Quantum Computing
with
Trapped Ions

…and laser cooling!

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Outline

- Quantum computing: overview and goals
  - Trapped Ions as a QC architecture
- Ion Trapping and Laser Cooling
- Second Harmonic Generation
- The Cavity (my part)

Quantum Computing - What it is

- Classical: Binary data (0s and 1s)
- Quantum: Superposition of 0 and 1
  - 0.5 ?
  - Two “Qubits”: $A|0>|0>+B\ |0>|1>+C\ |1>|0>+D\ |1>|1>$
- What do we do with the bits?
  - Manipulate them - logic gates
  - Store them - memory

Quantum Computing - What is it good for?

- Factoring!!!
  - Shor's Algorithm: $O((\log N)^3)$ vs. $O(2^{(\log N)^{1/3}})$
- Simulating complex quantum systems

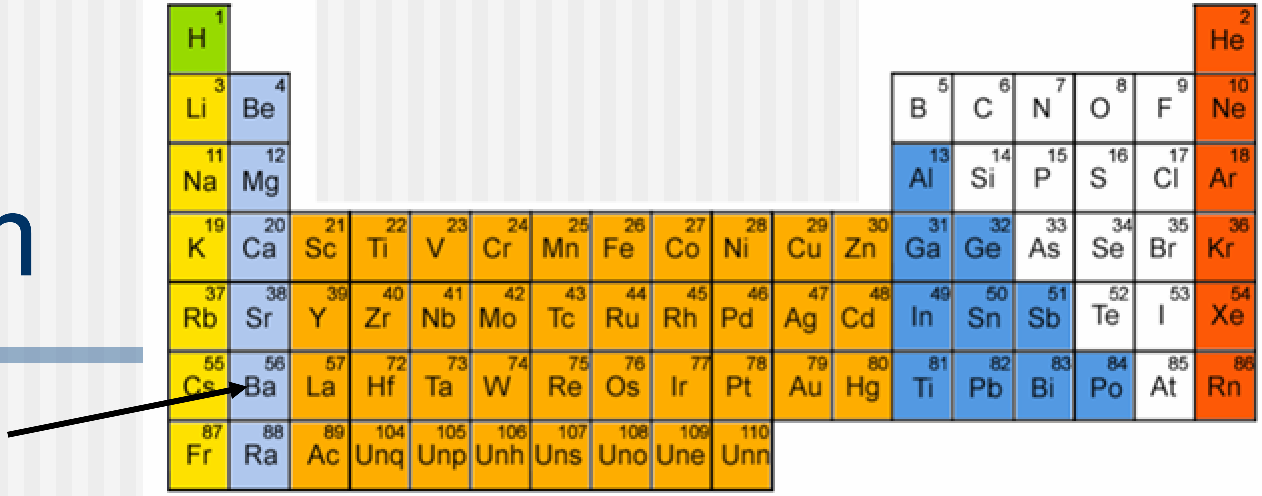
A QC Architecture with potential: Trapped Ions

- Two energy levels form qubit (optical or hyperfine)
  - Very stable
- Gates:
  - CNOT between two atoms in a trap
  - Single qubit rotation by fast pulses
- Scalable system!
  - Entangle with emitted photons for a “flying qubit”
  - Could connect large number of traps into a computing network

Trapping Ions

- Vacuum system isolates the element wanted
- A combination of static electric field and fields oscillating at radio frequency create potential well, stable only for narrow mass range
- Lasers cool ions until almost stationary

Our System



1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Ti	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Unq	105 Unp	106 Unh	107 Uns	108 Uno	109 Une	110 Unn								

- $^{137}Ba^{+}$ ions
- Two ground state hyperfine levels form the qubit
- Transitions between the two driven by varying-length microwave pulses

