Macro and Microscopic Ion Trap Junction Prototype for Quantum Computing

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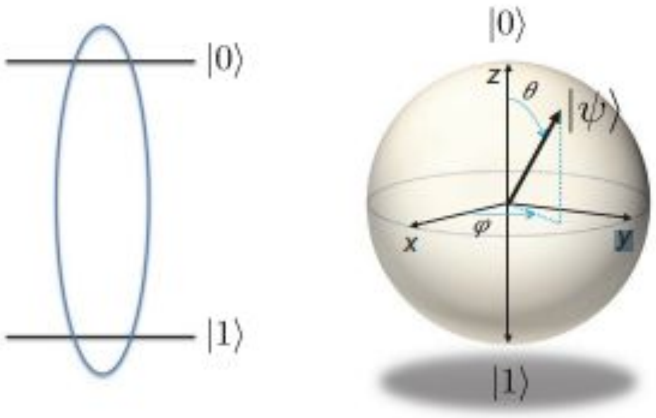
- Structural Engineer: Calvin
- Fabrication Engineer: Michael
- Verification Engineer: Andrew

- Client: Durga Paudyal
- Advisors: Durga Paudyal, Gavin N. Nop, Jonathan D. H. Smith

Context on Qubits and Coherence Time

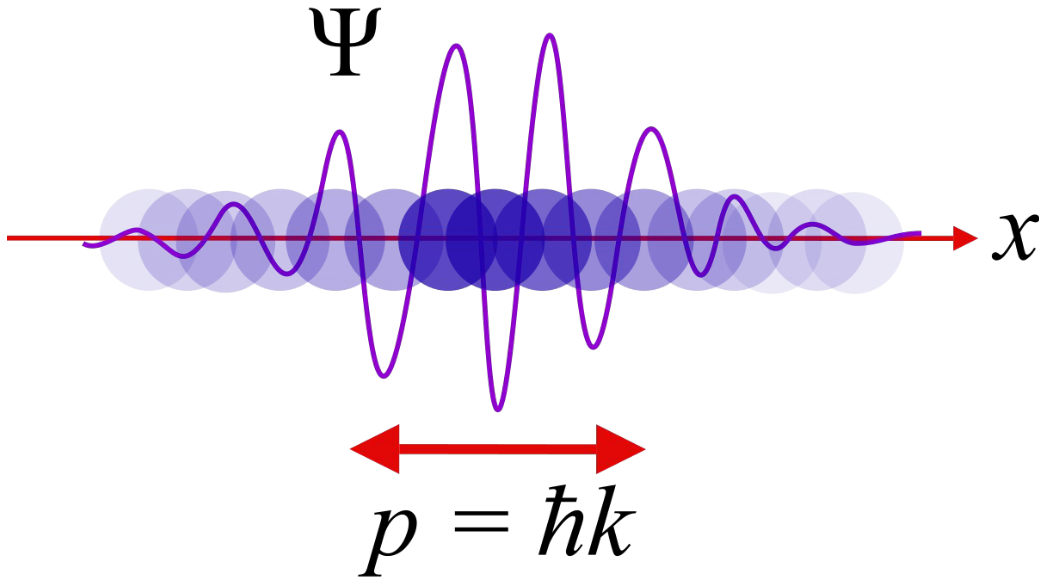
- Qubits exist in a superposition of states from 0 to 1

$$|\psi\rangle = \cos(\theta/2)|0\rangle + e^{i\phi}\sin(\theta/2)|1\rangle$$



$$|\psi\rangle = \cos(\theta/2)\,|0\rangle + e^{i\phi}\sin(\theta/2)\,|1\rangle$$

- Coherence time is the tendency of excited electrons to revert back to their initial state



Microscopic Project Vision

- The Microscopic goal of the project is to design a quantum junction using Rare Earths and a system around it (Ion Traps, Crystals, Ect.)

- Use cases are as critical components in Quantum Computers and Networks.

Macroscopic Project Vision

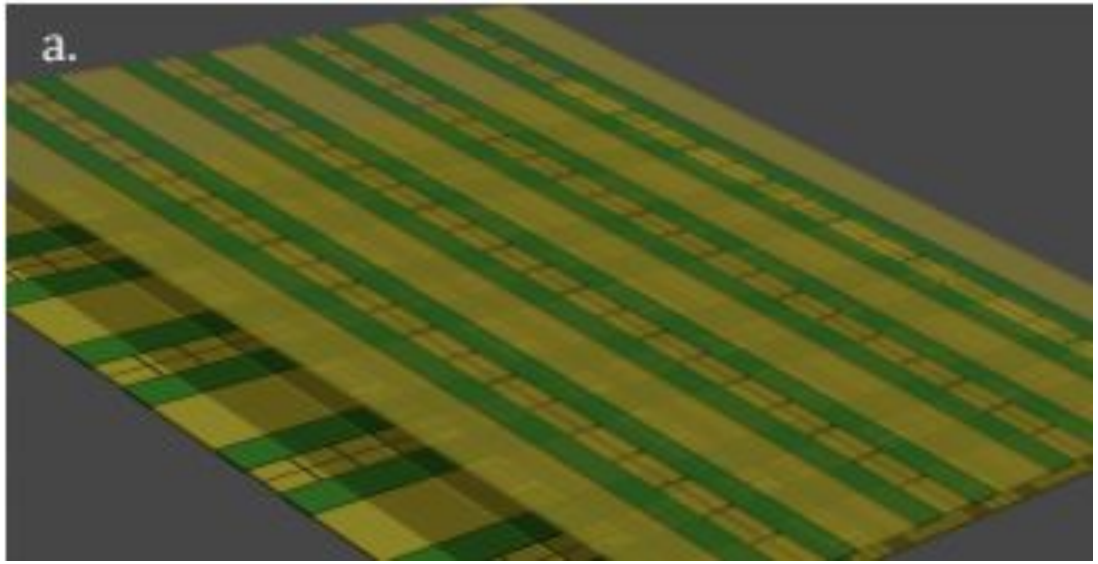
- The macroscopic goal is to design a larger ion trap, with the microscopic components scaled up.

