Design of Electric-Field Plates for a Rydberg-Atom Experiment

Chen, Yu-Ting[1, 2] (Vuletic group)

[1]Department of Physics, Harvard University

[2]Department of Physics, Massachusetts Institute of Technology

December 4, 2019

I. Introduction

I am currently building a new experimental setup for studying quantum computation with Rydberg atoms. Rydberg atoms are atoms with one electron excited to a highly excited state (ex. N = 80, where N is the principle quantum number). This electron forms a strong dipole moment with the rest of the atom, which carries a positive charge. Therefore, Rydberg atoms can interact with each other with strong dipole interactions. In the field of quantum computation, people can use Rydberg atoms as qubits and operate quantum gates. Furthermore, the dipole interactions between the qubits are useful for generation of interactions between qubits [1].

Due to the strong dipole moments that Rydberg atoms have, they are very sensitive to electric field nearby. Even a tiny amount of electric field can shift the energy levels of the Rydberg atoms. Therefore, it is highly recommended to have electrodes near the atoms to compensate the stray electric field.

In this report, I discuss about the design of the electric-field plates that are used in our experiment. I'll first discuss about the design in Section II. The simulation and the results are shown in Section III. Some discussions are in Section IV.

II. Design idea of the electric-field plates

When designing the electric-field plates, the first thing is to decide how many field-plates are needed to fully control electric fields and gradients around the atoms. To control electric fields Ex, Ey, and Ez, three degrees of freedom are needed. To control the gradients of the electric field, nine degrees of freedom are needed for ∂Ei/∂Ej, where i, j = x, y, z. From the argument above, it seems like 3 + 9 = 12 degrees of freedom would be needed. However, one actually doesn't need to control so many degrees of freedom! It is because the electric fields and gradients are not independent variables. Maxwell's equation tells us that the gradient and the curl of electric field follow the Gauss' law and the Faraday's law. These two Maxwell equations eliminate 1 (Gauss' law) + 3 (Faraday's law) = 4 degrees of freedom. Therefore, in the end we only need to control 12 – 4 = 8 degrees of freedom.

How many field plates are needed to control 8 degrees of freedom? Naively, one might think 8 is the answer. However, after thinking about it more carefully, it becomes clear that 8 is not enough. In the experiment, what people can control is the voltage of those field plates. The voltage difference between two field plates defines an electric field between them. One can also think it as one of the field plate is used as a “reference” and the other is used to control the amount of electric field. Therefore, in order to fully control 8 degrees of freedom, 9 field plates are actually needed, because one of them acts as a “reference”.

The design of the electric-field plates follows the paper by Leow et al [2]. As shown in Figure 1 and 2, four arcs are placed above the atoms and four arcs below the atoms. A metallic base plate acts as another field plates.

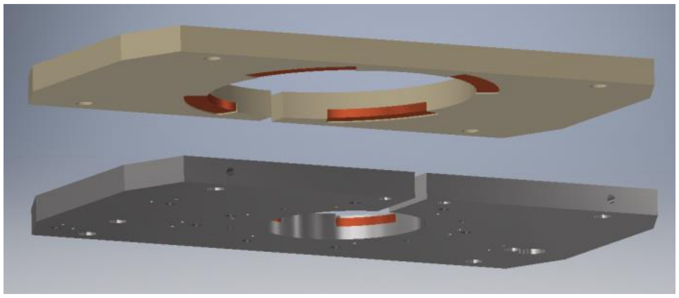

Figure 1. Side view of the experimental setup. Atoms are placed in between two plates. The material of the top plate is plastic (PEEK). The material of the bottom plate is 316 stainless steel. The eight arc field-plates are made from copper.

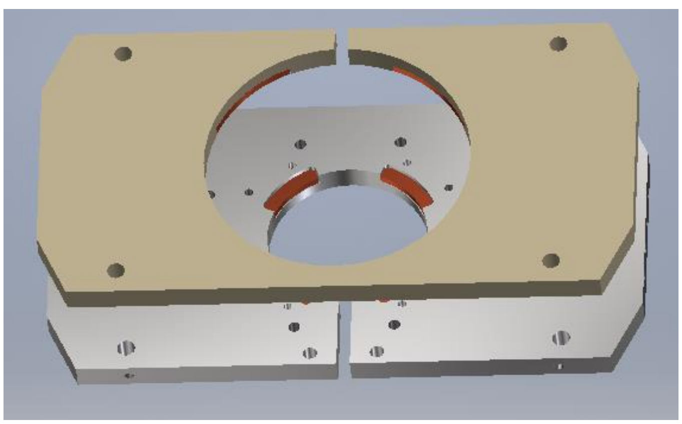

Figure 2. Top view of the experimental setup.