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

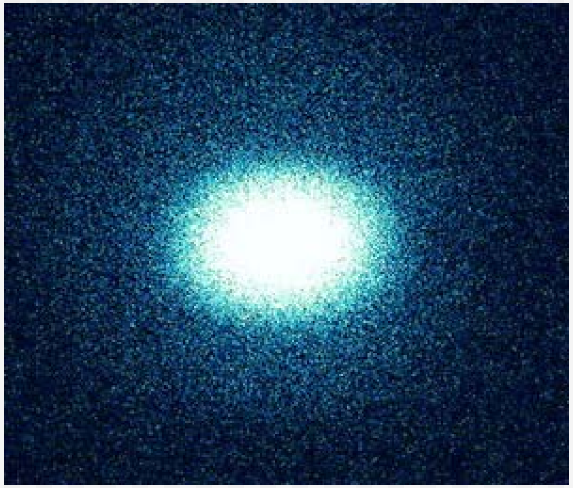
☐ B. Blinov et. al, "Barium Ions for Quantum Computation," Proceedings of The 9th International Workshop on Non-Neutral Plasmas, New York (2008).

Doppler Laser Cooling

- Uses an optical transition, here $S_{1/2}$ to $P_{1/2}$
- Laser is detuned slightly lower than the resonant frequency
- Ions moving towards the laser see a higher frequency from the Doppler shift, so are resonant
- Absorption adds photon momentum to ion, slowing it

Our laser can do more than cooling

- Allows us to see the ions



- Can inititialize the qubit to one state
  - Because of parity, transition depends on polarization

http://depts.washington.edu/qcomp/

Details of cooling scheme

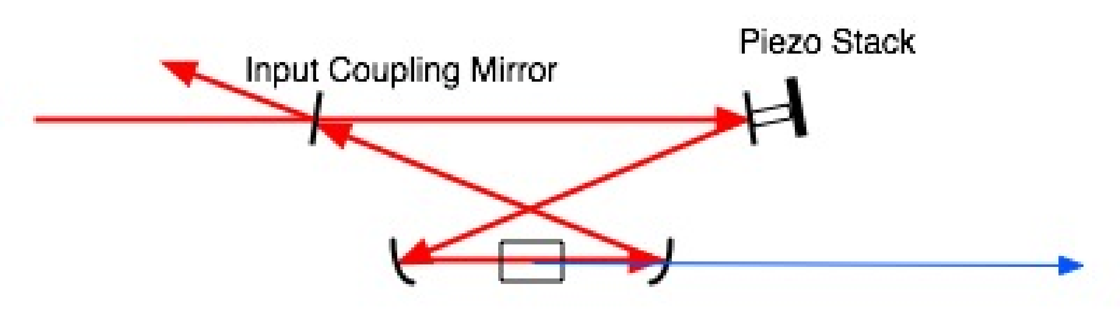
- Ground state hyperfine splitting (our qubit) is 8 GHz - our cooling transition is actually two - so we add sidebands to the laser with an EOM (Electro-Optic Modulator)
- One laser only slows in one direction… but trapping forces couple all directions of motion (if one slows, they all slow)

Second Harmonic Generation (493=986/2)