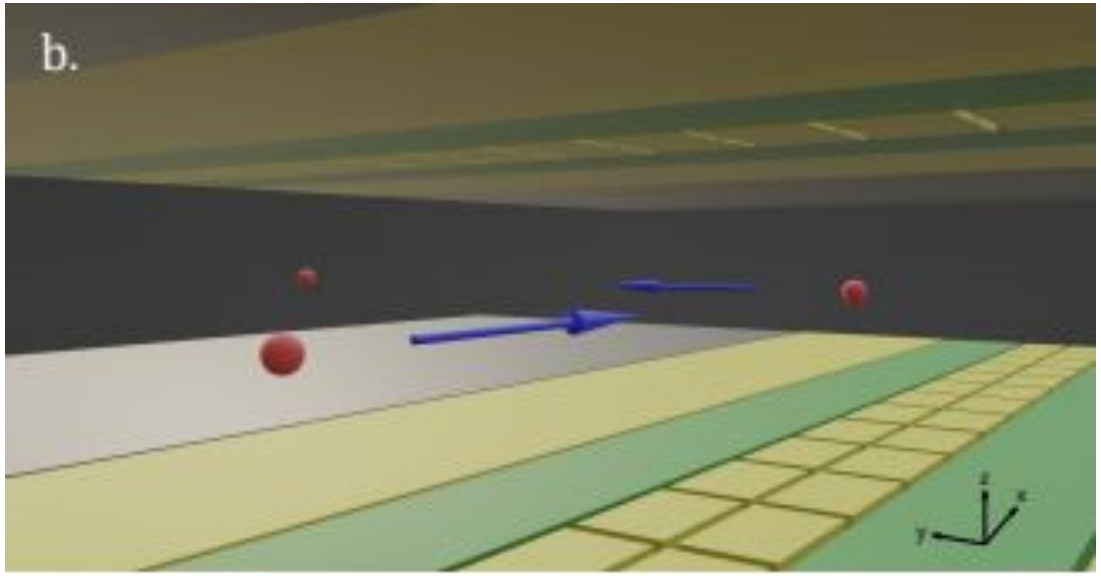
- This projects output will be a proof of concept for the novel Ion trap designed Gavin N. Nop, Jonathan D. H. Smith, Daniel Stick, and Durga Paudyal at a macro scale.

Context on Project iterations

- This project has changed from its original direction.
- It’s initial goal was to design a solid state qubit by selecting a crystal host and Rare Earth dopant, and build a simulator to test for coherence time.
- Upon researching extensively, we came to the choice of using Erbium as our dopant material because it operates at the same wavelength as Telecom and has a high absorption rate.
- These advantages of using Erbium in quantum applications led to our final design of a novel ion trap incorporating Erbium as the ionized material.
- Much of the research carried over, but this was a significant change between design iterations.

Conceptual/Visual Sketch





Requirements on Trap Functionality

- Functional Requirements
  - Must be able to suspend particles in the air using our trap
  - Must be able to move the particles in multiple directions, one at a time
  - The atom proposed must be a rare earth element with an optimal absorption and emission spectrum
- Technical Constraint
  - Need a high voltage (5kV) generator

Requirements on Proposed Element

Functional Requirements:

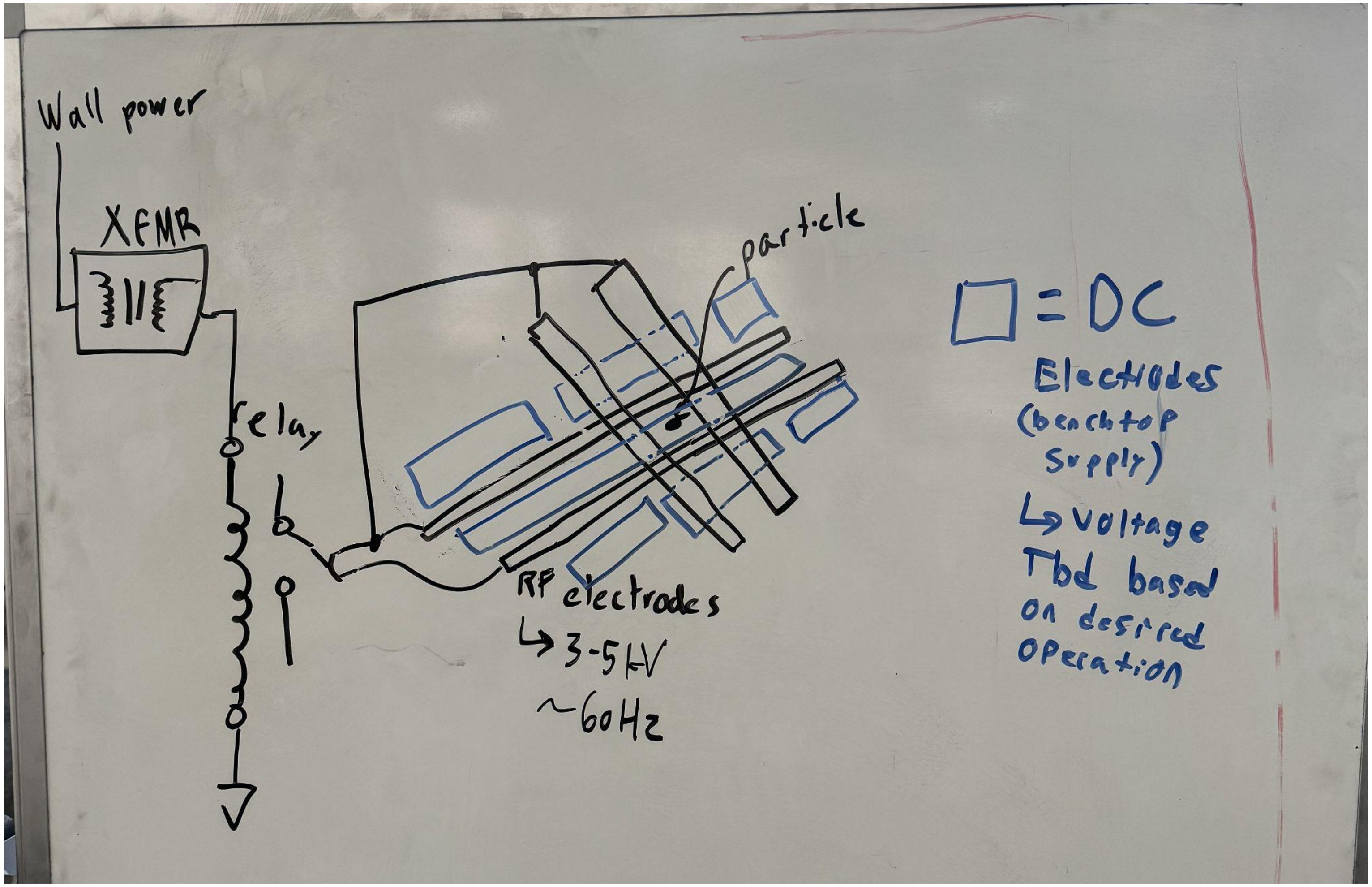
- The atom proposed must be a rare earth element

