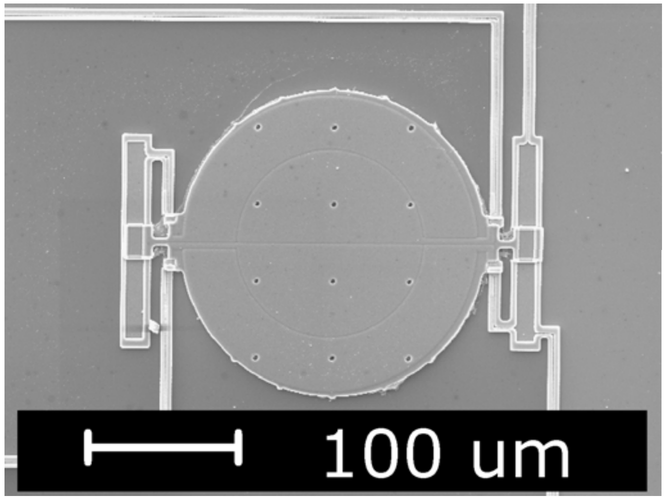
2D Tilt with MEMS Micromirrors

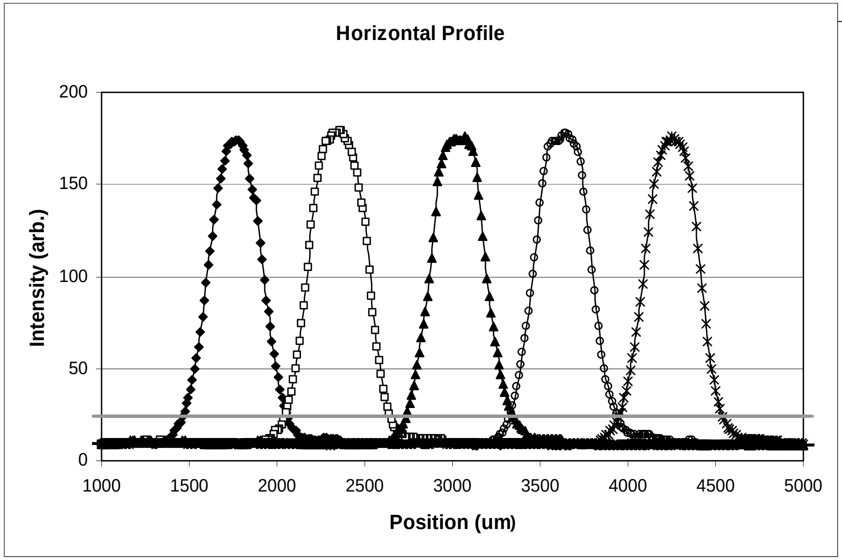
2D decoupled tilt



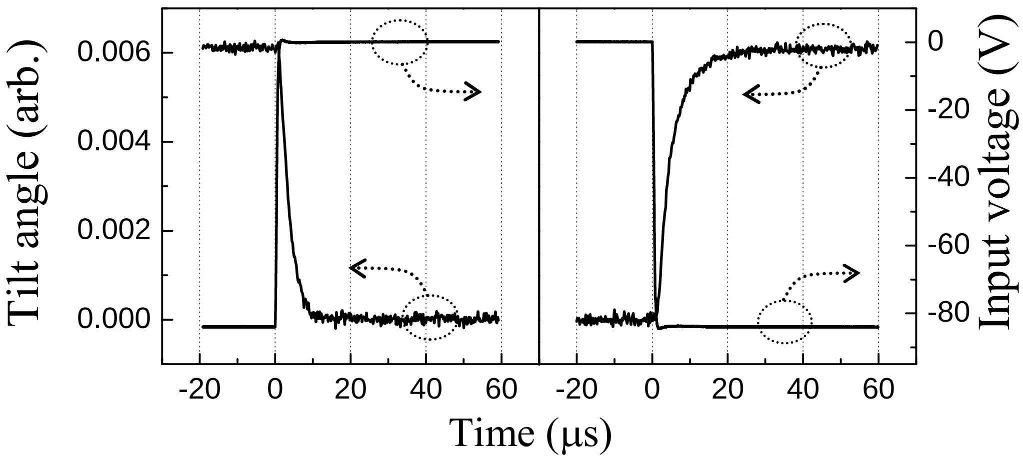


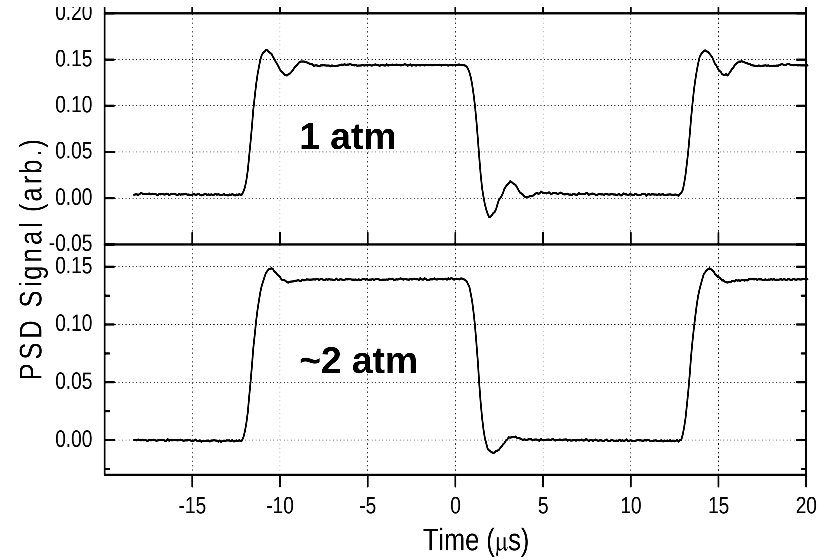




