Simulating Dynamics of 2D Trapped Ion Systems

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Abstract

Increasing the number of ions in ion crystals can be used to make more powerful quantum computers and quantum simulations. In order to do this, there must be a thorough understanding of the dynamics of ion crystals. In this research, I have improved upon the 2D trapped ion crystal simulation used by my team at the University of Washington by implementing a cooling laser which cools the crystals to the doppler limit. This laser works by a random and discrete process which causes the velocities of the ions to change as ions transition between the ground states and excited states. To show possible future uses for the simulation, I have included figures which demonstrate some aspects we can study such as phase transitions.

Motivation

- Trapped Ions can be used for Quantum Computing and Quantum Simulations
  - Quantum Computing uses quantum particles called qubits as fundamental unit of information
  - Some operations can be performed on quantum computers much quicker than conventional computers
  - Qubits can be different kinds of two-level system (ions, neutral atoms, molecules)

Theory

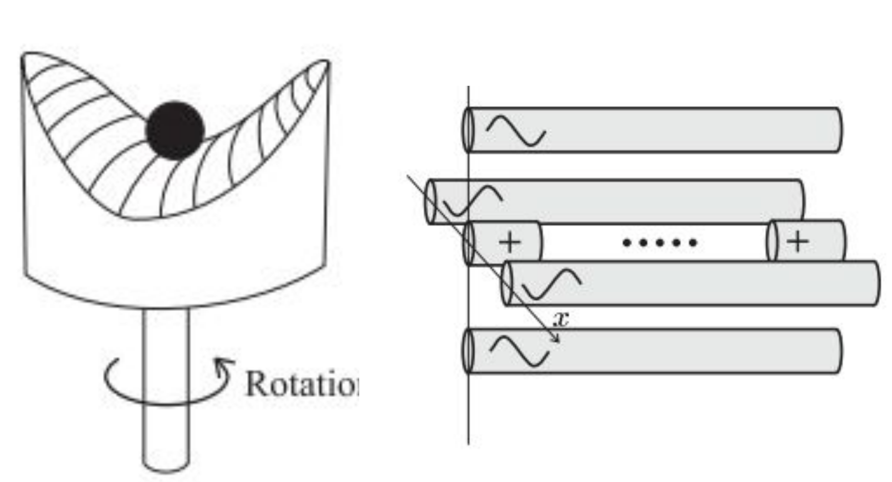

Figure 1: From *Atomic Physics* (2005) by Foot. Image on the left shows a particle in a rotating saddle. This is an analogy of how Paul traps keep ions in stable equilibria. Image on the right shows a simple model of a linear Paul trap.

Ion Trapping

- Earnshaw's theorem states that we cannot keep particles in a stable equilibrium with only electrostatic forces
- Instead, we can use dynamic electric forces to make a stable equilibrium
- Paul traps keep ions trapped with electric forces oscillating at radio frequencies (RF) ~MHz

Figure 2: Barium ion Paul trap used in the University of Washington ion trapping lab. This trap uses eight planar electrodes and two axial electrodes to make 2D ion crystals.

Laser Cooling

- We can use lasers to cool trapped atoms
  - Atom's experience doppler shifted laser frequency
  - If we tune laser frequency lower than resonance frequency of atoms, atoms will feel an overall slowing force
  - Absorption and emission of atoms is a random process, which tends to slow atoms down
  - Because of spontaneous emissions, there is a limit to how much you can cool the atoms called the Doppler Temperature ~1mK

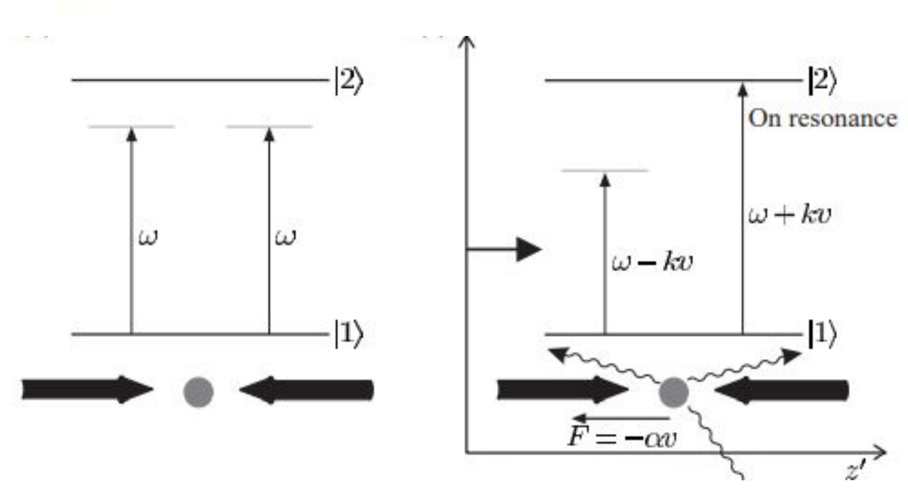

Figure 3: From *Atomic Physics* (2005) by Foot. Diagram on the left shows two counter propagating lasers pointing on a stationary atom with the lasers detuned below the atomic resonant frequency. The right shows a similar diagram now with the atom moving to the right with speed v. The atom experiences doppler shifted laser light, which causes a net force in the opposite direction to the velocity.