Technical Requirements:

- The atom proposed must have a useful absorption and emission spectrum

- The element must have a relatively high coherence time (~ 1 second)

Conceptual Final Design Diagram

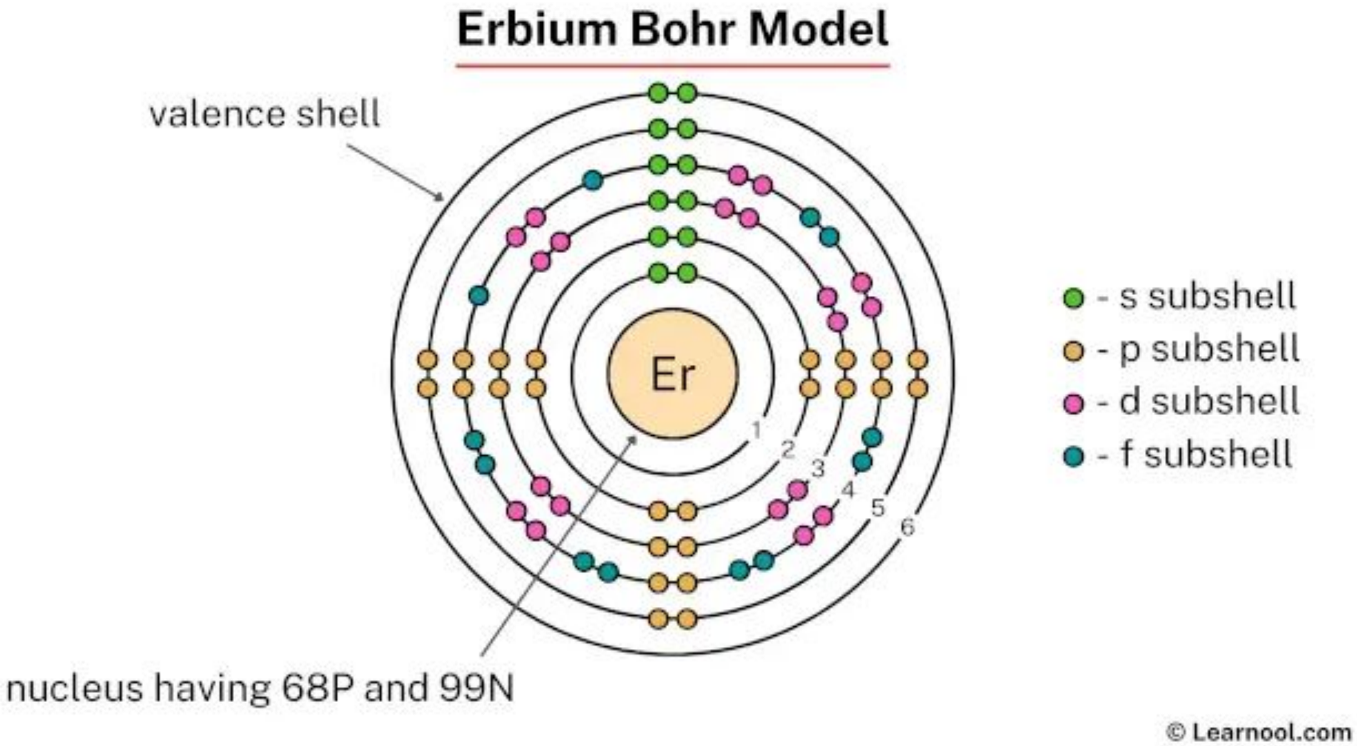


System Design: micro vs macro

- Microscopic model
  - Real-world implementation would include the use of an Erbium Ion
  - Ability to manipulate the location of the ion without changing the electron configuration of the particle
- Macroscopic model
  - Utilizes a piece of styrofoam or paper that has been charged by some method (TBD) to represent the ion
  - Uses large copper rods or strips as the electrodes