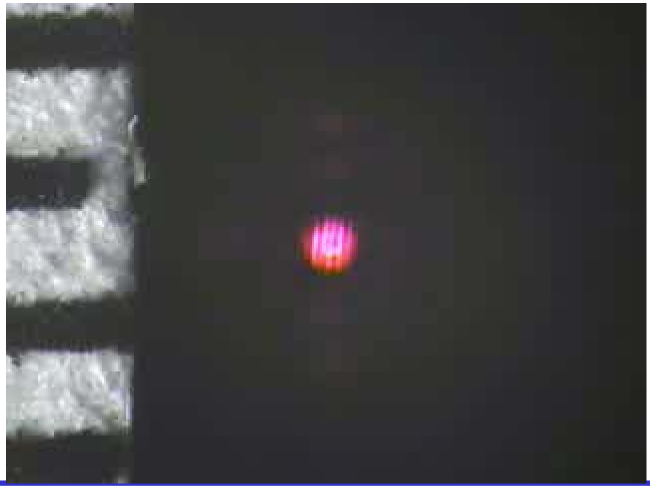


Speed, Controllability & Scalability





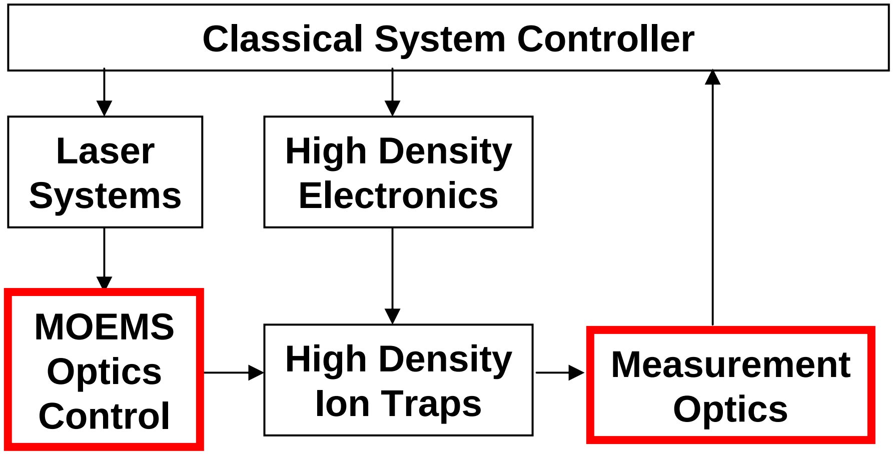
- 10 – 15 μs system settling time
- <5 μs demonstrated
- Push down to 1 - 2 μs