Simulations

- In my project, I worked on improving Python simulations of the ion trapping system in the UW Lab
- Simulations could explore different aspects of the ion trapping system: cooling dynamics, crystal structure, micromotion
- Velocity-Verlet Algorithm numerically solves for the position, velocity, and acceleration of each ion for each time step
- Forces experienced by ions: Trap electric field, electric field between ions, laser force

Figures Demonstrating Capabilities of Simulation

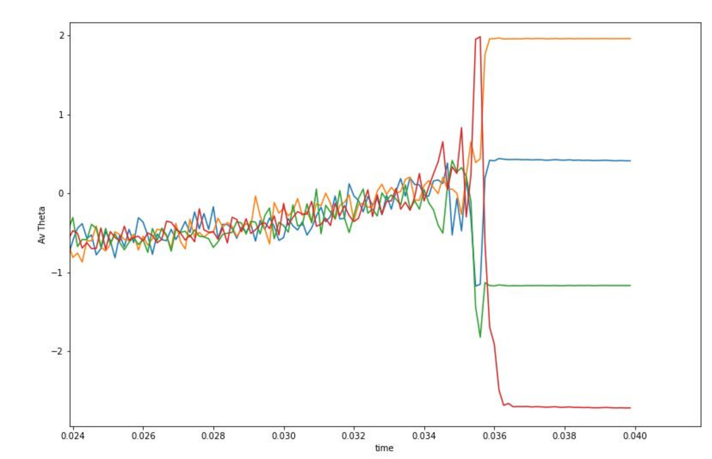

Figure 4: Angular position of 4 ions, represented by different colors, during crystallization phase transition. Cooling laser slows ions down until the ions localize.

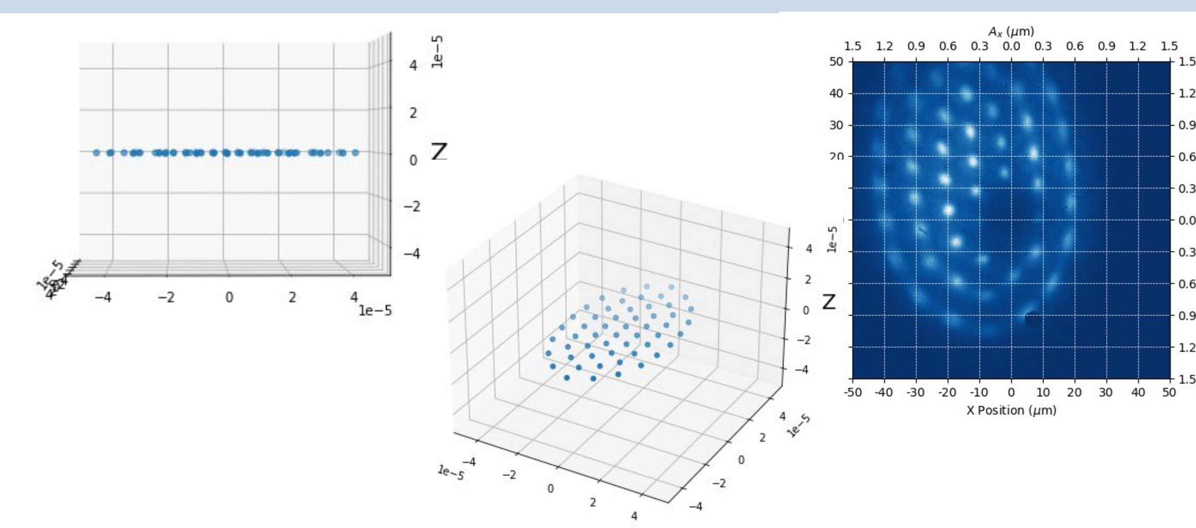

Figure 5: Right) Image of ion crystal with 54 ions, largest crystal made in the UW lab, alongside the simulated version of this crystal (left) seen in two orientations.

