Magnetic Mirror Effect in Magnetron Plasma: Modeling of Plasma Parameters

Controlling Plasma stream with Helmholtz coils

We now perform two studies with our setup.
Simulation data

- 100 particles of Hydrogen ions (relative atomic mass: 1.008 g mol^{-1}).
- Duration of 1 step of update: 0.001 ms
- Number of steps: 3 x 100 = 300
- Total duration of simulation = 0.3 ms

1 Study 2: Familiar distributions

For this study we use the following data:
Sampling of the Initial Positions and Velocities of the particles

- Speeds are sampled from a Maxwellian distribution with plasma temperature 10000 K.
- Velocity directions are sampled from uniform distribution.
- Positions are sampled such that all particles start at [-0.5, 0, 0] (A box 1m x 1m x 1m from [-0.5, -0.5, -0.5] to [0.5, 0.5, 0.5] maybe considered for reference)

We use the standard Maxwellian distribution for the initial speeds of the particles and have all particles start at the same position.

1.1 Magnetic field along a fixed axis, with constant current

For the first part of this study, we use the following field configurations.
Configurations of the Electric and Magnetic Fields

- Magnetic field due to a Helmholtz coil (number of turns: 1000 in each coil, radius: 0.1 m): for 100 steps each
  first 20A current, orientation along the z-axis [0,0,1]
  second -20A current, orientation along the z-axis [0,0,1]
  third 20A current, orientation along the z-axis [0,0,1].
- Electric field constantly set to 0.

We see that we always use the coil oriented in the z-direction and we change the direction of the current while keeping the amplitude at a constant value of 20 A. We get the following results. First we plot the positions and components of positions of a particle in the simulation.

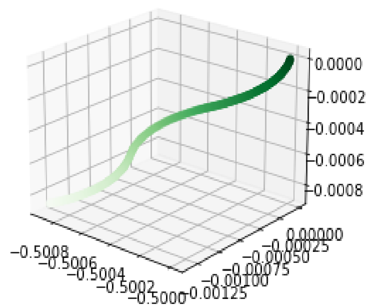

Figure 1: position

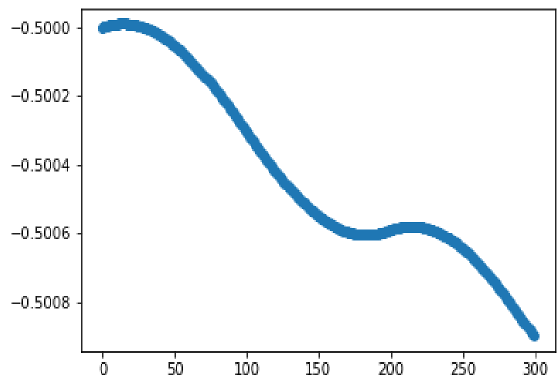

Figure 2: x-component of position

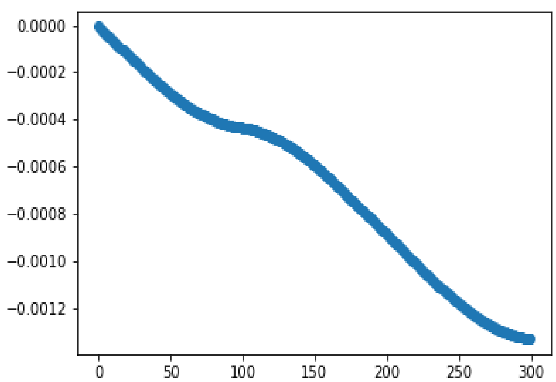

Figure 3: y-component of position

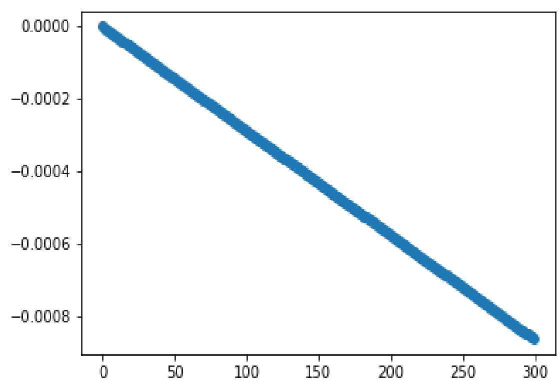

Figure 4: z-component of position

We see in figure (1), that the trajectory has three regions of curves which correspond to the three epochs of the positive, negative and then positive sign of the magnetic field. We see the same pattern of three curves in figures (2) and (3) and they appear to be out of phase with respect to one another. Things become more clear when we look at the velocities, as the change in the velocities caused by acceleration due to the fields (only the magnetic field is non zero in our case) is more intuitive. So now let's plot the velocities and components of velocities of the same particle.

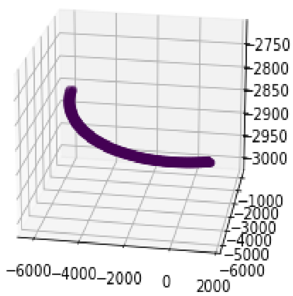

Figure 5: velocity

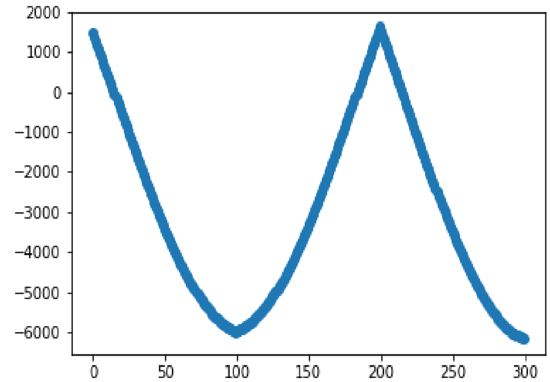

Figure 6: x-component of velocity

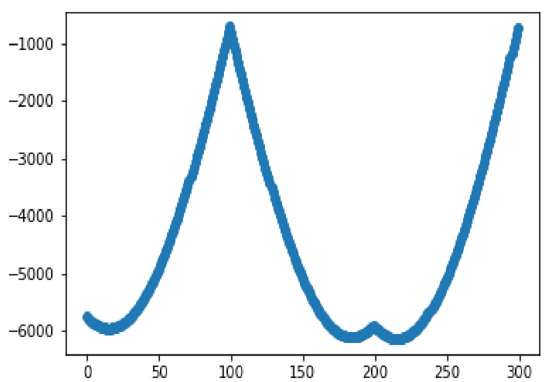

Figure 7: y-component of velocity

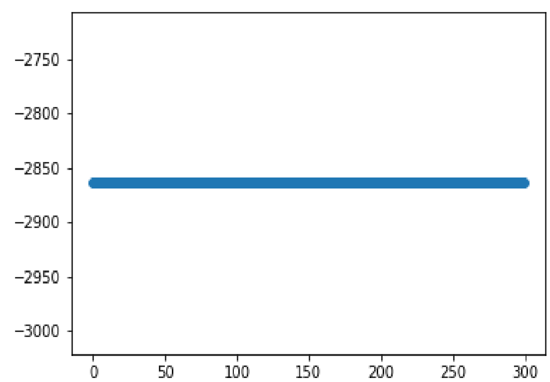

Figure 8: z-component of velocity

We see in figure (8) that the z-component of the velocity remains constant, as the acceleration along the z-axis is zero since the magnetic field is along the z-axis and the $\mathbf{B} \times \boldsymbol{v}$ acceleration caused by the magnetic field is perpendicular to the direction of the magnetic field. The acceleration is nonzero only in the x-y plane. In figures (6) and (7) we see two events of non-smooth change in the velocity components at 100^{th} and 200^{th} update steps which correspond to the change in the sign of the current supplied to the coil, hence the direction of the magnetic field and therefore the direction of the acceleration. Otherwise we see the harmonic oscillation velocity profile in each epoch, which would describe such a situation. We now plot the positions and the components of positions for 10 particles in the simulation.

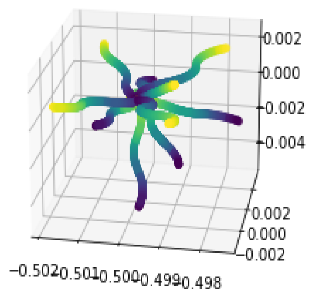

Figure 9: positions

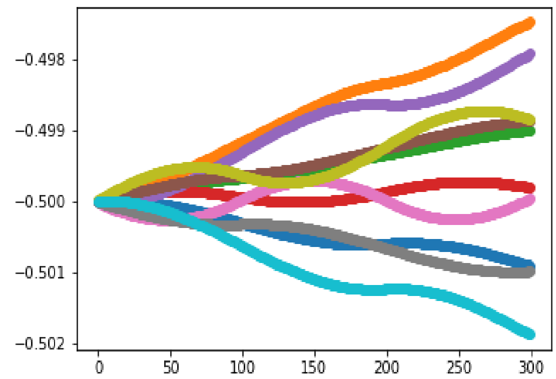

Figure 10: x-component of positions

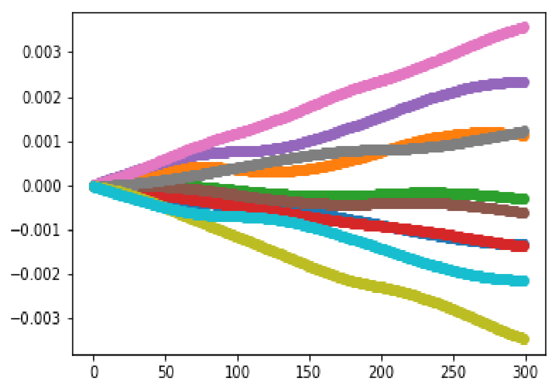

Figure 11: y-component of positions

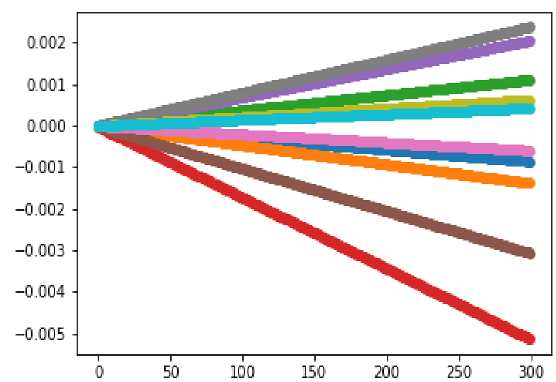

Figure 12: z-component of positions

Like with the single particle, we see the trajectories curve three times in figure (9), and figures (10) and (11). We also plot the velocities and the components of velocities for the same 10 particles.