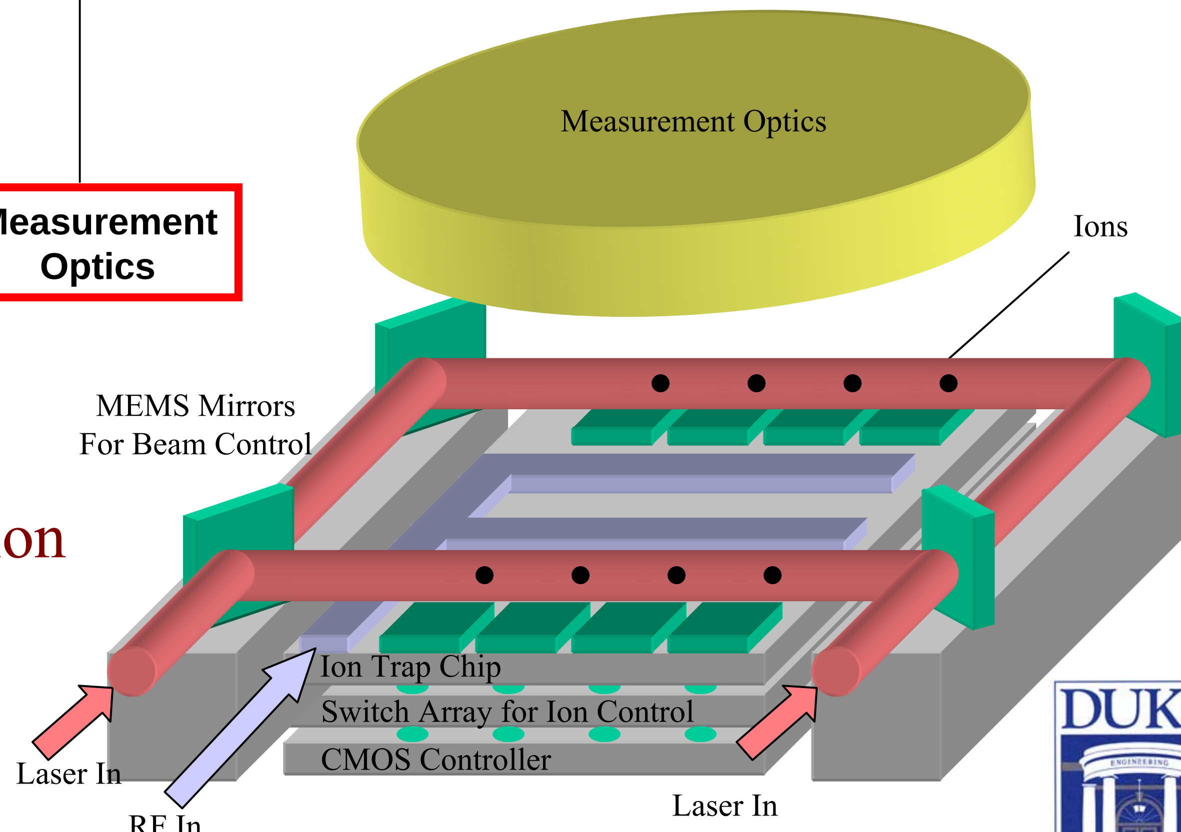
- Scaling to multiple simultaneous spots