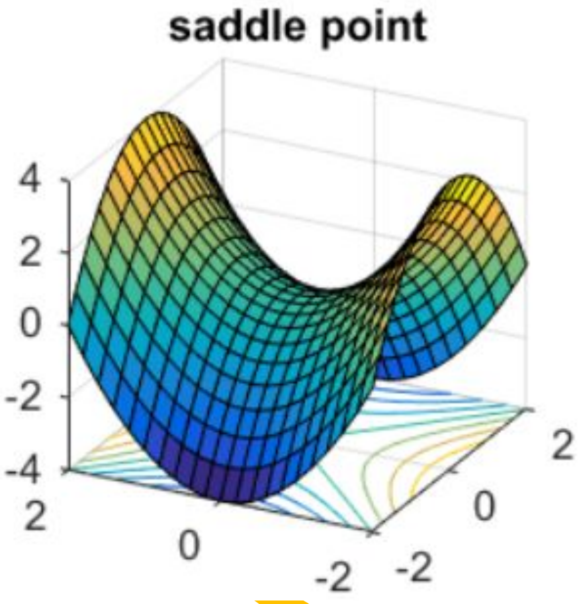
System Design: Ion

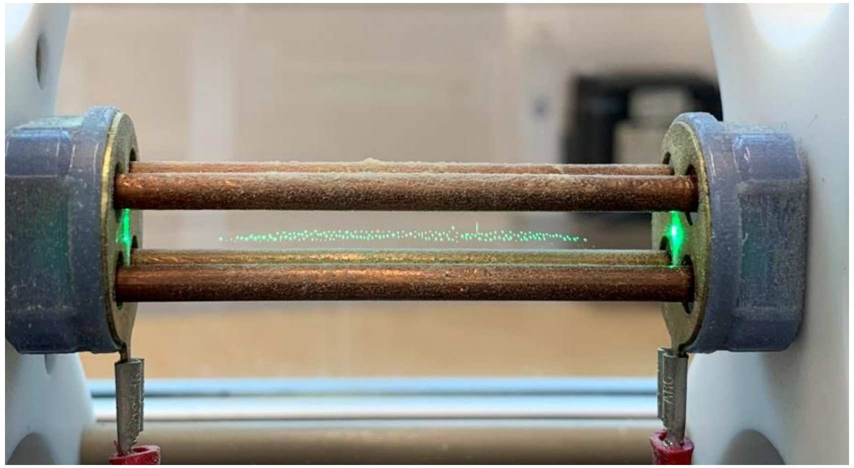
- Erbium Ion can be created by adding or removing an electron to charge the particle (unexplored)
- Natural shielding of the 4f subshell by the 5th valence band, allowing for more precise qubit operations and longer coherence times when using electrons in the 4f subshell

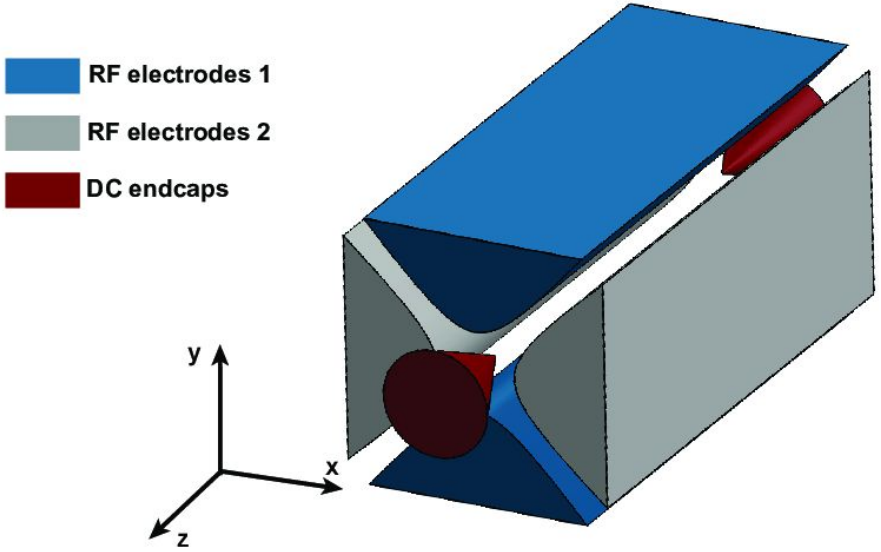


System Design: Electromagnetic fields

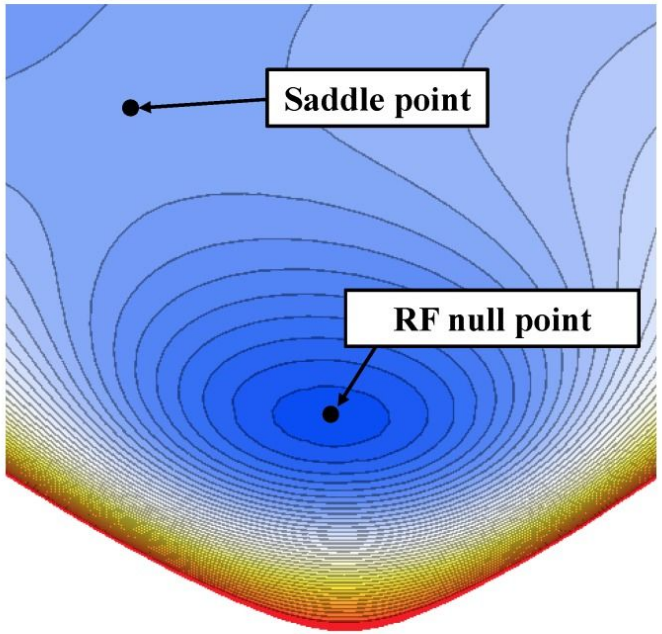
- RF Electrode voltages will vary in order to create a saddle point in the electric field (time-averaged null space) that will constrain the particle in 3D space (Earnshaw's Theorem, linear Paul trap)