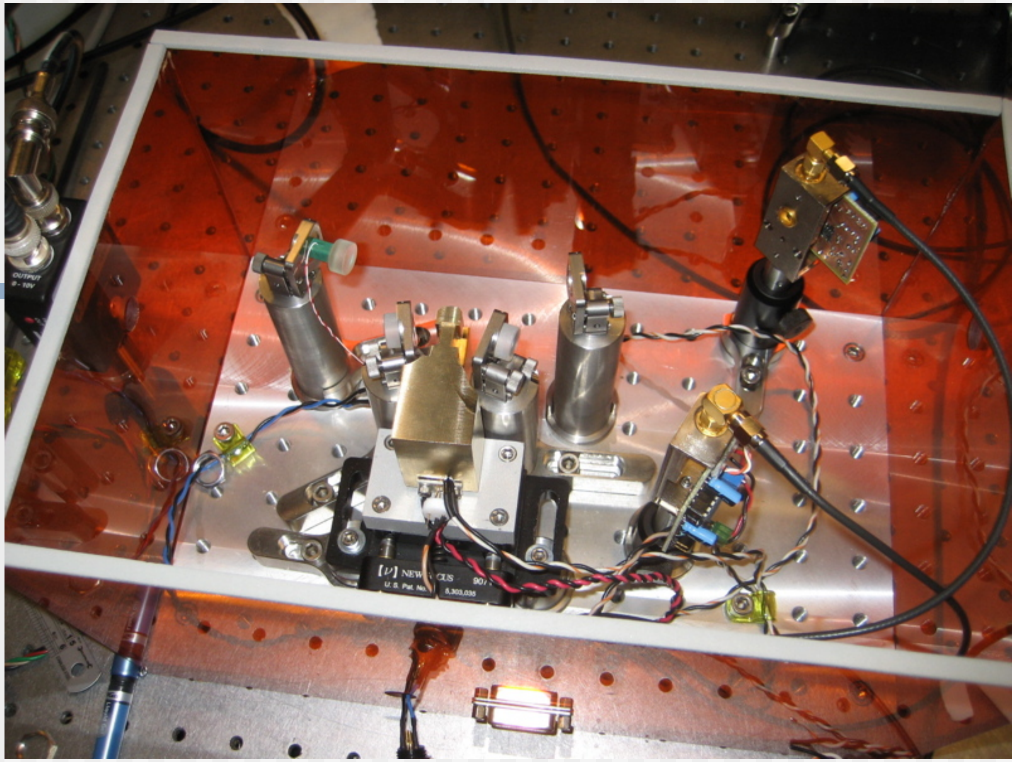
- Difficult to find lasing materials at 493 nm, so we use a 986 nm diode laser and double the frequency
- Uses nonlinear crystal: $P=xE+x^{(2)}E^2$
- E^2 has twice the frequency of E, and the polarization changing at this frequency generates a new EM wave

Resonant Enhancement Cavity

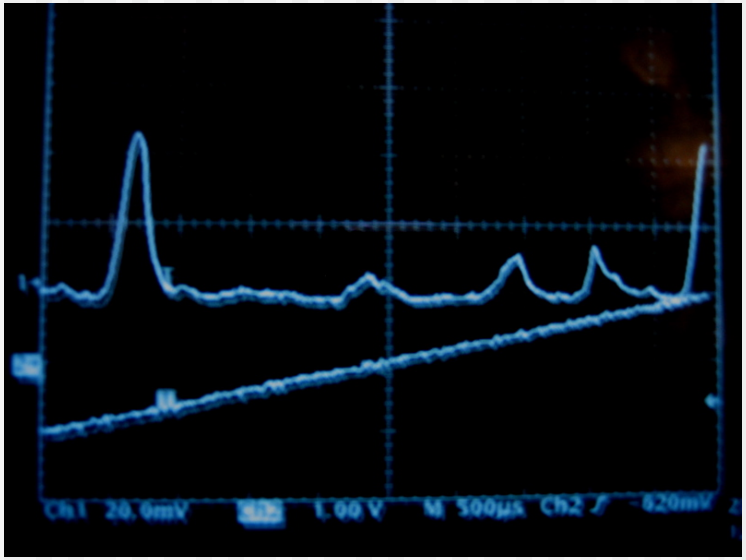
- $P_2 = \alpha P_1^2$
- Problem: for significant harmonic power, need very high fundamental power in the crystal
- Solution: put the crystal in a cavity resonant with the fundamental ($L=n\lambda$). The circulating beam constructively interferes with itself