Technology for Scaling Ion Traps

Elements of Ion Trap Quantum Computer



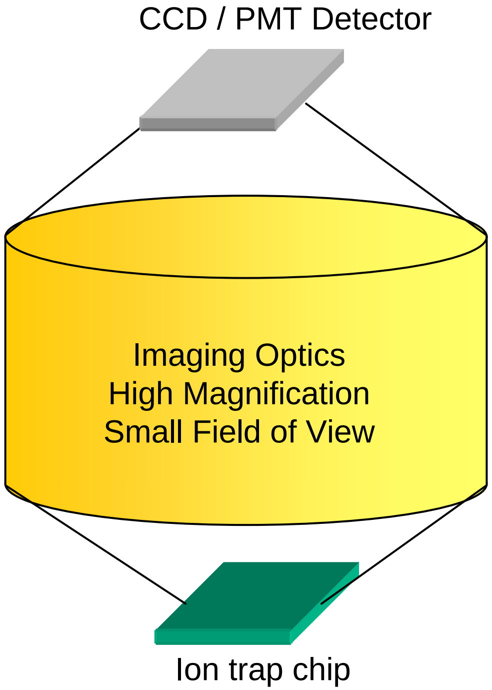
Technology for Realization

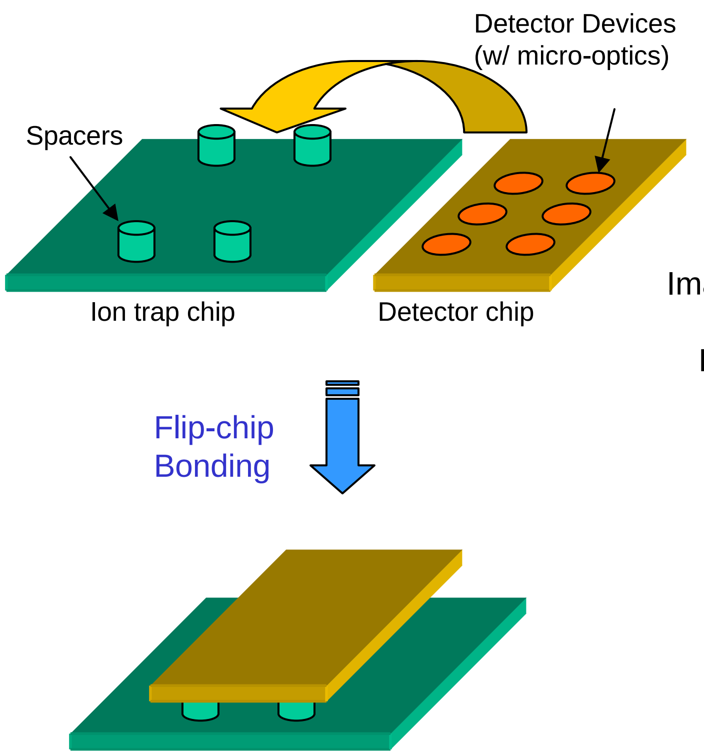


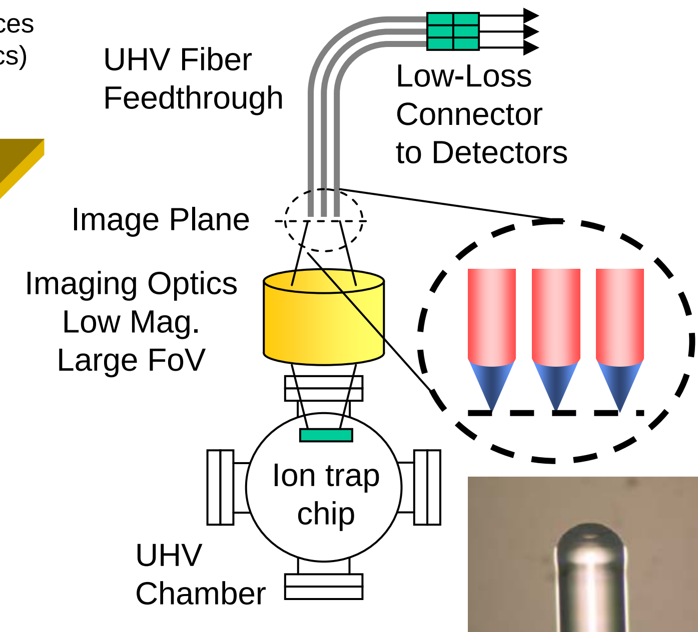
Kim et al., Quant. Inf. Comp. 5, 515 (2005)