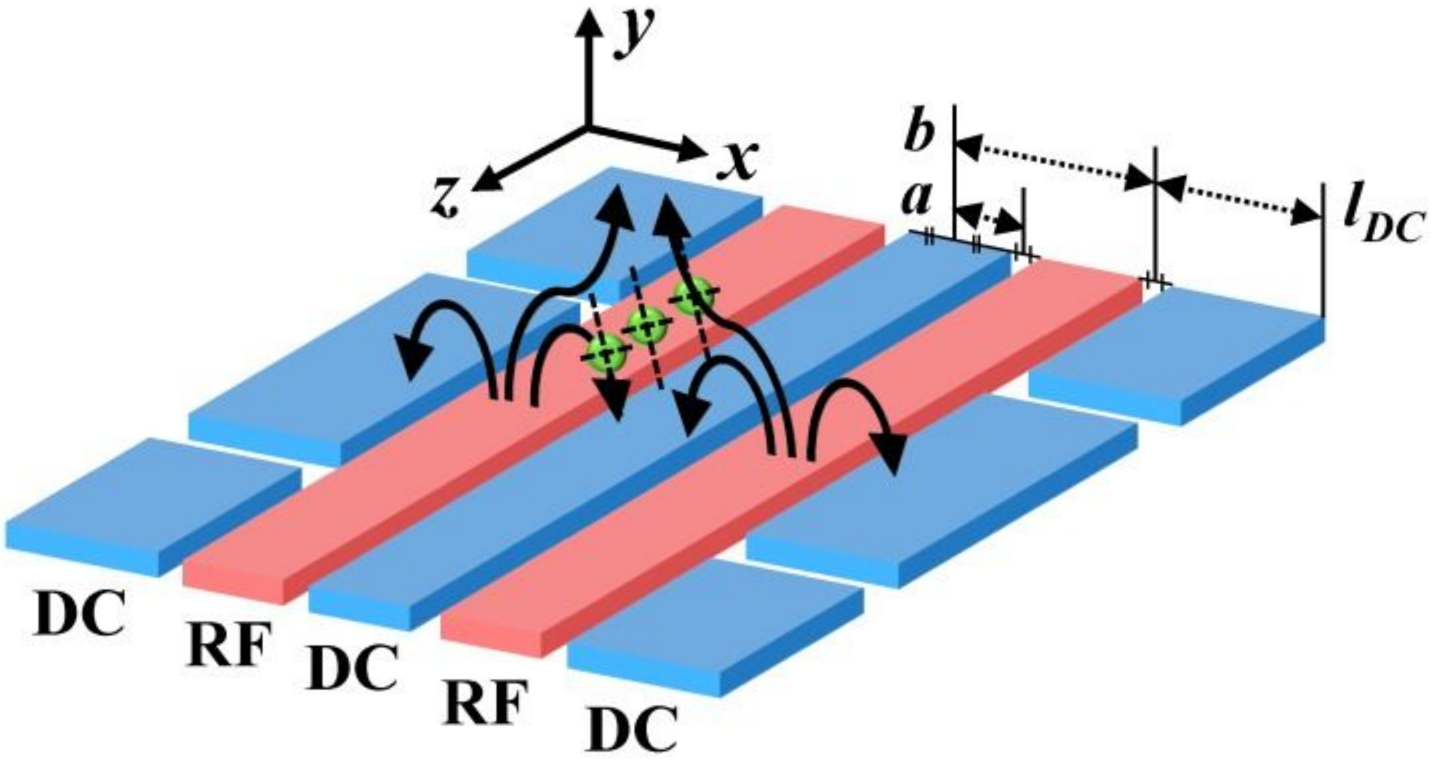




System Design: Electromagnetic fields (cont.)

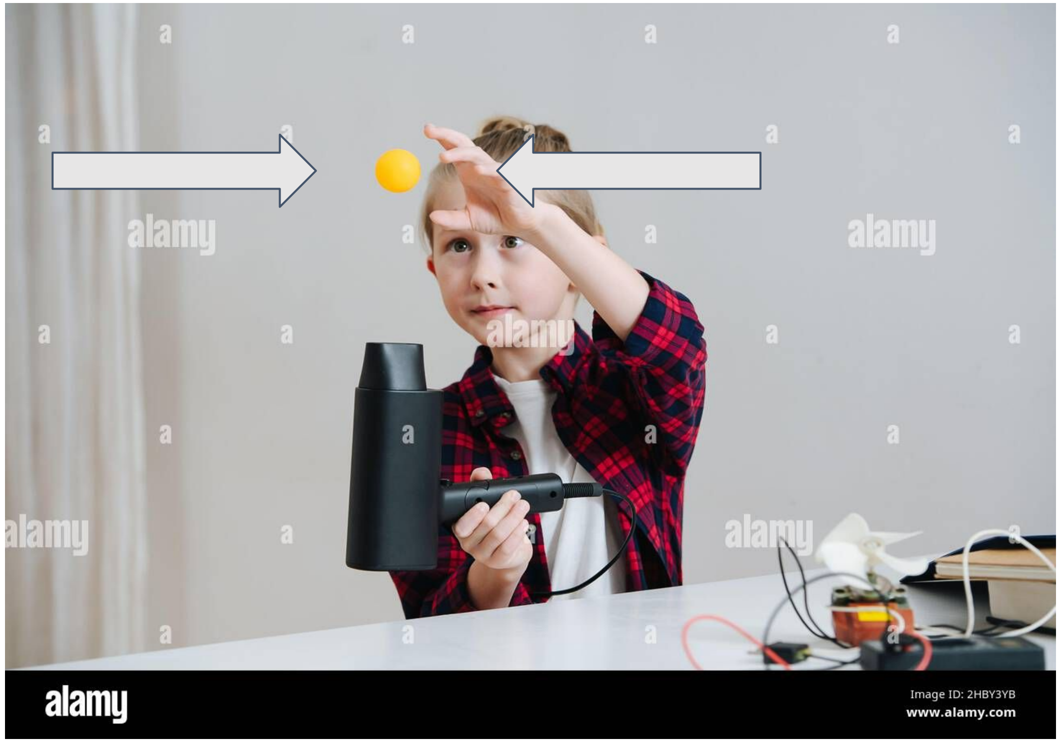


Contour plot of total potential generated by a surface ion trap indicating the RF null point and saddle point