Technical Issues

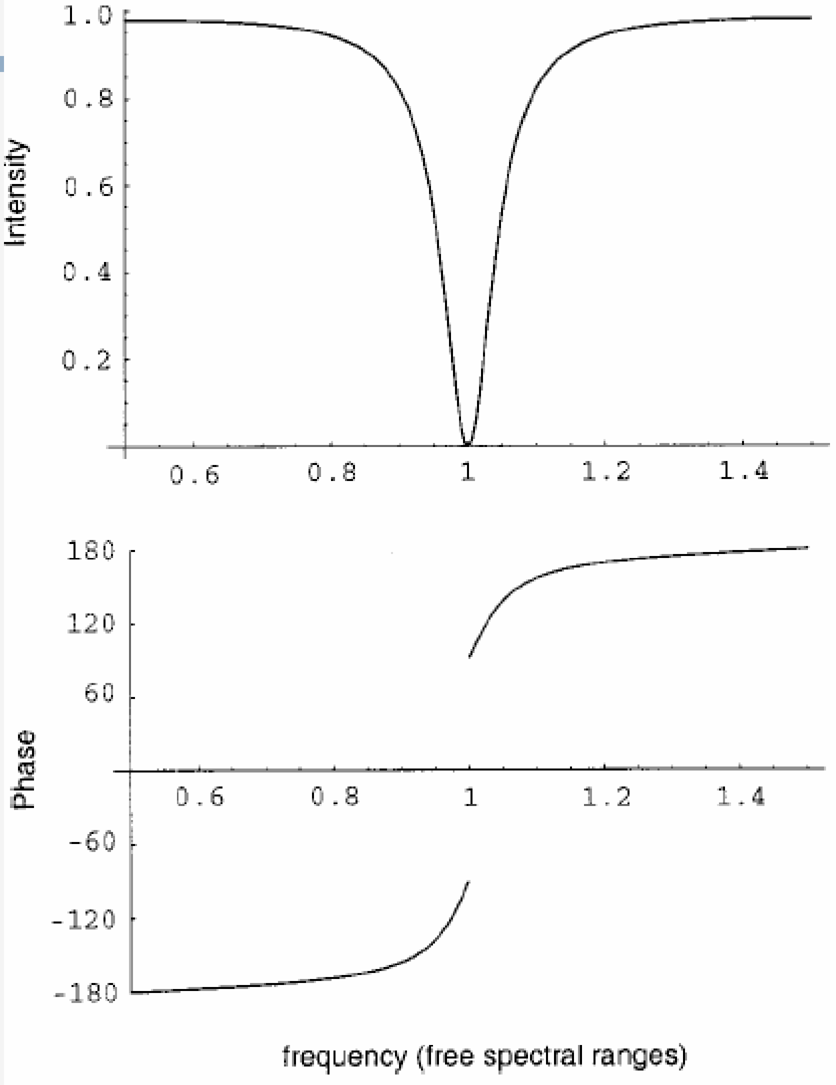


- Input Coupling
- Mode-matching
- Alignment
- Stabilization
  - PDH Feedback system



Pound-Drever-Hall Lock

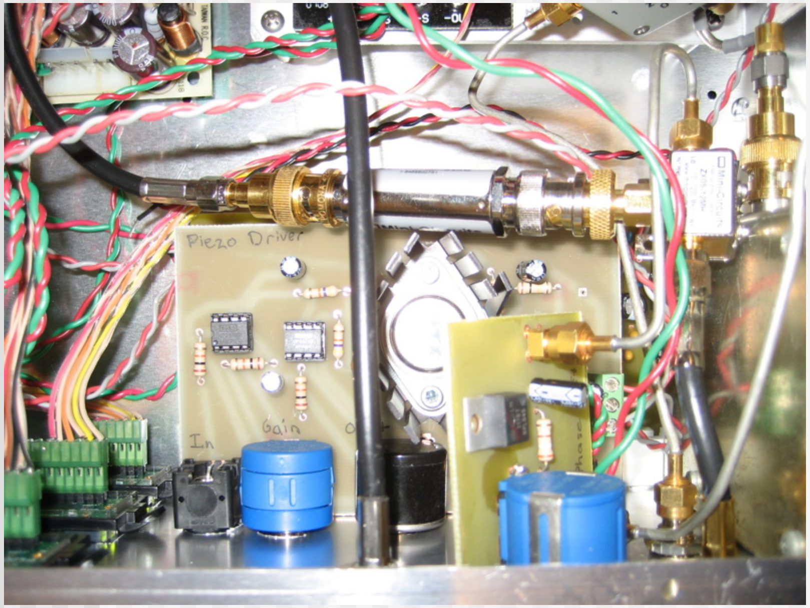
- Reflected signal shows when off resonance
- Intensity is symmetric, so must use phase to know which direction to move for resonance
- Use reference frequency to measure phase shift