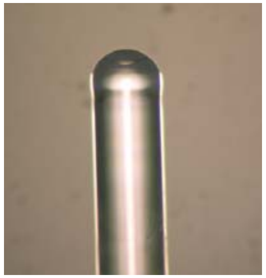
Scalable Photon Collection

- *Low F/# for efficient collection*
- *Large field-of-view for multiple detection zones*
- *Use of micro-optical element: magnify locally!*



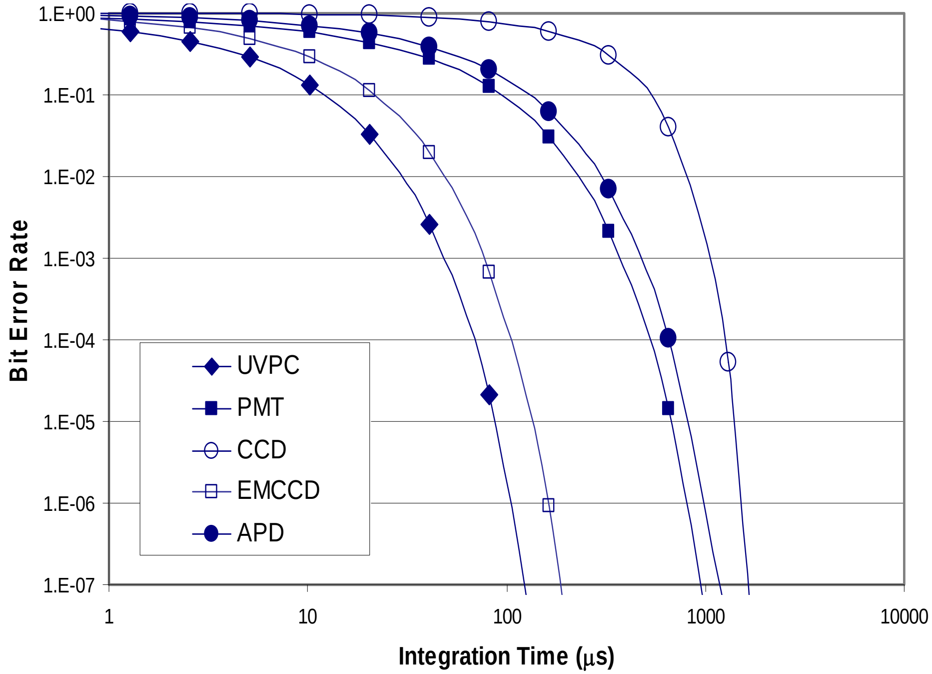






Bit-Error-Rate of State Detection

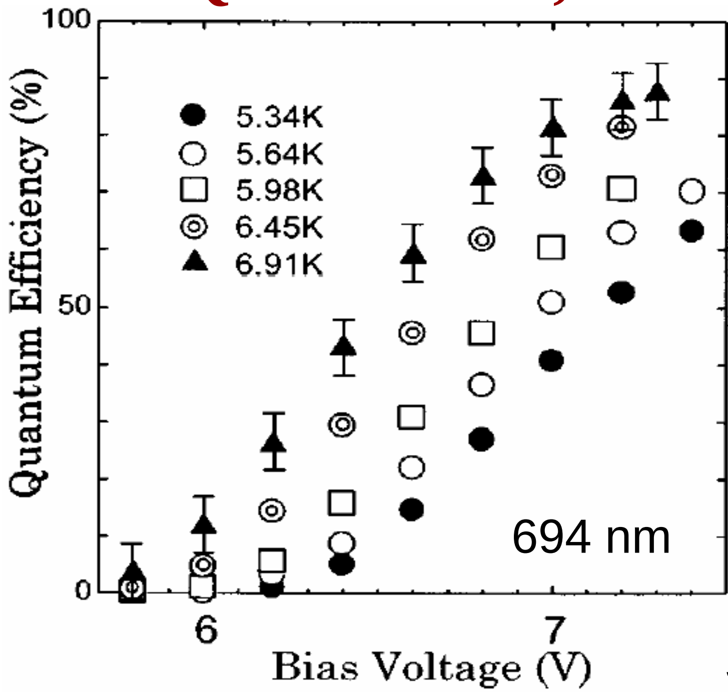
- ***Assumptions***
  - Photons collected at the detector is about 10^6/sec
  - Various detectors considered:
    - QE, gain, multiplication noise & dark count