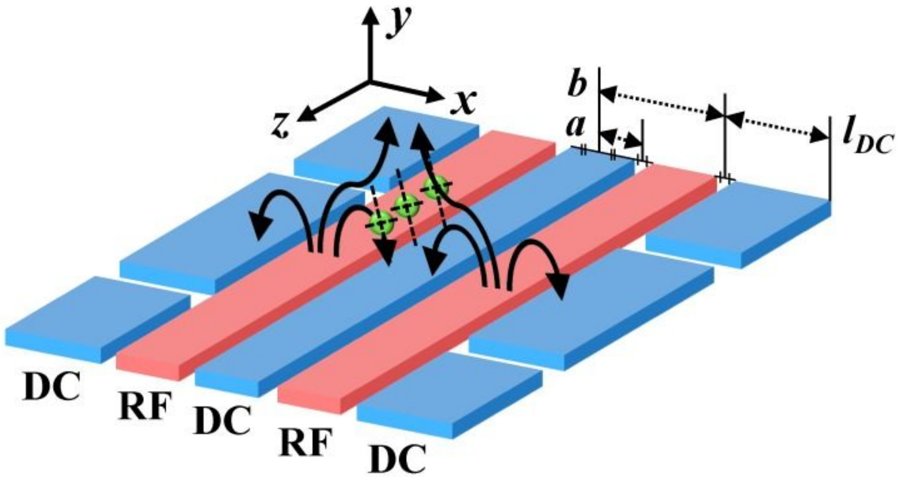


Schematic of a surface ion trap in a symmetric five-rail geometry. The red and blue rectangles indicate the RF and DC electrodes, respectively. The curved arrows denote the direction of the electric field when the RF voltage is positive.

System Design: Electrodes (Single trap)

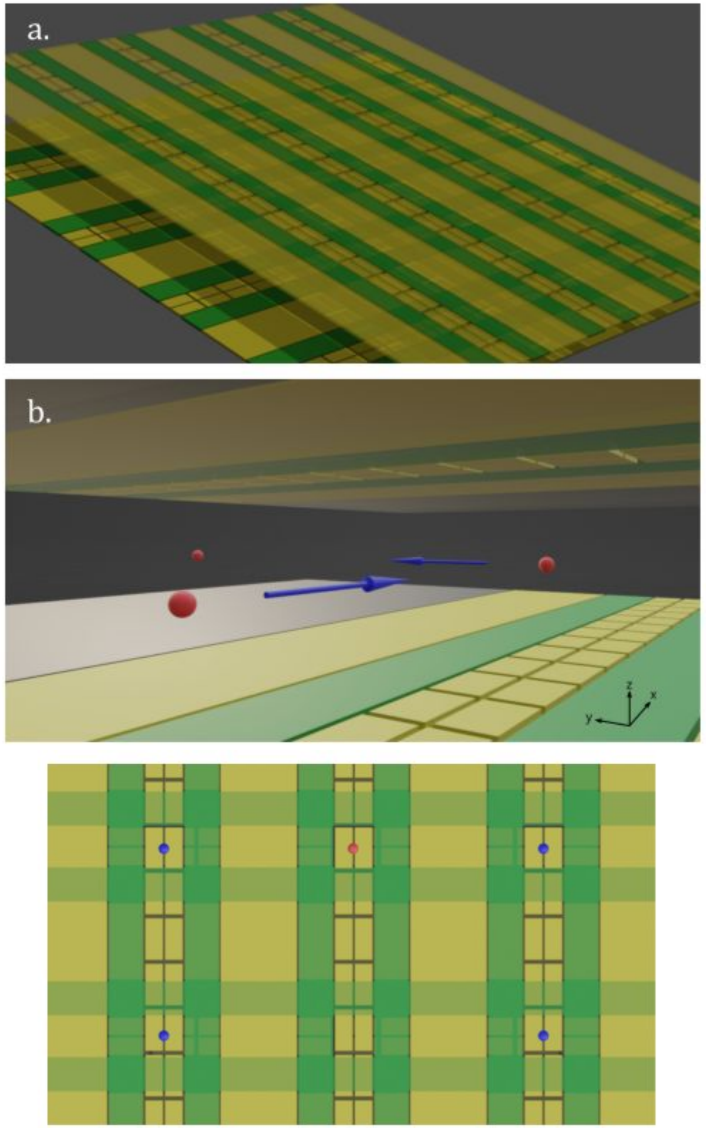


- Hair dryer represents DC electrode, strength of field dictates ion trap height
- Arrows represent time-averaged forces from RF electric field leading to 360° confinement on a horizontal plane
- Due to natural shielding, EM fields used for confinement do not affect the electron configuration of the ion