☐Eric D. Black, "An introduction to Pound-Drever-Hall laser frequency stabilization," Am. J. Phys. 69, 1 (Jan. 2001).

- Modulating the laser beam adds sidebands
- These are far off resonance, so entirely reflected, giving a reference mixed with the fundamental reflected beam

- Fast photodiode and tricky electronics extract error signal



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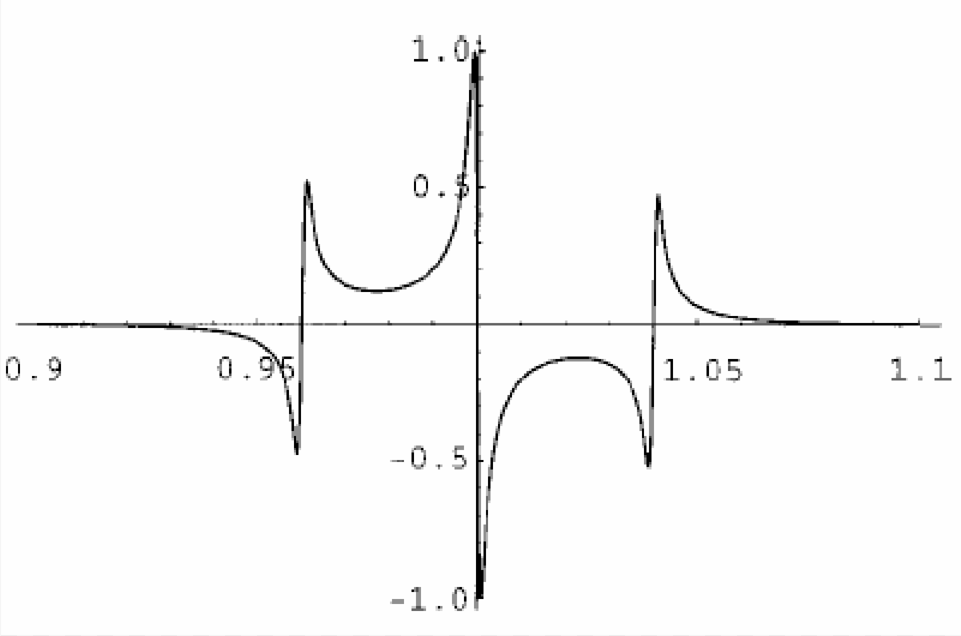
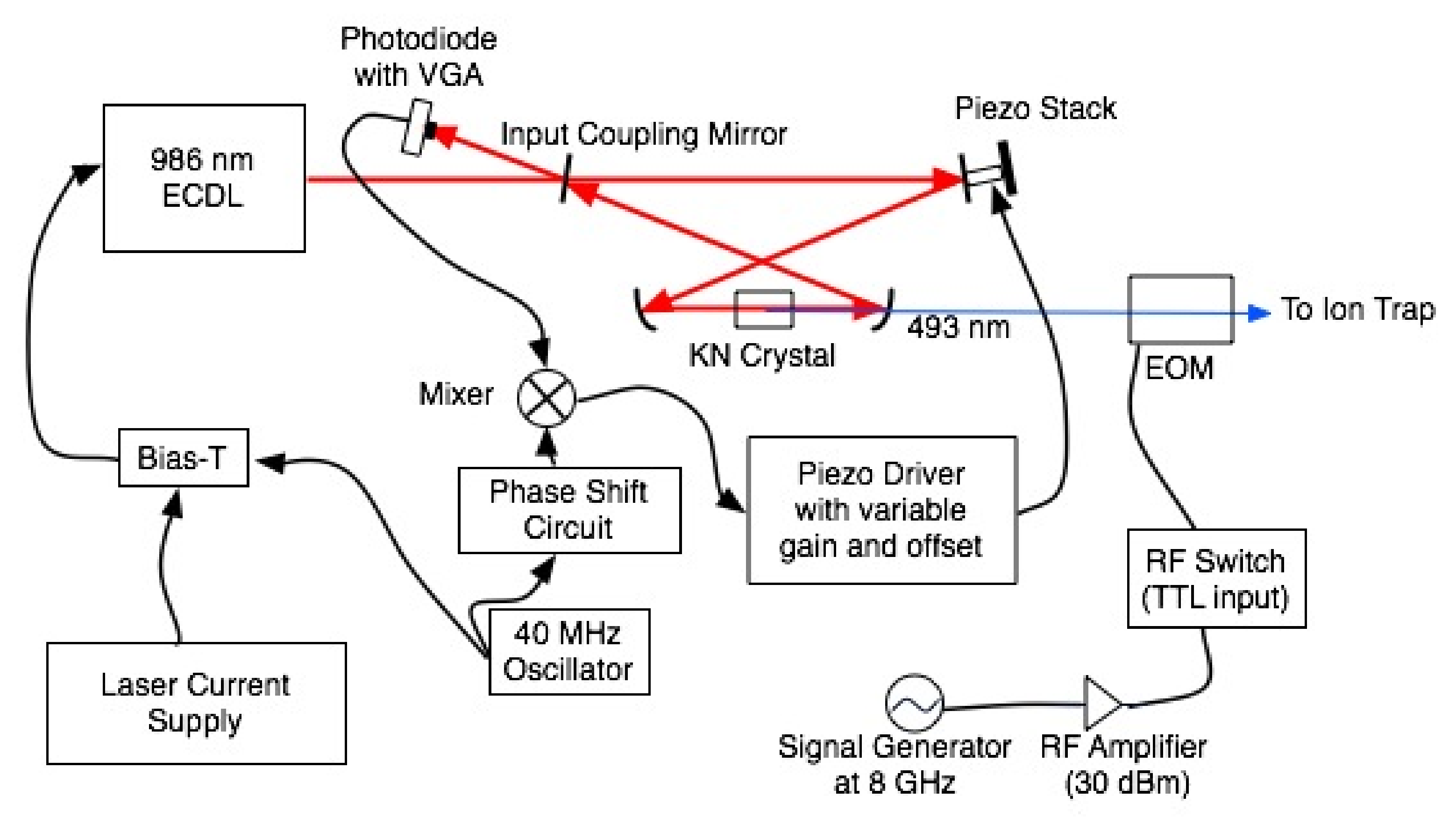


□Eric D. Black, "An introduction to Pound-Drever-Hall laser frequency stabilization," Am. J. Phys. 69, 1 (Jan. 2001).

The Laser System



References

- UW Trapped Ion Quantum Computing web page. http://depts.washington.edu/qcomp/
- B. Blinov et. al, "Barium Ions for Quantum Computation," Proceedings of The 9th International Workshop on Non-Neutral Plasmas, New York (2008).
- Wikipedia
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- Eric D. Black, "An introduction to Pound-Drever-Hall laser frequency stabilization," Am. J. Phys. 69, 1 (Jan. 2001).

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