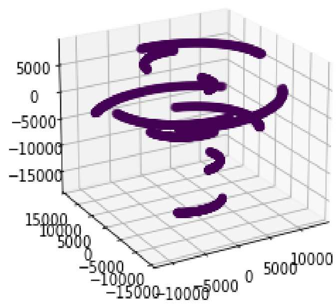

Figure 13: velocities

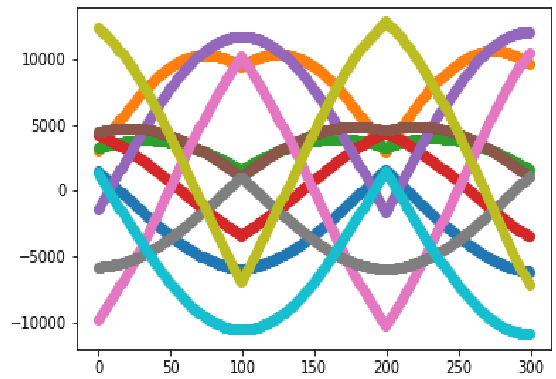

Figure 14: x-component of velocities

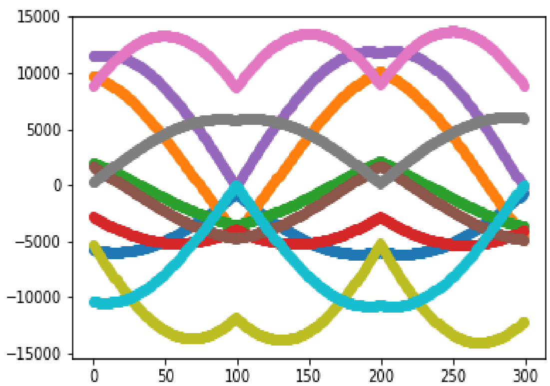

Figure 15: y-component of velocities

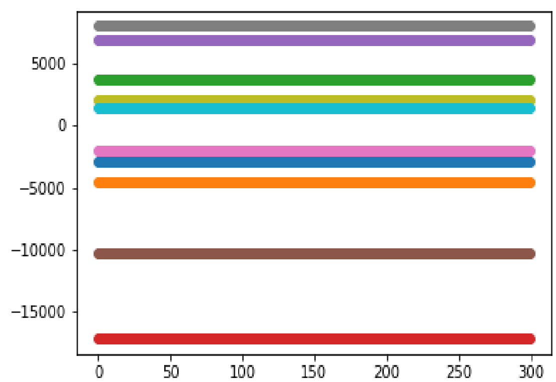

Figure 16: z-component of velocities

Like with the single particle we see in figure (16) that the z-components of the velocities remain constant and in figures (14) and (15) that the x and y components of the velocities change non-smoothly in the 100^{th} and the 200^{th} iterations while they follow harmonic oscillations in each epoch of unchanging magnetic fields.

1.2 Magnetic field with changing current and orientation

For the second part of the study, we use a slightly different magnetic field configuration. We change the axis of the coil and also the current.

Configurations of the Electric and Magnetic Fields

- Magnetic field due to a Helmholtz coil (number of turns: 1000 in each coil, radius: 0.1 m): for 100 steps each
  first 100A current, orientation along the z-axis [0,0,1]

second -20A current, orientation along the x-axis [1,0,0]
third 50A current, orientation along the y-axis [0,1,0].

- Electric field constantly set to 0.

We first plot the positions and the components of positions for a particle in the simulation.

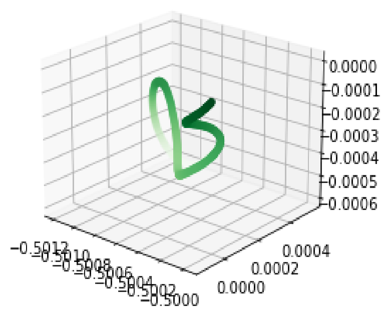

Figure 17: position

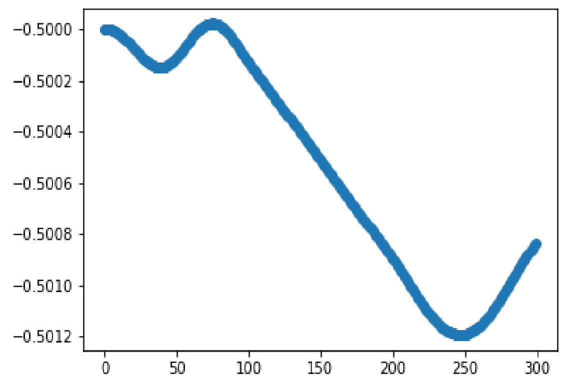

Figure 18: x-component of position

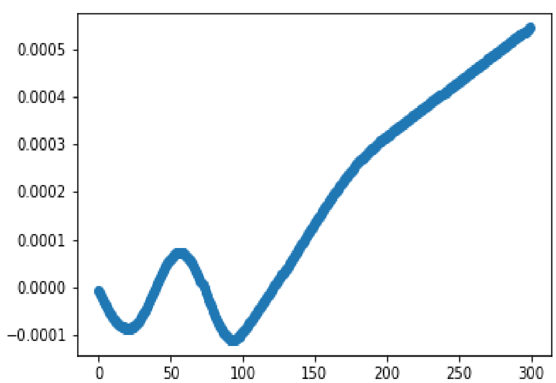

Figure 19: y-component of position

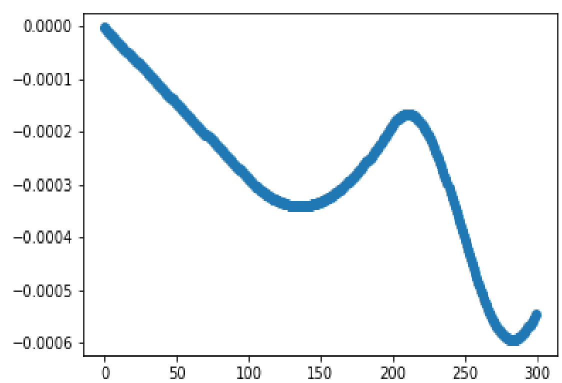

Figure 20: z-component of position

Because we change the direction of the magnetic field from along the z-axis to along the x-axis and then along the y-axis, in figures (18), (19) and (20), we see two epoch of curves and one epoch of straight line. In figure (17) we see one loop about the y quite clearly while the other two curves are less clear to understand. Let's plot the velocities and the components of velocities for the same particle to see if we can understand better.

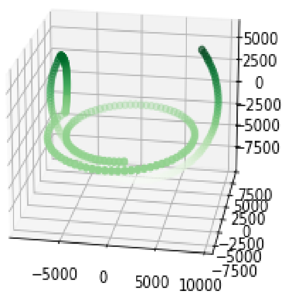

Figure 21: velocity

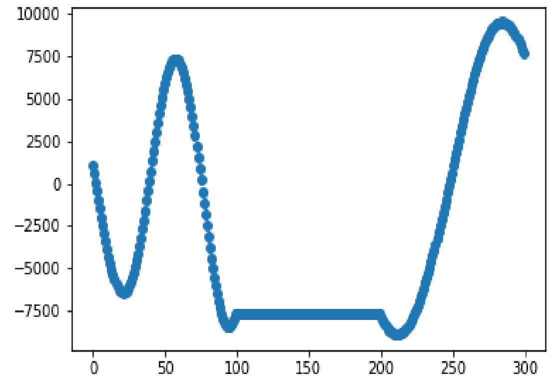

Figure 22: x-component of velocity

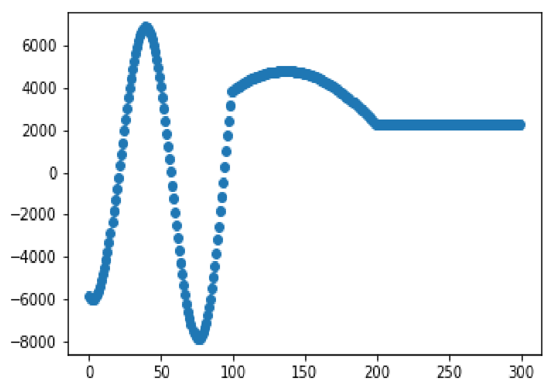

Figure 23: y-component of velocity

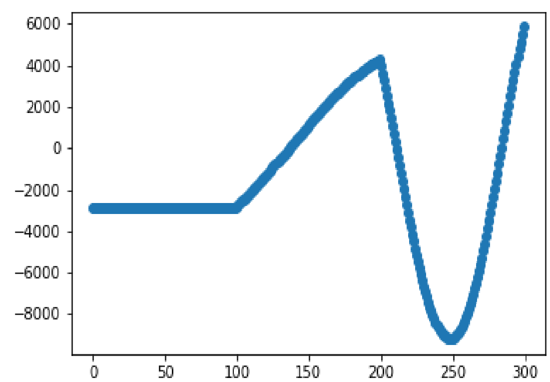

Figure 24: z-component of velocity

We see two epochs of curved lines and one epoch of constant components of velocity in figures (22), (23) and (24). The corresponding component of the velocity stays constant when the direction of the magnetic field is along that axis, otherwise the sharpness of the curves depends on the current applied in the coil. In figure (21) we can see three loops about the three axes, which correspond to harmonic motion in the plane perpendicular to the magnetic field in each epoch. We now plot the positions and the components of positions for 10 particles in the simulation.

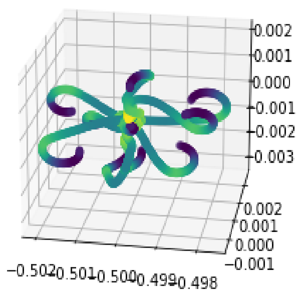

Figure 25: positions

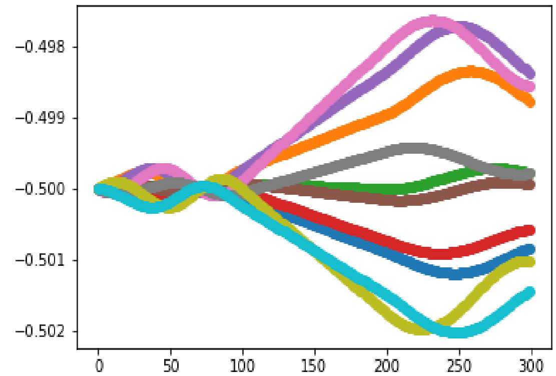

Figure 26: x-component of positions

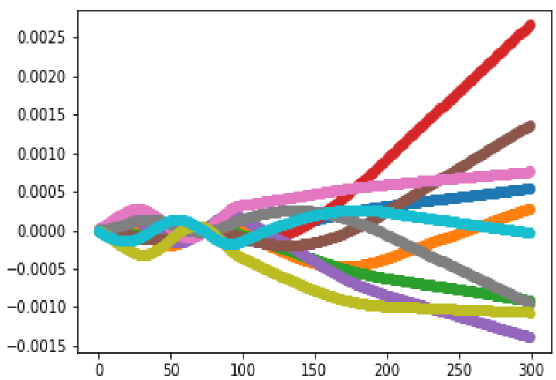

Figure 27: y-component of positions

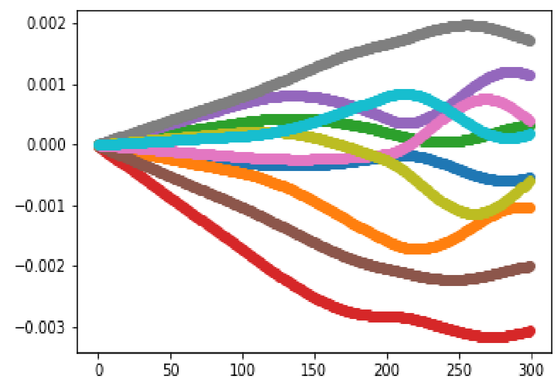

Figure 28: z-component of positions

Like with the single particle, we see two epochs of curves and one epoch of straight line in figures (26), (27) and (28), and in figure (25) we see one of the arcs (in what looks like the arms of and octopus) quite clearly for some of the particles. We also plot the velocities and the components of velocities for the same 10 particles.