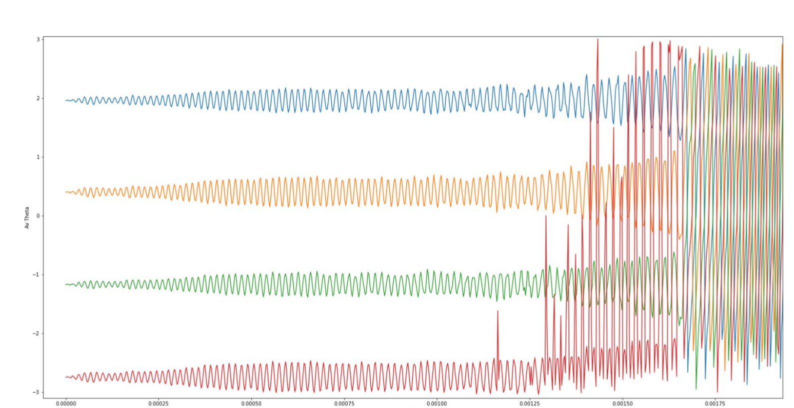

Figure 6: Angular position of 4 ions, different colors, during melting phase transition. Here, the cooling laser is being dominated by a second heating laser which is causing the energy of the system to increase over time.

Figure 7: Angular position of ions in an unstable 8 ion configuration. We can see that the ions undergo intermittent melting and exchange positions with each other.

Improving Cooling Dynamics

Improving the Simulated Laser Force

- Old simulated laser function was a time-average force which cooled the crystal to T=0 K
- I implemented a more realistic laser which cools the ions with random, discrete process
  - Spontaneous emissions make there a limit to the laser cooling
- Equations for probability for absorption and emission for discrete laser:

$$P_{abs} = \frac{R_{scatt}}{1 - R_{scatt}/\Gamma}\Delta t \qquad P_{em} = \Gamma \Delta t$$

where,

$$R_{scatt} = s_0 \frac{\Gamma/2}{1 + s_0 + [2(\delta - \mathbf{k}.\mathbf{v})/\Gamma]^2}$$

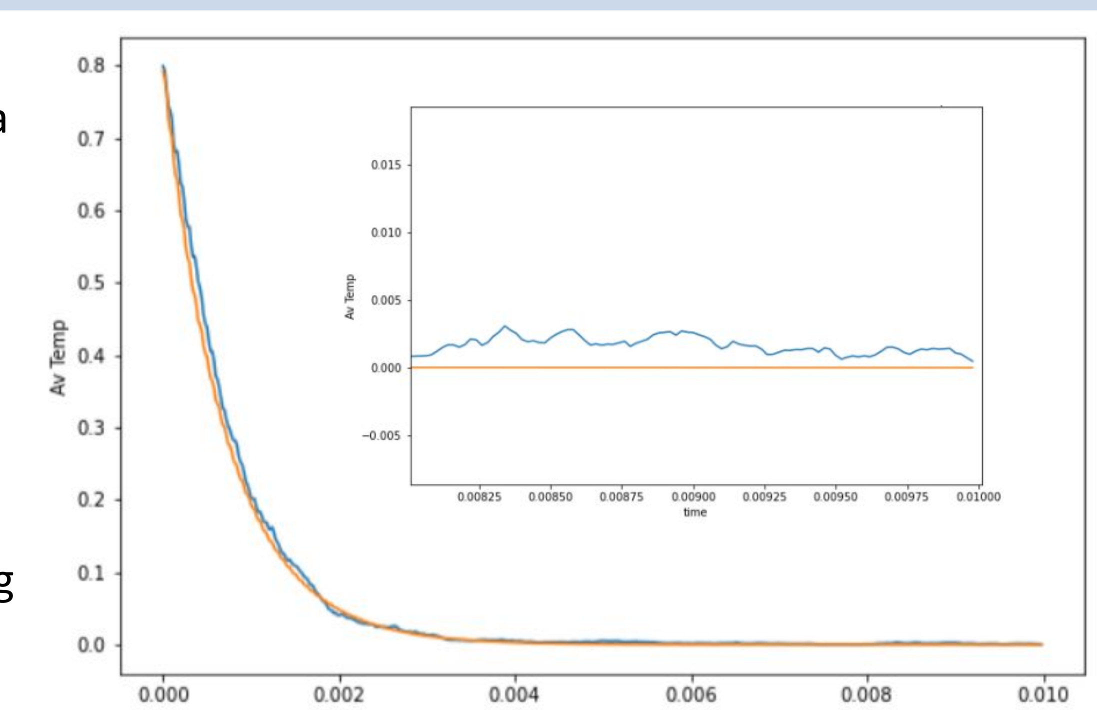

Figure 8: Single simulated ion is cooled with two functions, time averaged laser force (orange) and discrete laser force (blue). The overall exponential decay of the temperature of both cooling functions is the same. Smaller plot is the last 2ms of the simulations, and shows that the discrete laser force oscillates around T= 1.605 mK. This demonstrates that the discrete laser function cools to the doppler limit.

Moving Forward

- Want to form larger ion crystals with around 100 ions. The way we will do this is by having two different lasers: one laser which will cool inner ions and another to cool outer ions.
- Want to learn more about the normal modes of vibration of larger crystals and how they relate to temperature

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Citations

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