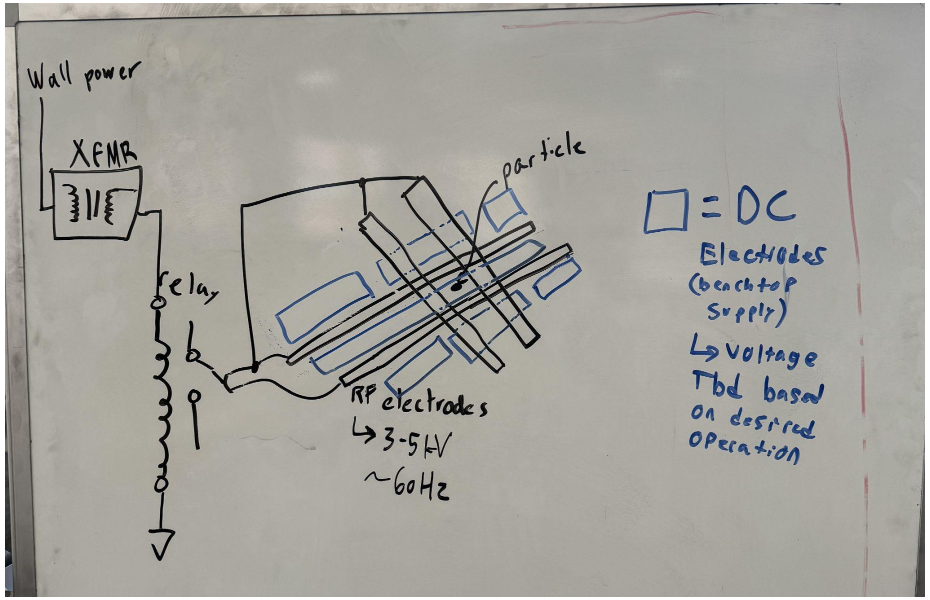
System Design: Electrodes (Dual traps)

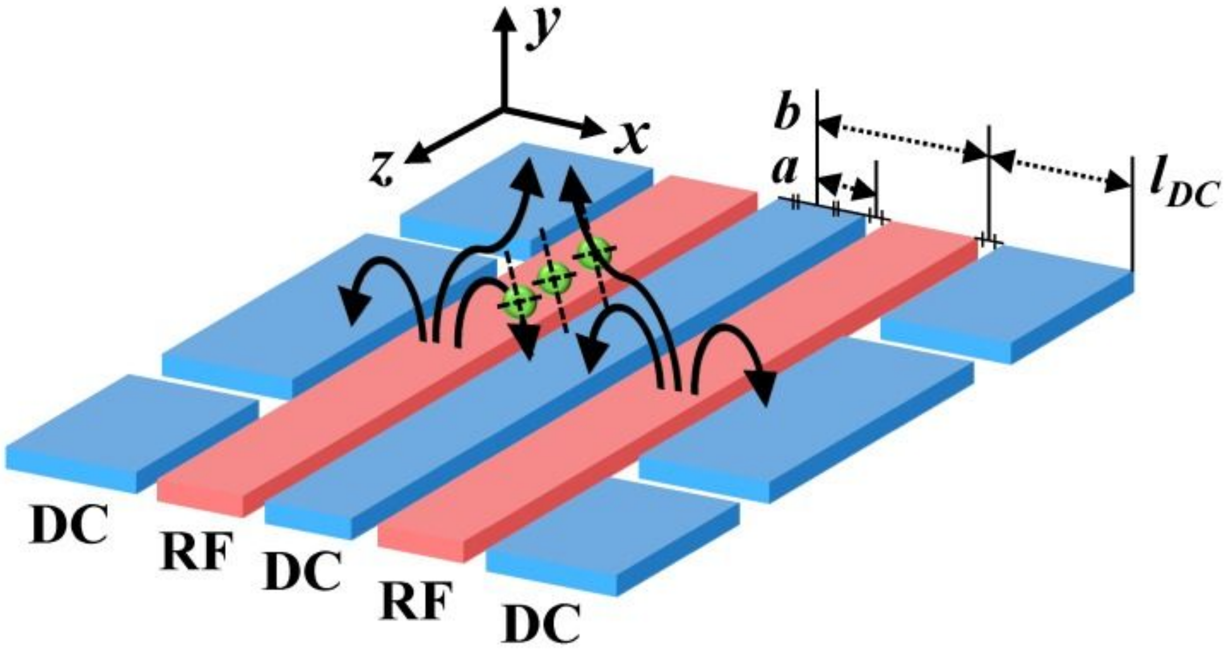
- Grid of traps where ions can exist during measurement or manipulation
- Green represents RF electrodes, gold represents DC control electrodes
- RF electrodes are responsible for ion confinement, control electrodes are used for movement



System Design: Macroscopic model

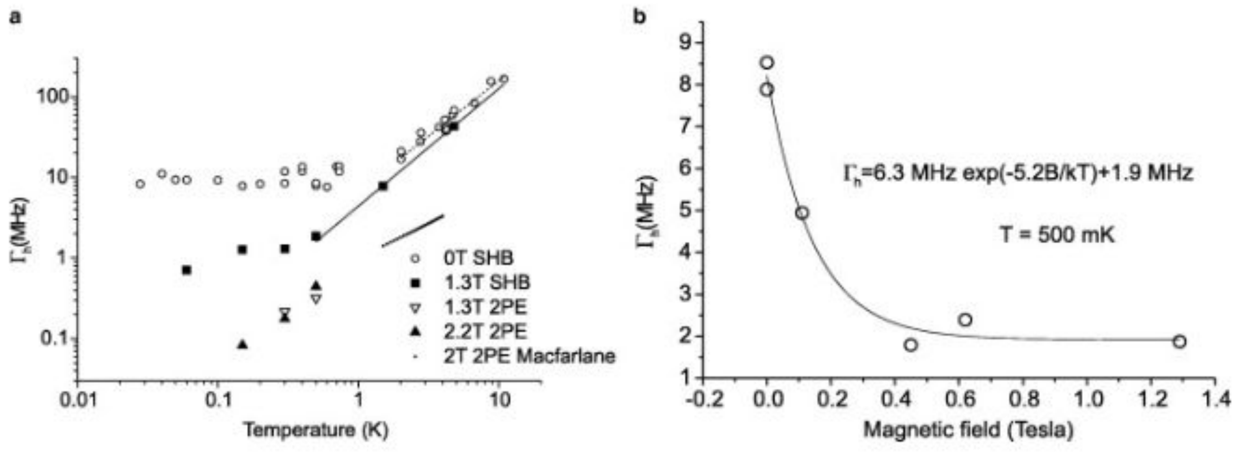
- Charged item such as a small piece of paper or bit of styrofoam to represent the ion
- Step one: Single surface trap
  - RF electrodes: 3kV, 60Hz AC electrodes (in phase)
  - DC electrodes: TBD based on ion representation and outcomes of testing