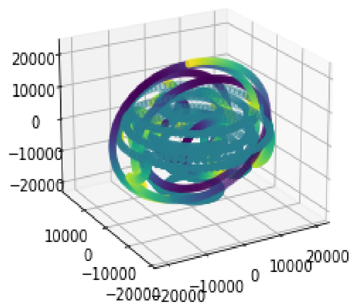

Figure 29: velocities

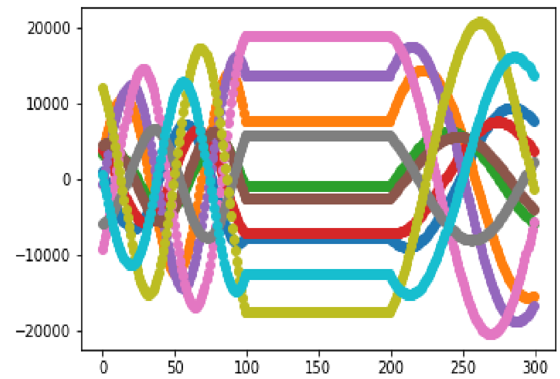

Figure 30: x-component of velocities

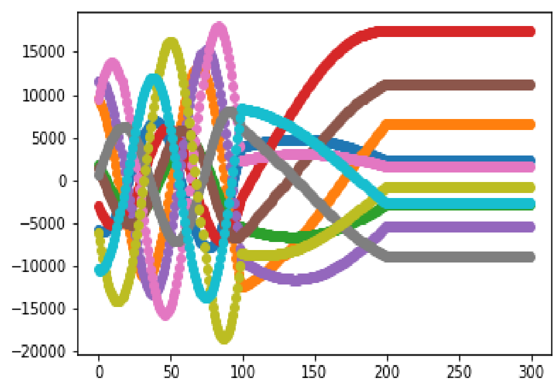

Figure 31: y-component of velocities

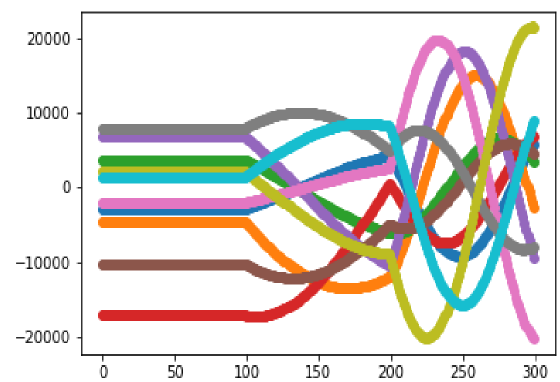

Figure 32: z-component of velocities

Although figure (29) is quite messy, we can notice loop-like circular trajectories. In figures (30), (31) and (32) we see two epochs of harmonic motion and one epoch of constant component of velocity when the magnetic field is along the corresponding axis, like with the single particle plots.

2 Study 3: Different distributions

For this study we use the following data:
Sampling of the Initial Positions and Velocities of the particles

- Speeds are sampled from a parabolic distribution with an equivalent temperature of 10000 K for a Maxwellian distribution.

- Velocity directions are sampled from uniform distribution.

- Positions are sampled such that all particles start at 0.5 m distance from the center [0, 0, 0] (Particles injected or reflected from the walls of the chamber may be considered for reference).
- Positions are based on uniform distribution sampling of the position vector.

The mean speed of a Maxwellian distribution is given by

$$\langle v \rangle = \sqrt{\frac{8RT}{\pi M}} = \sqrt{\frac{8 \cdot 8.31446261815324 \text{ J K}^{-1} \text{ mol}^{-1} \cdot 10000 \text{ K}}{\pi \cdot 1.008 \times 10^{-3} \text{g mol}^{-1}}} = 14492.952993825971 \text{ m s}^{-1}$$

and the root mean speed is given by $v_{rms} = \sqrt{\frac{3RT}{M}}$. We get that the variance $\sigma^2 = \langle v^2 \rangle - \langle v \rangle^2$ giving the standard deviation

$$\sigma = \sqrt{\frac{RT}{M}} \sqrt{3 - \frac{8}{\pi^2}} = \sqrt{\frac{8.31446261815324 \text{ J K}^{-1} \text{ mol}^{-1} \cdot 10000 \text{ K}}{1.008 \times 10^{-3} \text{g mol}^{-1}}} \cdot \sqrt{3 - \frac{8}{\pi^2}} = 13438.549997326772 \text{m s}^{-1}$$

The speeds for the parabolic distribution were sampled using the rdist distribution of the scipy library [2] with parameters c = 2 (which makes the distribution parabolic), loc = 14492.952993825971, scale = 30049.5113130523 which produces samples from the distribution with mean 14492.952993825971 m s^{-1} and standard deviation 13438.549997326772 m s^{-1}. The value for the scale was obtained by iterating until the value close to the required was produced until the maximum precision used by the library.

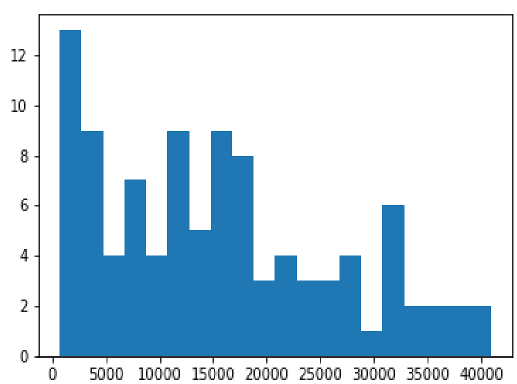

Figure 33: Parabolic speeds of study 3

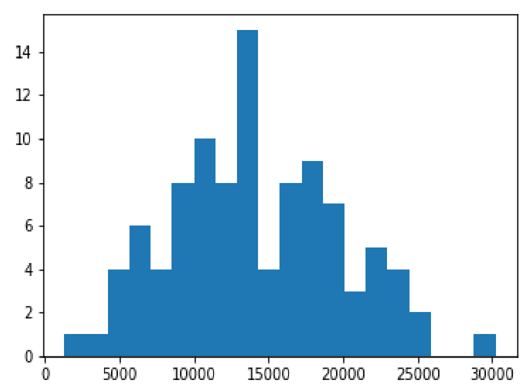

Figure 34: Maxwellian speeds of study 2

On the right in figure (34) we see the histogram of Maxwellian sampled speeds from study 2. On the left in figure (33) we see the histogram of speeds sampled from a Parabolic distribution. Both distributions have the same mean and standard deviation. One can observe that a parabolic distribution approximates the half of the Maxwellian distribution, which is why it is interesting to us. It would also be interesting to have a double parabolic distribution that would approximate the entire Maxwellian distribution.

2.1 Magnetic field along a fixed axis, with constant current

For the first part of this study, we use the same field configurations as in the first part of study 2.

Configurations of the Electric and Magnetic Fields

- Magnetic field due to a Helmholtz coil (number of turns: 1000 in each coil, radius: 0.1 m): for 100 steps each
  first 20A current, orientation along the z-axis [0,0,1]
  second -20A current, orientation along the z-axis [0,0,1]
  third 20A current, orientation along the z-axis [0,0,1].
- Electric field constantly set to 0.

We plot the positions and the components of positions for a particle in the plasma.

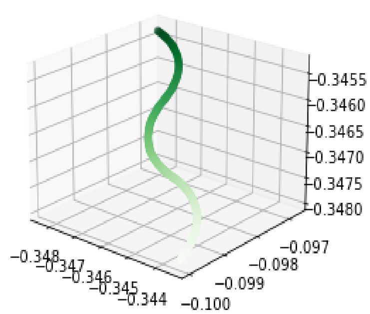

Figure 35: position

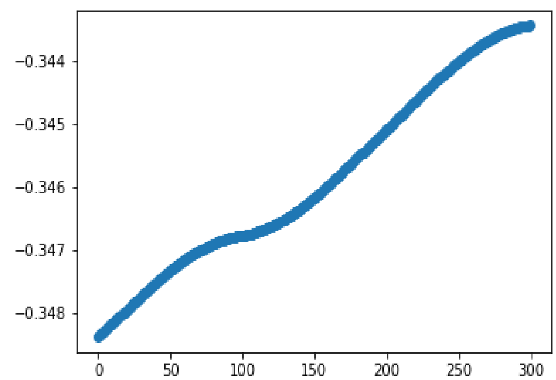

Figure 36: x-component of position

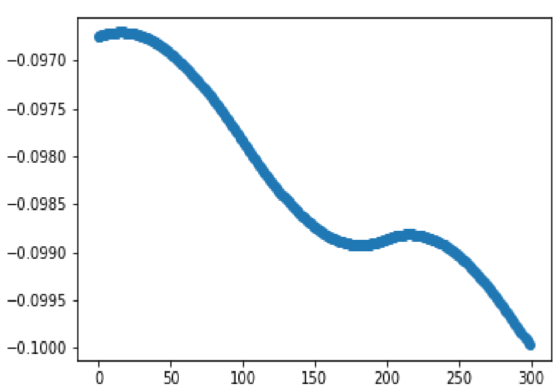

Figure 37: y-component of position

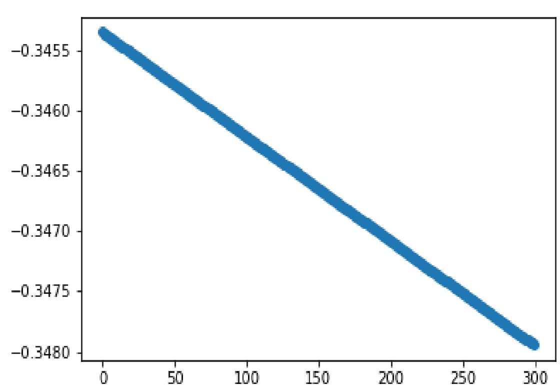

Figure 38: z-component of position

We also plot the velocities and the components of velocities of the same particle.