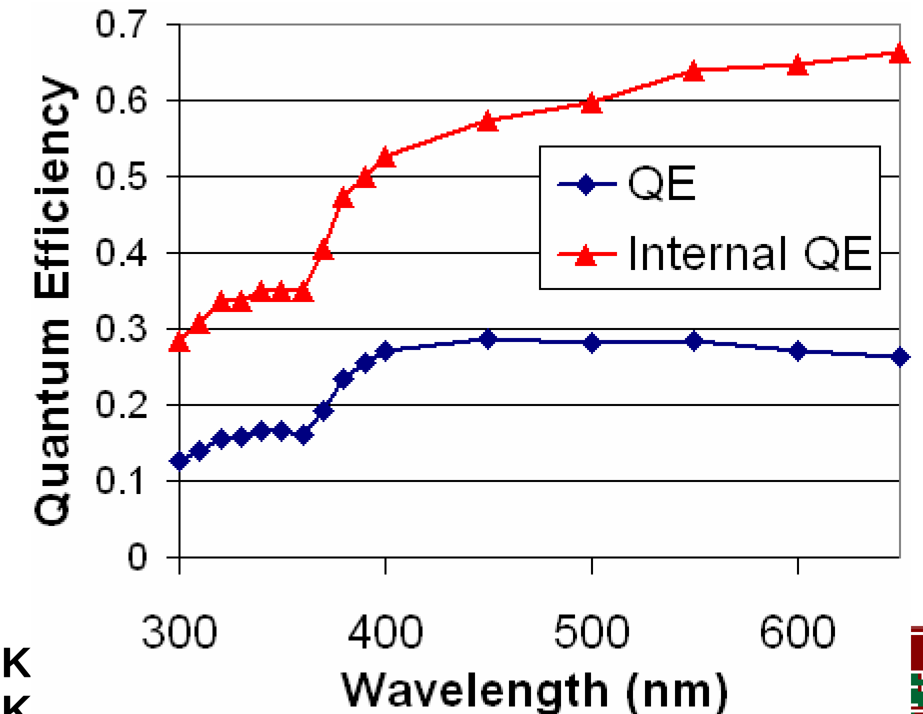


- High quantum efficiency with (noise-free) internal gain
- Fast "frame rate" and low latency

“Ideal” Detector: Modified VLPCs

- *Visible Light Photon Counters (VLPCs)*
  - **High QE single photon detection (88% @visible)**
  - **Noise-free Multiplication (Gain ~30,000, ENF ~ 1.025)**
  - **Large portcount (71,680) demonstrated in FermiLab**
  - **Low QE in the UV, device modification is needed**