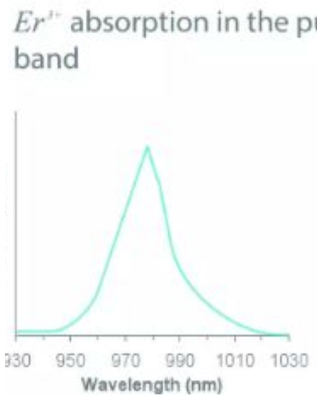


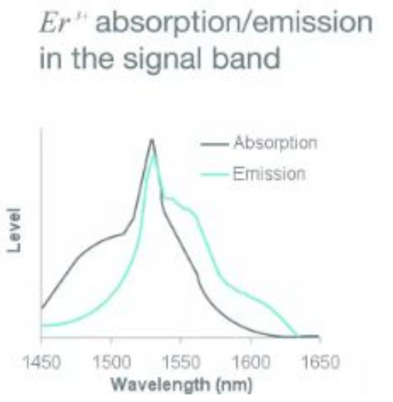


Complexity: Multi-Dimensional Movement

- One major necessity is the traps need for multidimensional movement
- This is made difficult due to the mathematical concepts like Earnshaw's theorem and the nature of Paul Traps.
- There is further complexity in choosing an element that has the properties desired.



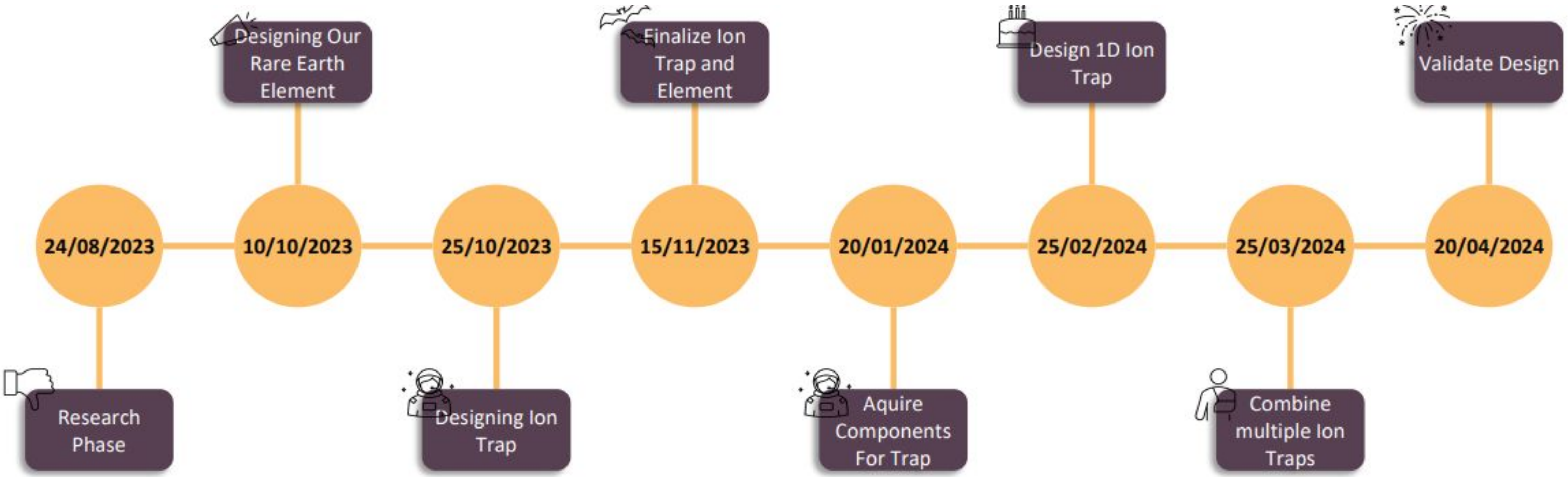




Project Plan

- Risks
  - Trying to combine the two traps might not work as well as we'd hope
    - Interference with each other
    - Unwanted multi-dimensional movement or locking in position of ion
  - Operating with high voltage generator without proper care could be extremely dangerous

Project Milestones



Unit testing

The units to be tested are the two individual traps used in our larger scheme. These individual traps will be tested to ensure that they can

- Trap an Ion
- Allow for at least 1D movement
- Structural stability

Interface/Integration Testing

- Primary Interface
  - Between the two ion traps
  - Ensures multidimensional movement of the trapped ion
  - The suspension must avoid electromagnetic interference
- Secondary Interface
  - Involves secondary electrodes in between the planes for precise movement of the trapped ion
- Integration
  - Most critical integration will be between the two units. These have to work together in order to provide out multidimensional control over the trapped ions

Acceptance Testing

- Client Involvement
  - Client and advisors will be present for development of design and potentially the actual testing
- Demonstration of Method and Criteria
  - Viable manipulation of trapped particles
  - No strict requirements on height or speed
- Overall Goal
  - Establish proof of concept with a video demonstration to showcase functionality

Conclusions

- Up to this point we have all been involved in extensive amounts of research
- For the next semester however, we have planned on us doing the following roles
    - Calvin: Structural lead
    - Andrew: Verification lead
    - Michael: Fabrication lead
    - Ezra: Research lead
- Currently working on acquiring components
- Our plans for next semester mostly include building and testing our proposed design at MRC