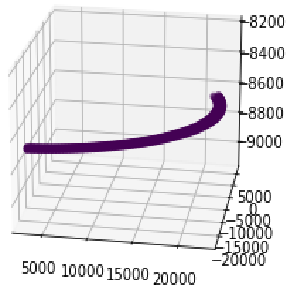

Figure 39: velocity

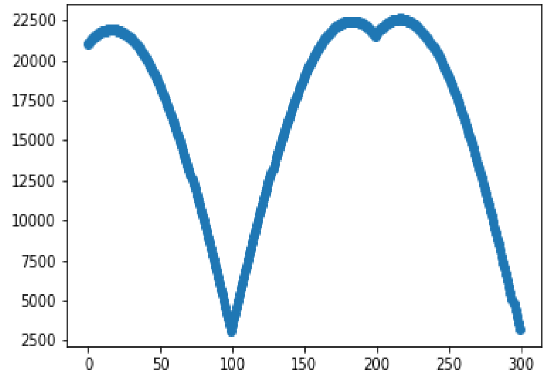

Figure 40: x-component of velocity

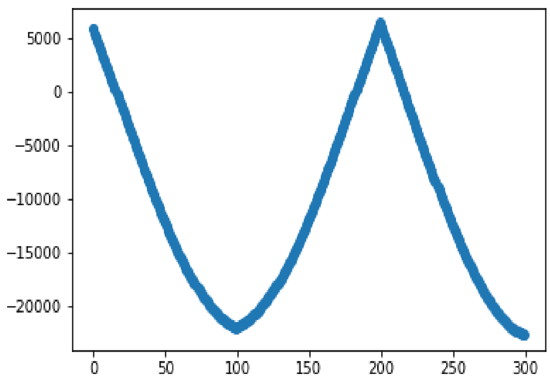

Figure 41: y-component of velocity

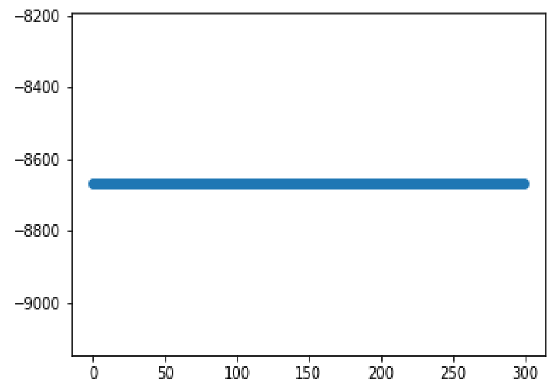

Figure 42: z-component of velocity

We see a similar behavior to the first part of study 2, because the setup of the fields are the same in this case. We also plot the positions and the components of positions for 10 particles in the plasma. Due to a bug in the program that we were unable to debug, we could not make plots for the 10 particles in the same figure, so we made them instead in different subplots. It is not the same as plotting them in the same figure, but we can also get a pretty good idea from plotting them in different subplots.