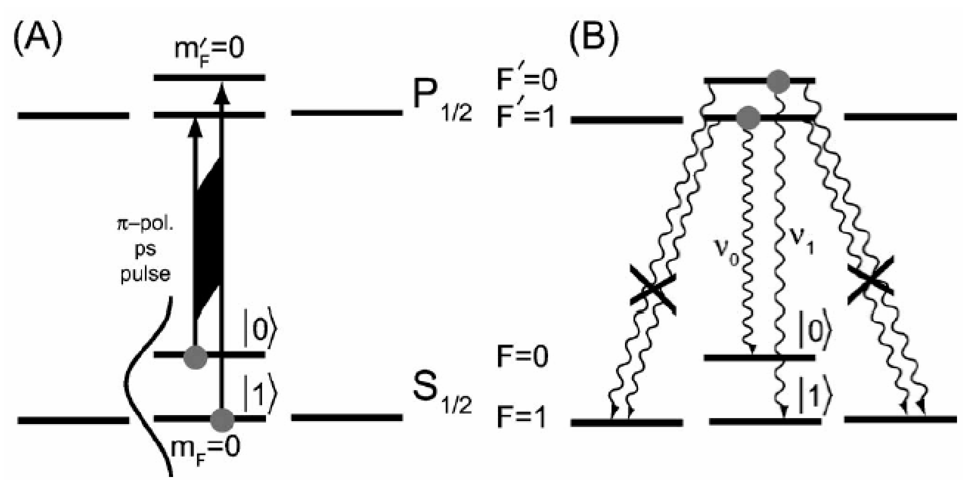


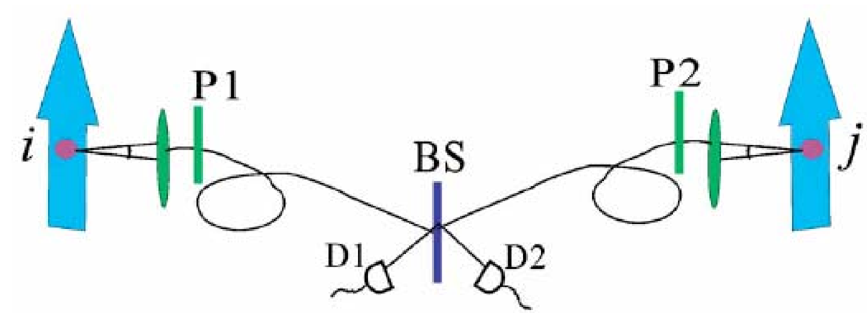
J. K

J. K

New Architectural Elements?

- ***Remote Entanglement Generation***
  - **Entanglement of internal atomic state and photon (color)**
  - **From a pair of such systems, interfere the photons**
  - **Based upon measurement, remote entanglement is probabilistically generated between ions**
  - **Use the entanglement for logic operation**