IV. Simulation method and results

The simulation is done by EMWorks EM Simulation software [3]. The detailed procedures are the following:

1. Draw the object in SolidWorks
2. Create an air region around the object. In my simulation, I draw a large cylinder around the object as “air”.
   (Insert → Component → New Part → draw the air region)
3. Subtract the object from the air (Click “Edit Part”, Insert → Molds → Cavity → choose the parts to be excluded, Click "Edit component" after editing)
4. Name the air region as "air" and make it transparent (Right click and click on the change transparency icon)
5. Create the electric field study
6. Choose the object and air material
   (select the component under the Material folder and select Apply Materials)
7. Enter simulation conditions
   (For example, use load constraints to enter fixed voltage)
8. Right click on Study and Run
9. The simulation results are in the "Results" folder

Try different air geometries to get a reasonable result (the edge of the air should have vanishing field). Also try different mesh settings.

An example of the simulation settings:

Boundary conditions

- Metallic base plates: 0 V
- 4 bottom arc field-plates (at -z): 0 V
- 4 top arc field-plates (at +z): 10 V

The result is shown in Figure 3. It shows that the Z electric field is -0.2 V/cm at the atoms. With the similar method, I simulated the electric field along all three directions.

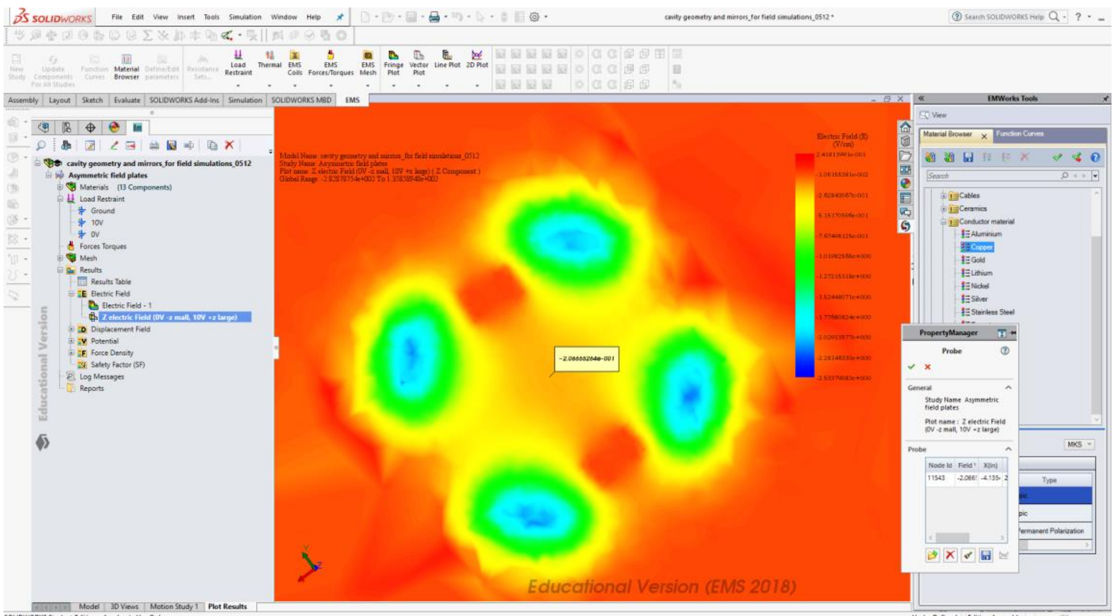

Figure 3. An example of the simulation result.

VI. Discussion

With the EMWorks simulation, I've designed the electric-field plate for the Rydberg atom experiment. The field-plates are able to generate hundreds of millivolts per centimeter under normal experimental conditions.

In the designing process, I found two things about the software that isn't that straightforward. At some point, I was curious about the electric-field gradient that can be generated by those field-plates. I was hoping to plot electric gradient along a pre-defined axis. However, it seems like the software doesn't have this function. In the end, I was still able to get an estimate of the gradient by calculating the electric field along nearby points. Another thing is about mesh settings. I haven't fully understood how to set the mesh size correctly to avoid errors but also give accurate results.

Overall, EMWorks is a very useful tool because it is nicely integrated into SolidWorks, which is the software many people use for designing experimental setups. They offer free educational version and their engineering department is helpful answering questions as well. I had good experience using it.

VII. References

[1] M. Saffman, T. G. Walker, and K. Mølmer, Quantum information with Rydberg atoms, Rev. Mod. Phys. 82, 2313 – Published 18 August 2010

[2] Robert Löw, Hendrik Weimer, Johannes Nipper, Jonathan B Balewski, Björn Butscher, Hans Peter Büchler, and Tilman Pfau, An experimental and theoretical guide to strongly interacting Rydberg gases, Journal of Physics B, Published 22 May 2012

[3] https://www.emworks.com