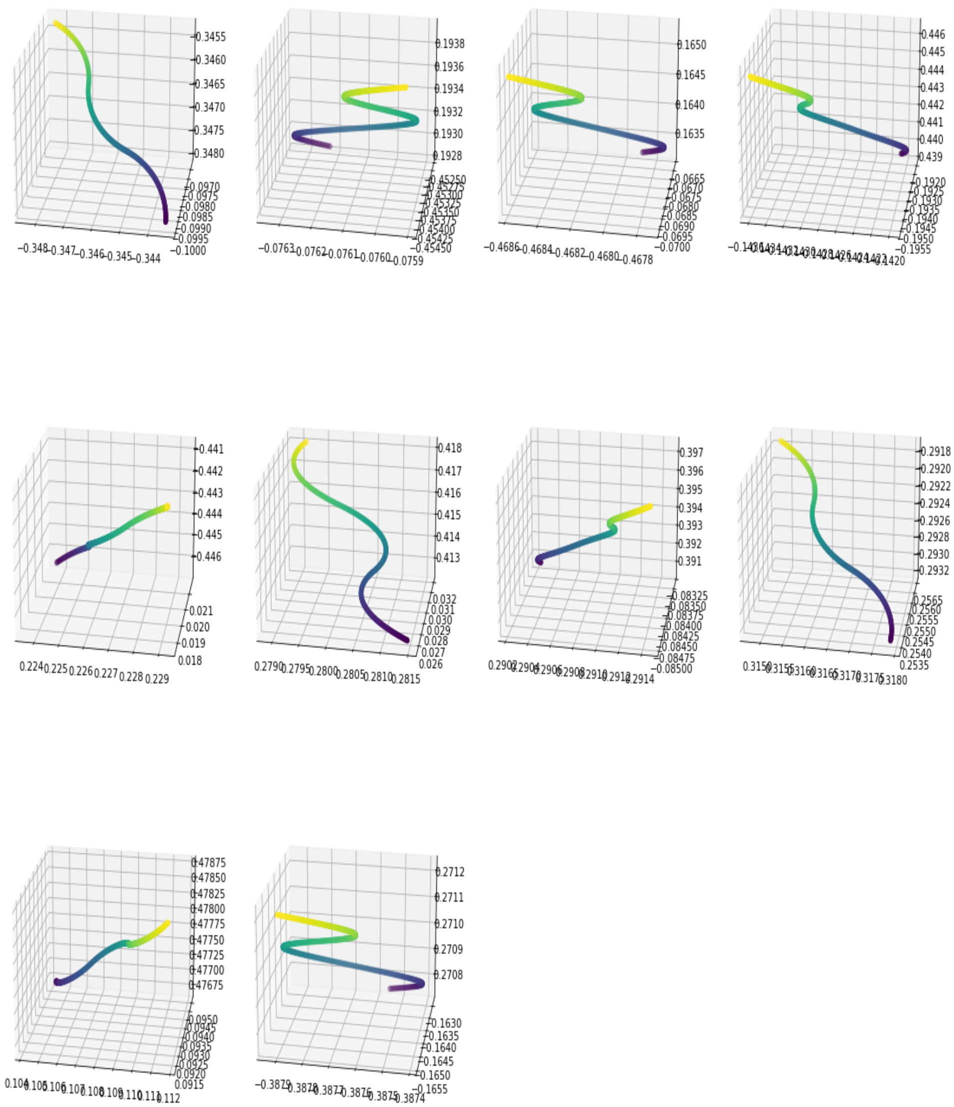

Figure 43: positions

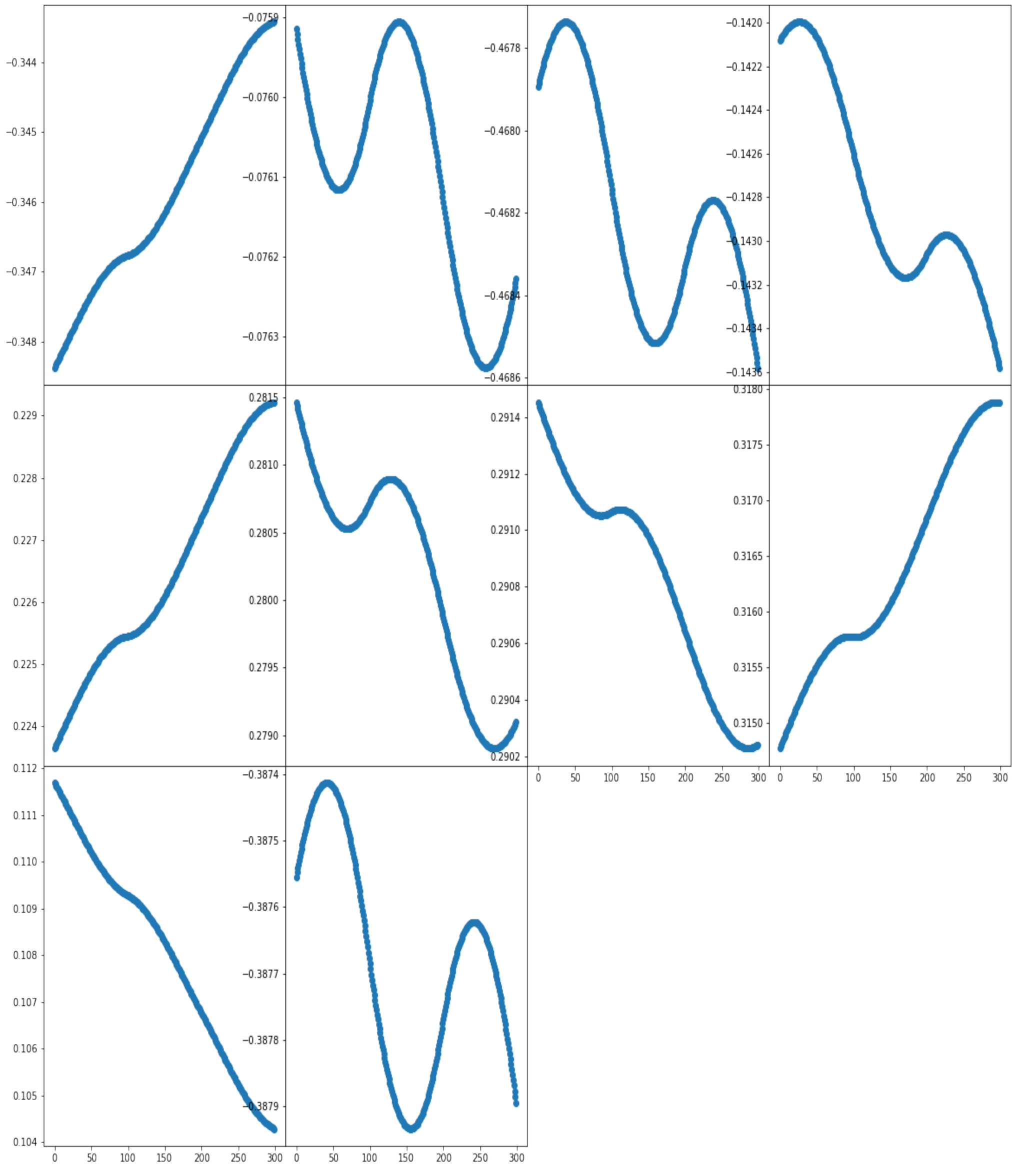

Figure 44: x-components of positions

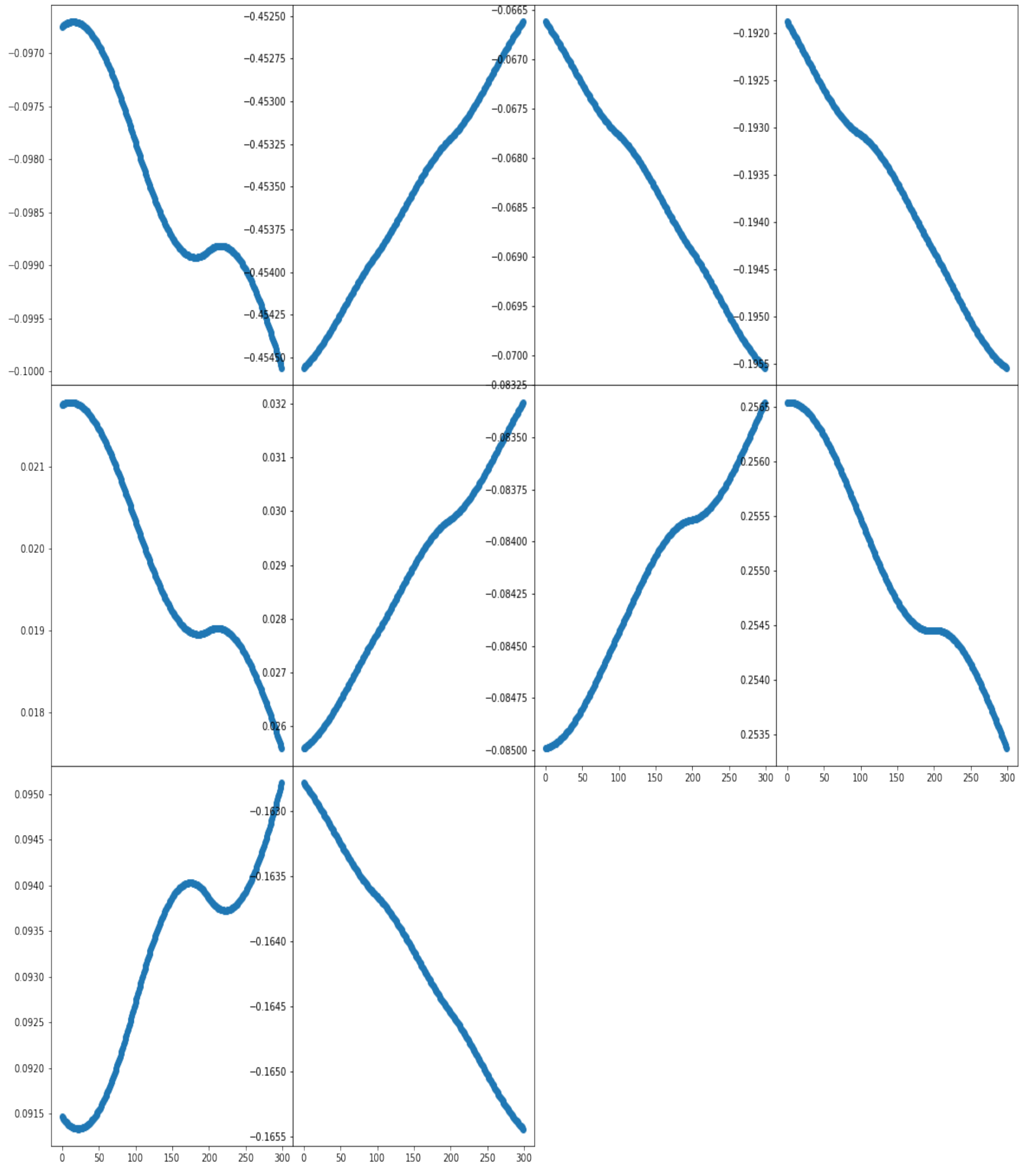

Figure 45: y-components of positions

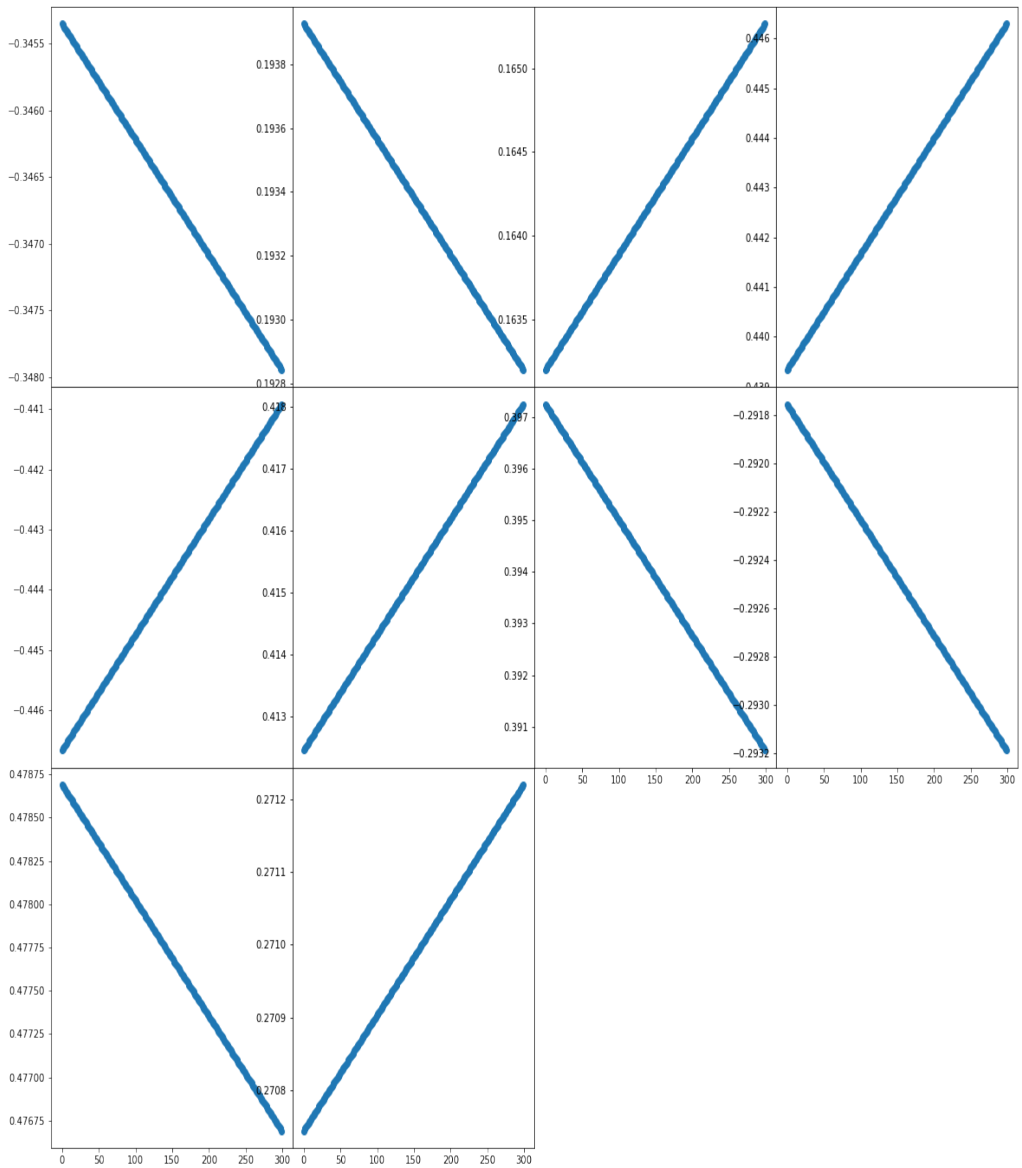

Figure 46: z-components of positions

We then plot the velocities and the components of velocities for the same 10 particles.