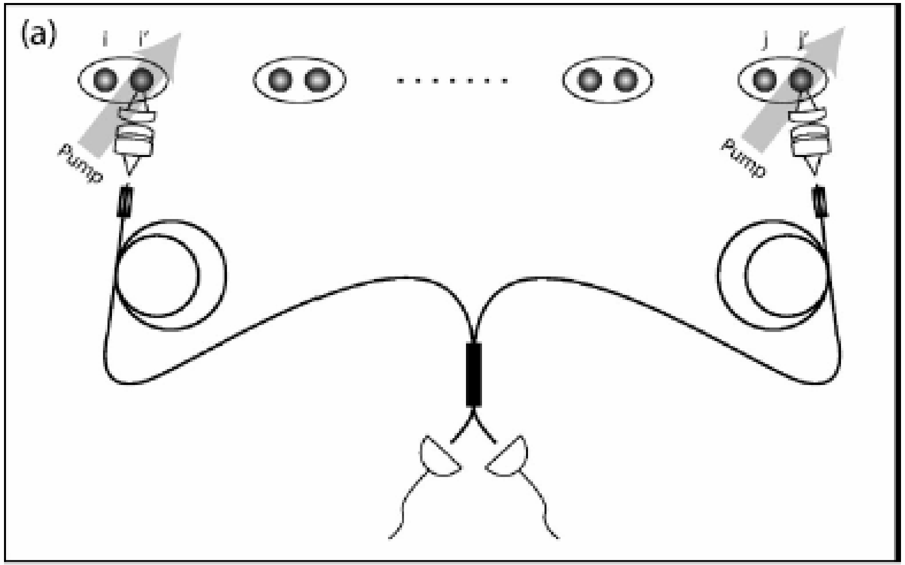


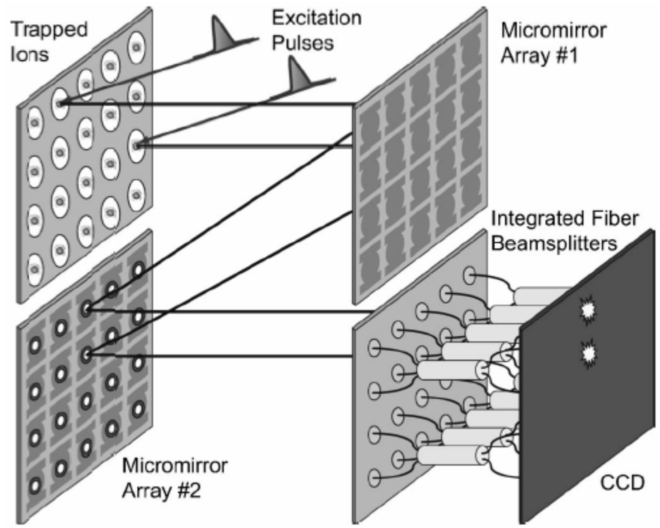


Duan et al., Phys. Rev. A 73, 062324 (2006)

Scalable Quantum Computation

- *Based on remote entanglement generation*
  - Once entanglement is generated, it can be used for gates
  - Optical switching network can be used to create entanglement network
  - Using photonic degree of freedom, the entanglement operation becomes scale-free w.r.t. qubit separation

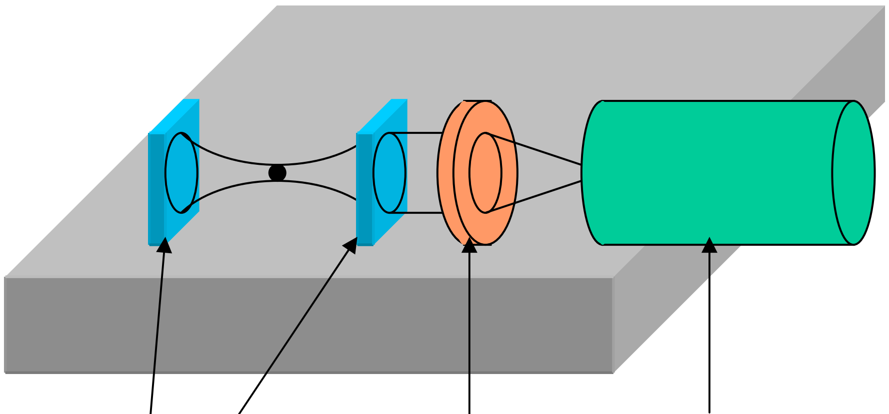


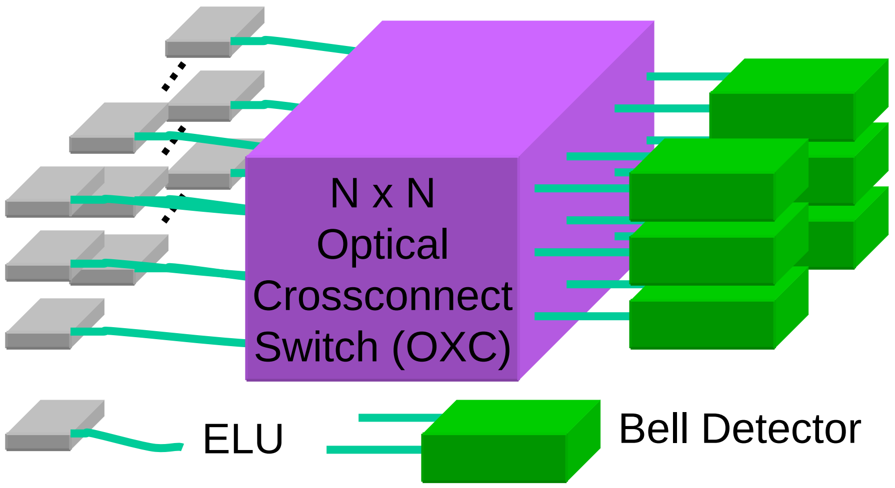


Moehring et al., JOSA B 24, 300 (2007)

Conclusions

- ***Are Quantum Computers Feasible??***
  - **Integration technologies are needed to take us to next step**
    - **Can quantum tolerance be implemented?**
    - **Controlling large quantum entanglement?**
  - **Architecture optimization**
    - **Interplay between task and hardware**





ELU consists of a few logical qubits and quantum teleport