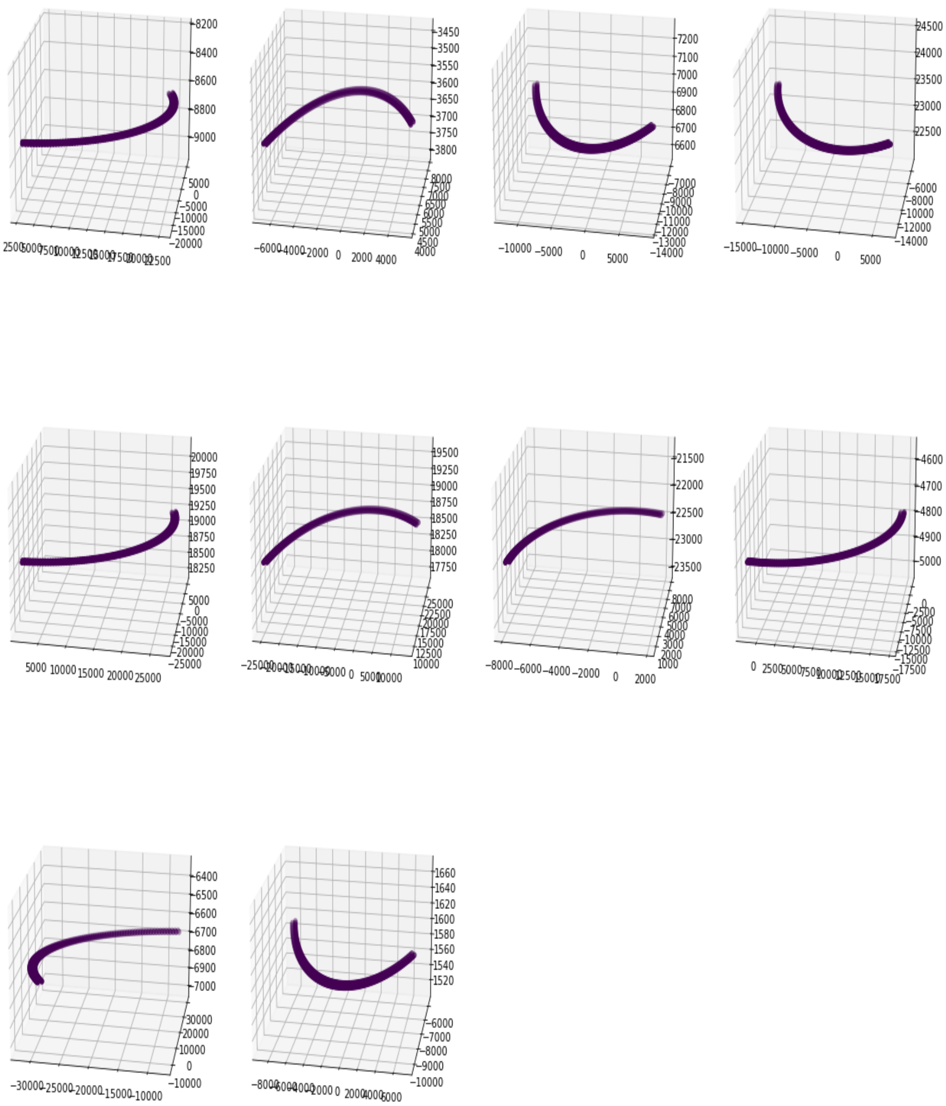

Figure 47: velocities

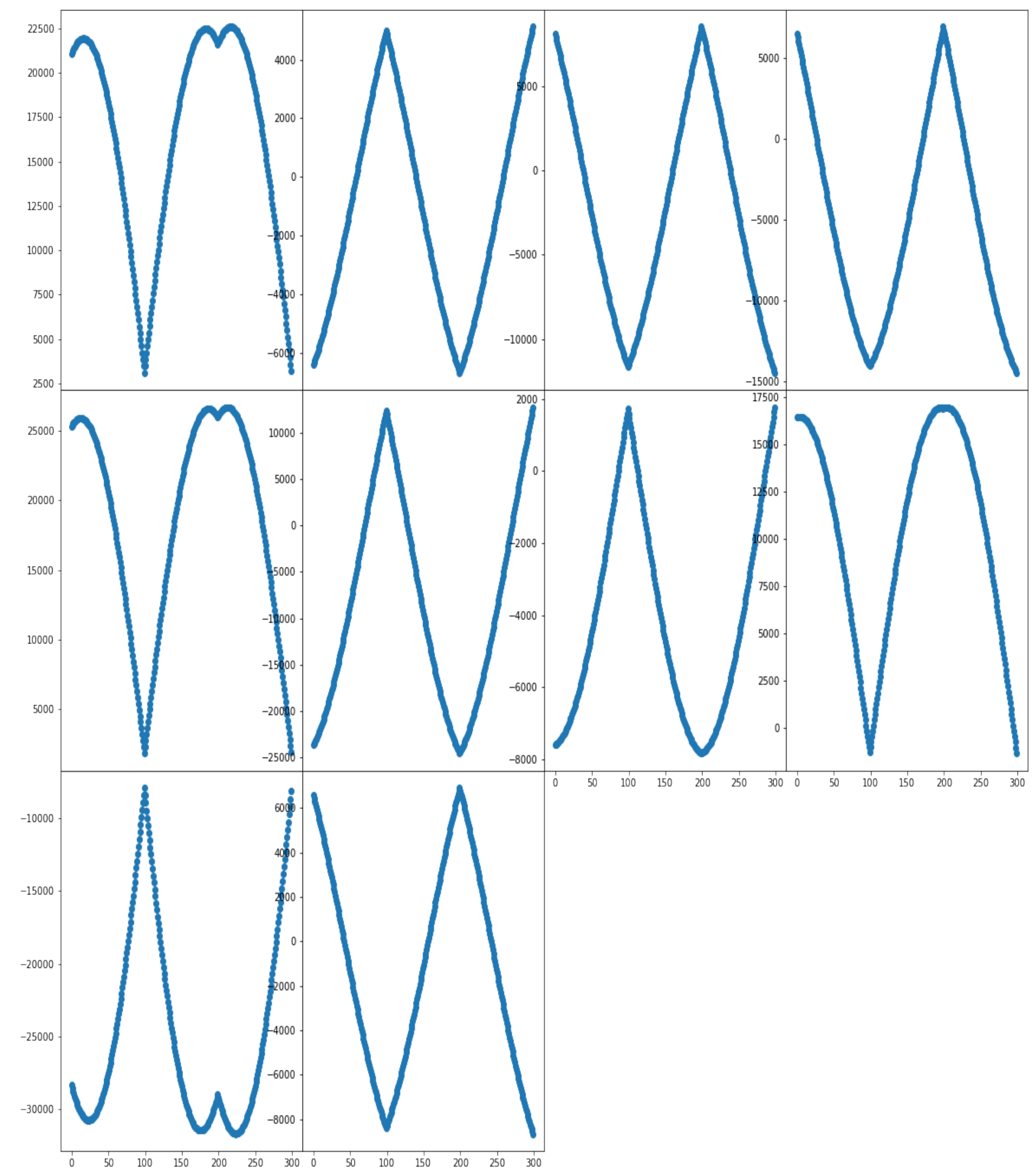

Figure 48: x-components of velocities

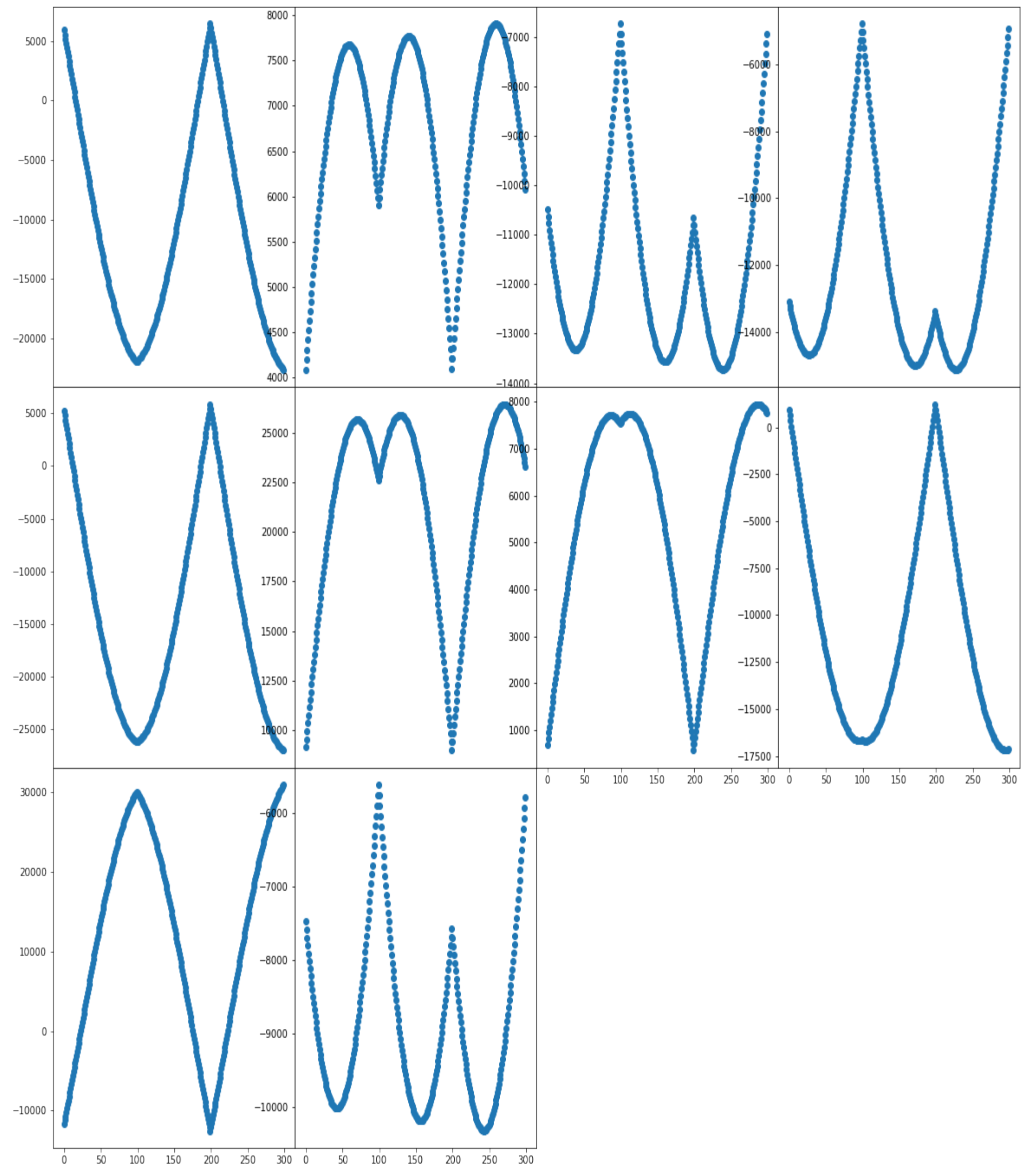

Figure 49: y-components of velocities

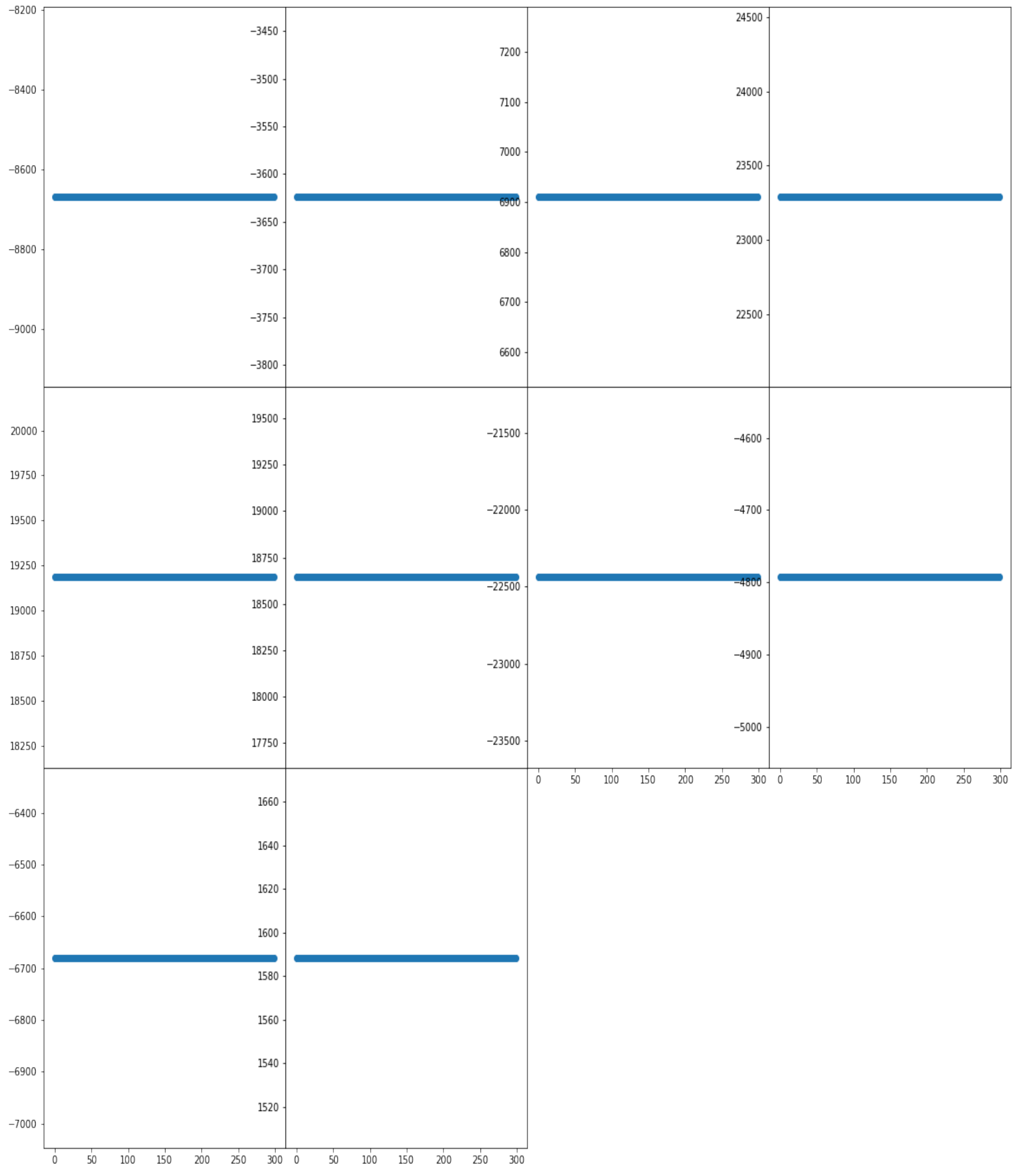

Figure 50: z-components of velocities

As with the single particle, we see a similar behavior to the first part of study 2, because the setup of the fields are the same in this case. However, the particles don't all start in the same position. It is a bit more difficult to understand that the initial distribution of positions and velocities is different in this case, especially being unable to plot all the particles in the same figure.

2.2 Magnetic field with changing current and orientation

For the second part of the study, we use the same field configurations as in the second part of study 2.

Configurations of the Electric and Magnetic Fields

- Magnetic field due to a Helmholtz coil (number of turns: 1000 in each coil, radius: 0.1 m): for 100 steps each
  first 100A current, orientation along the z-axis [0,0,1]
  second -20A current, orientation along the x-axis [1,0,0]
  third 50A current, orientation along the y-axis [0,1,0].

- Electric field constantly set to 0.

We first plot the positions and the components of positions for a particle in the simulation.

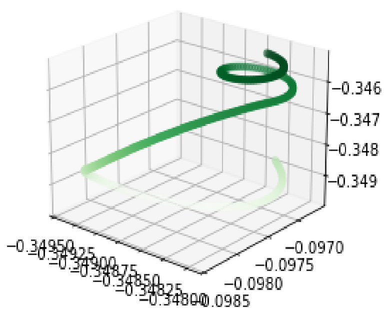

Figure 51: position

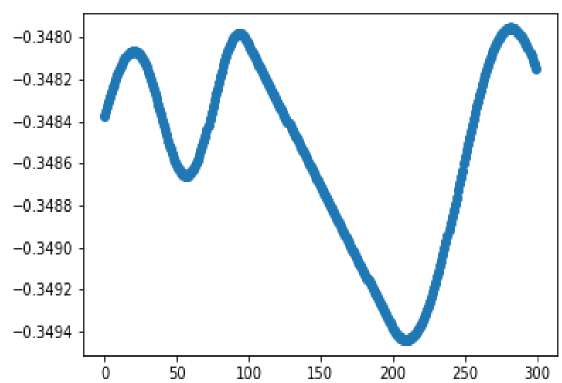

Figure 52: x-component of position

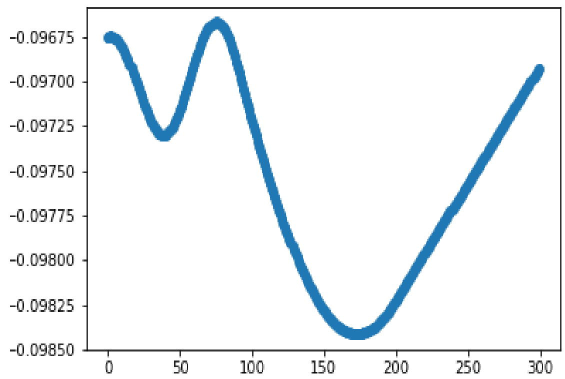

Figure 53: y-component of position

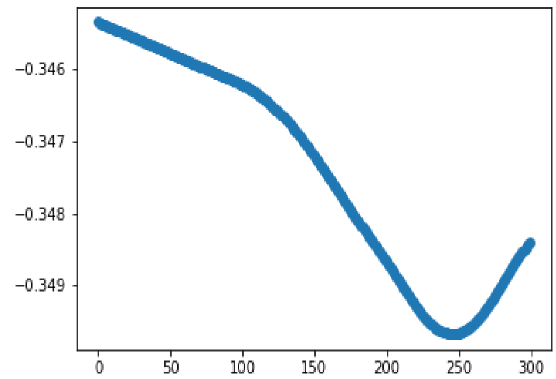

Figure 54: z-component of position

We then plot the velocities and the components of velocities for the same particle.

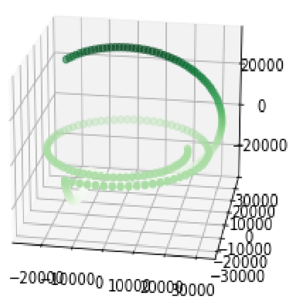

Figure 55: velocity

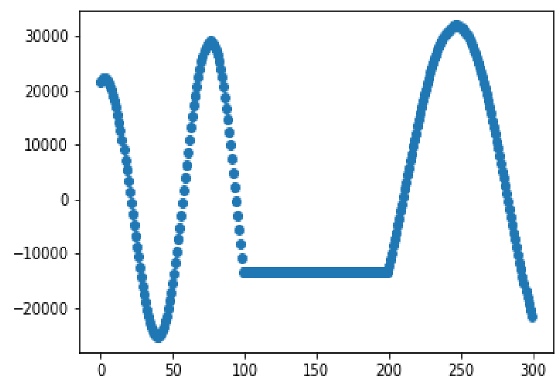

Figure 56: x-component of velocity

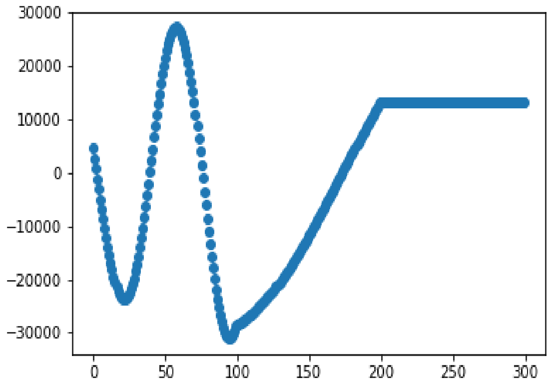

Figure 57: y-component of velocity

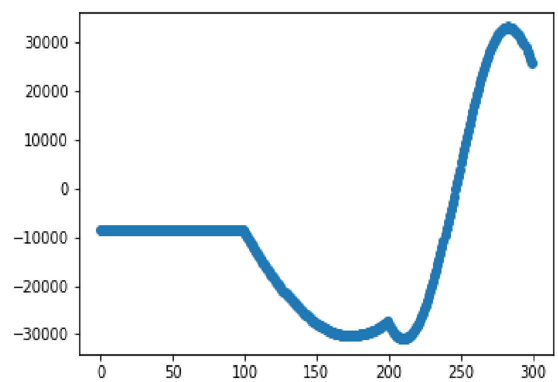

Figure 58: z-component of velocity

Like with the first part of study3, we see that the evolution of the particle resembles that in study 2 (the second part in this case) since the field setup is the same. We also plot the positions and the components of positions for 10 particles in the simulation. Like with the first part of study 3, we were unable to make plots for 10 particles in the same figure and had to use subplots.

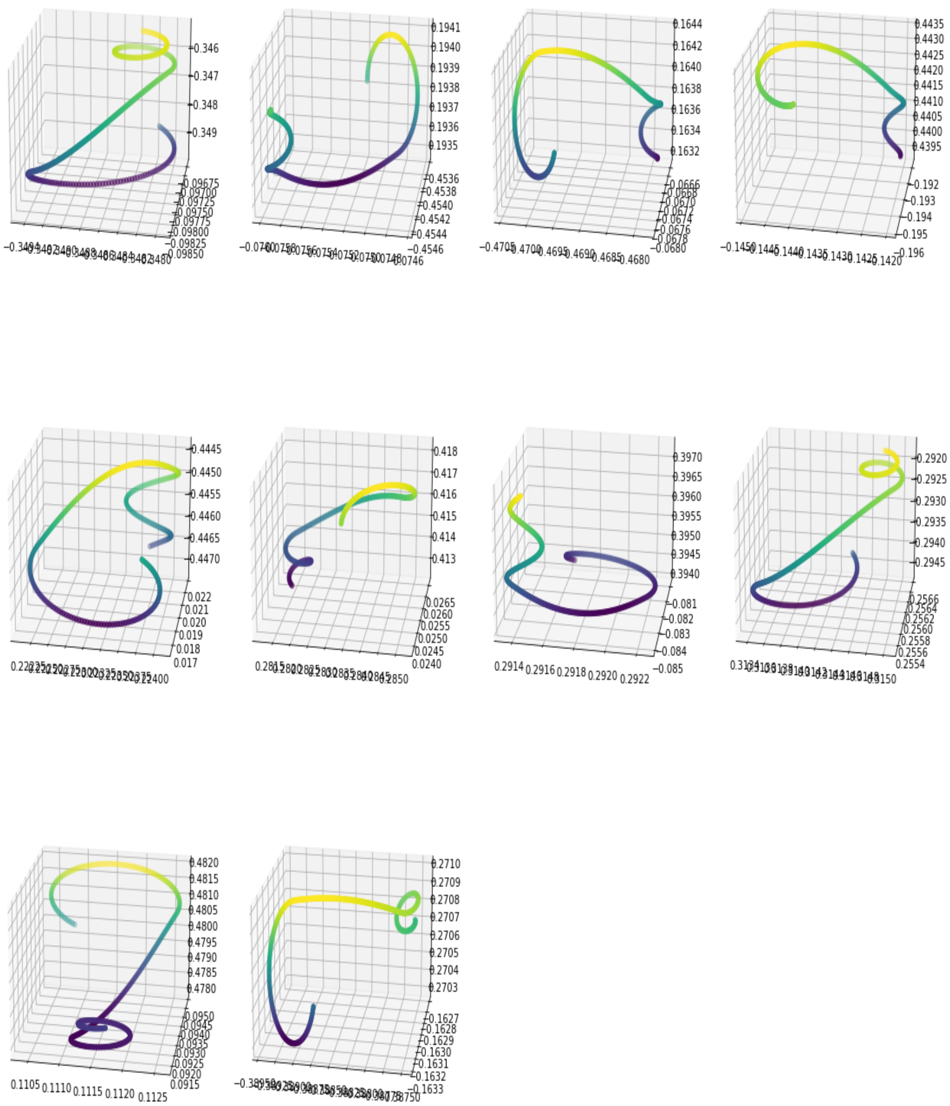

Figure 59: positions

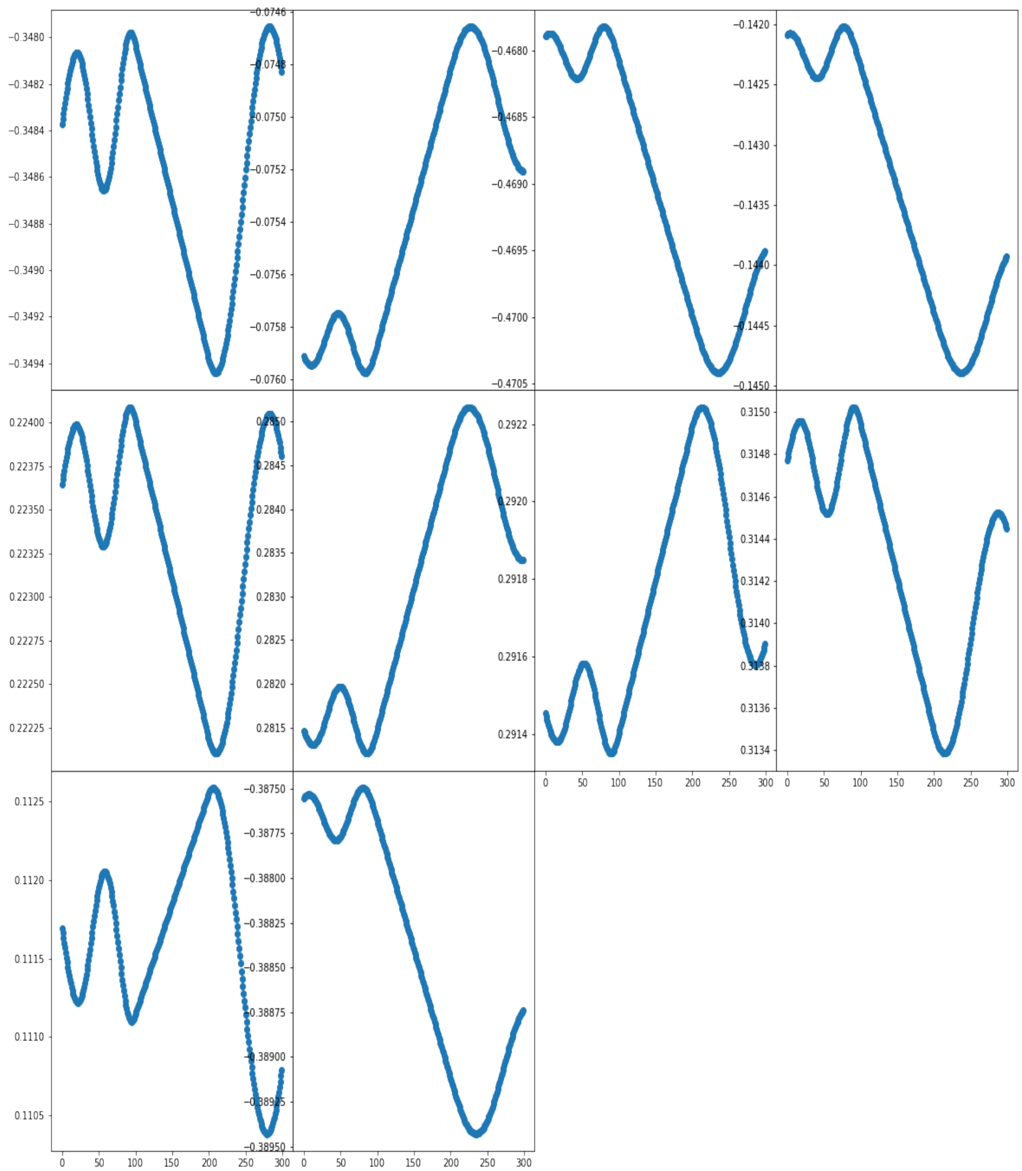

Figure 60: x-components of positions

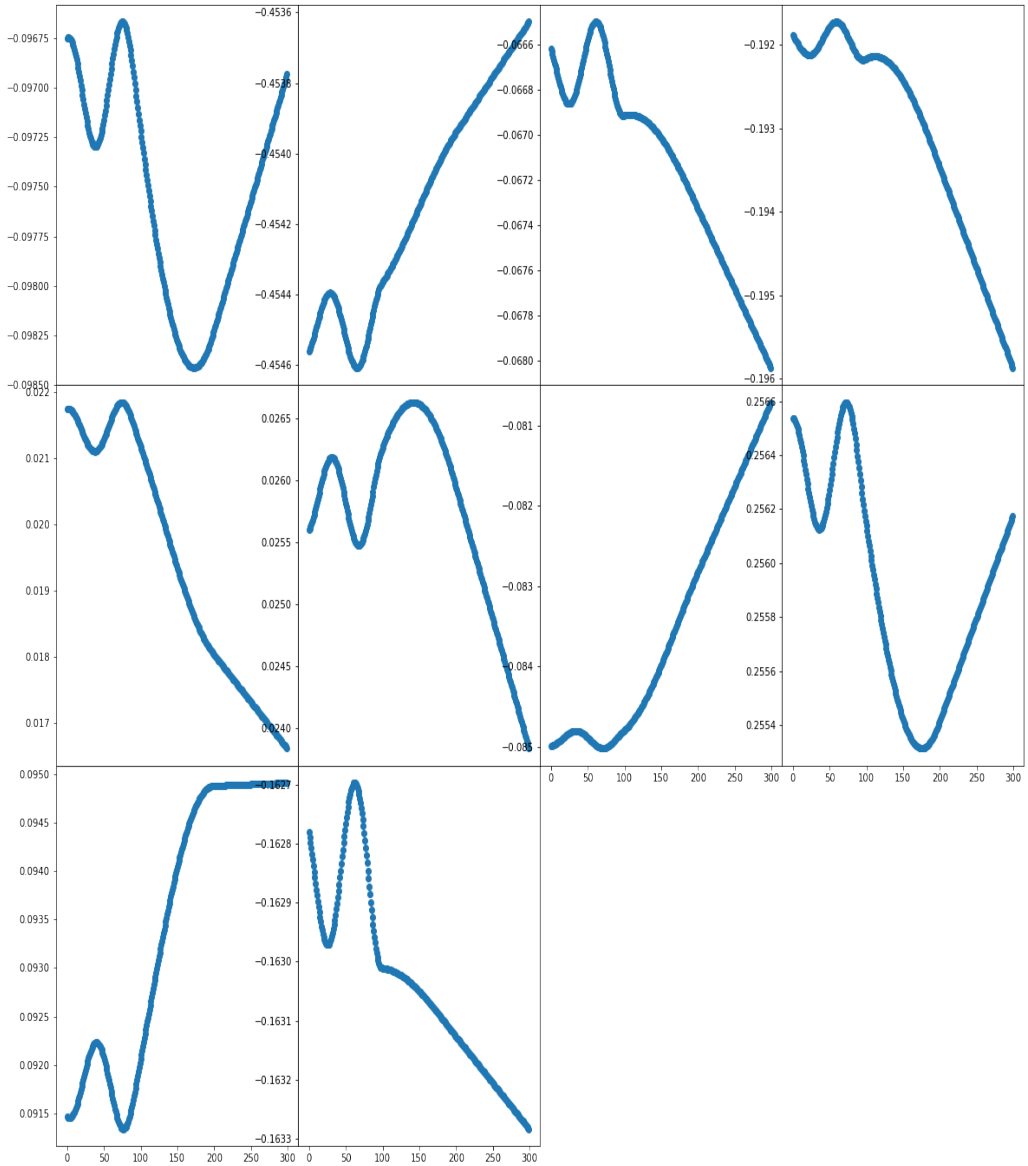

Figure 61: y-components of positions

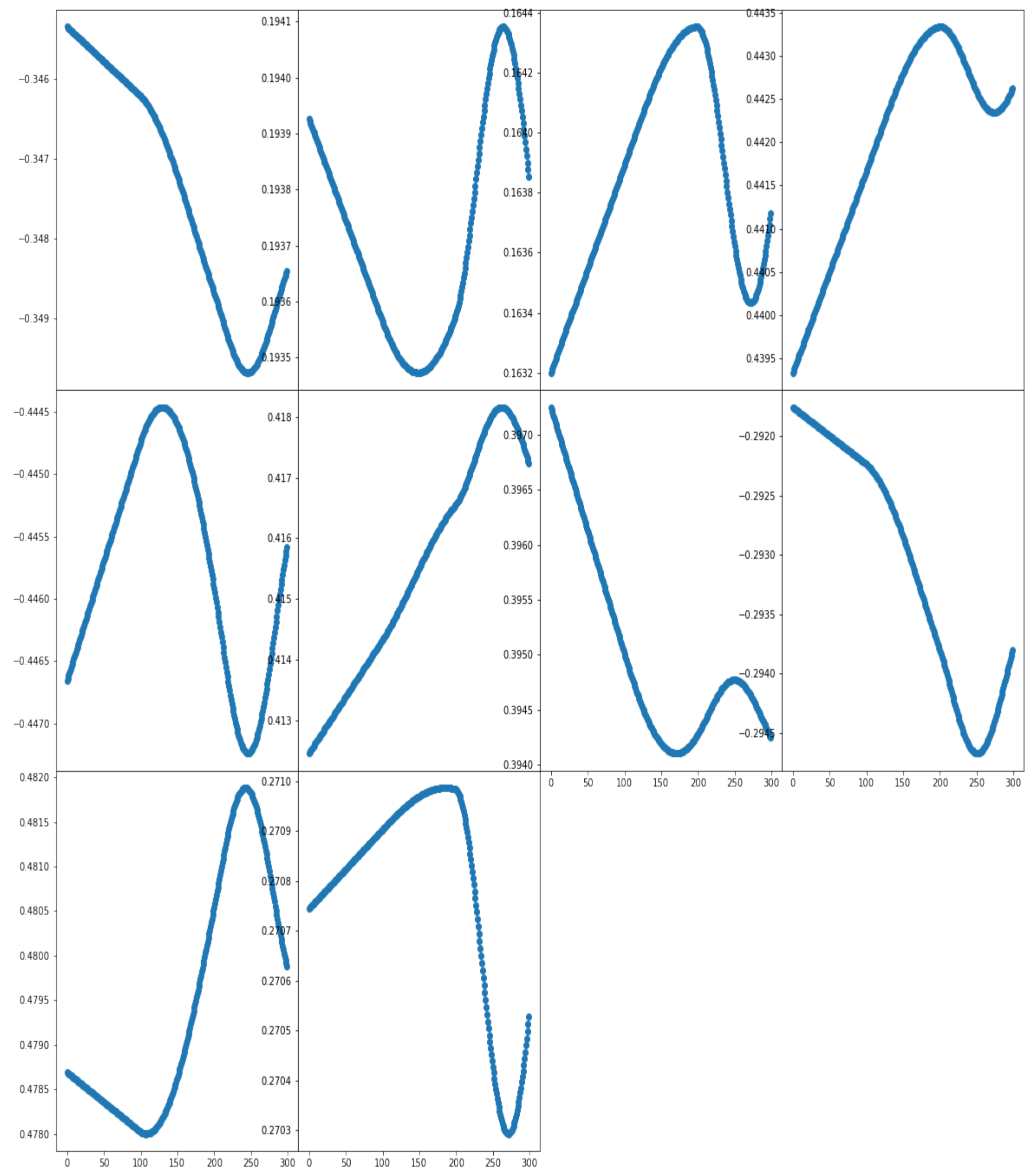

Figure 62: z-components of positions

We the plot the velocities and the components of velocities for the same 10 particles.

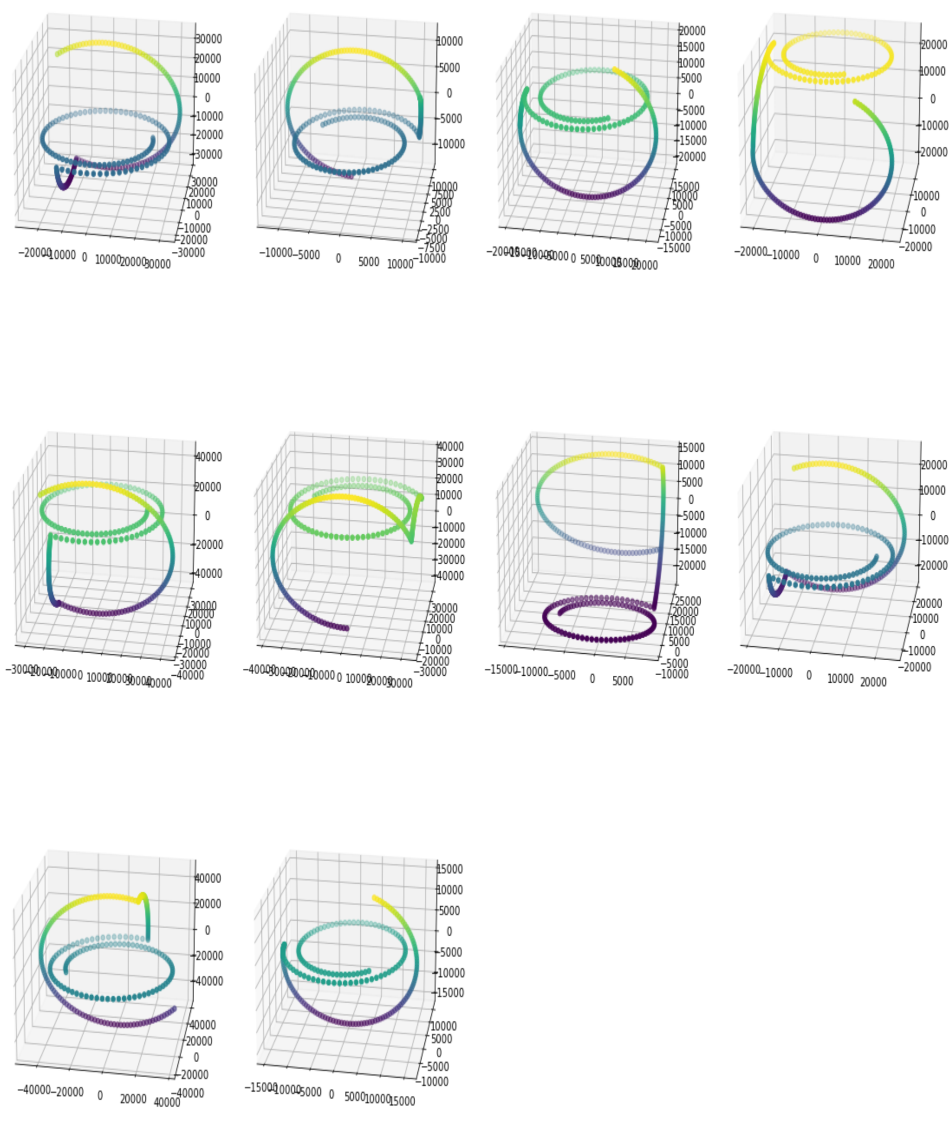

Figure 63: velocities

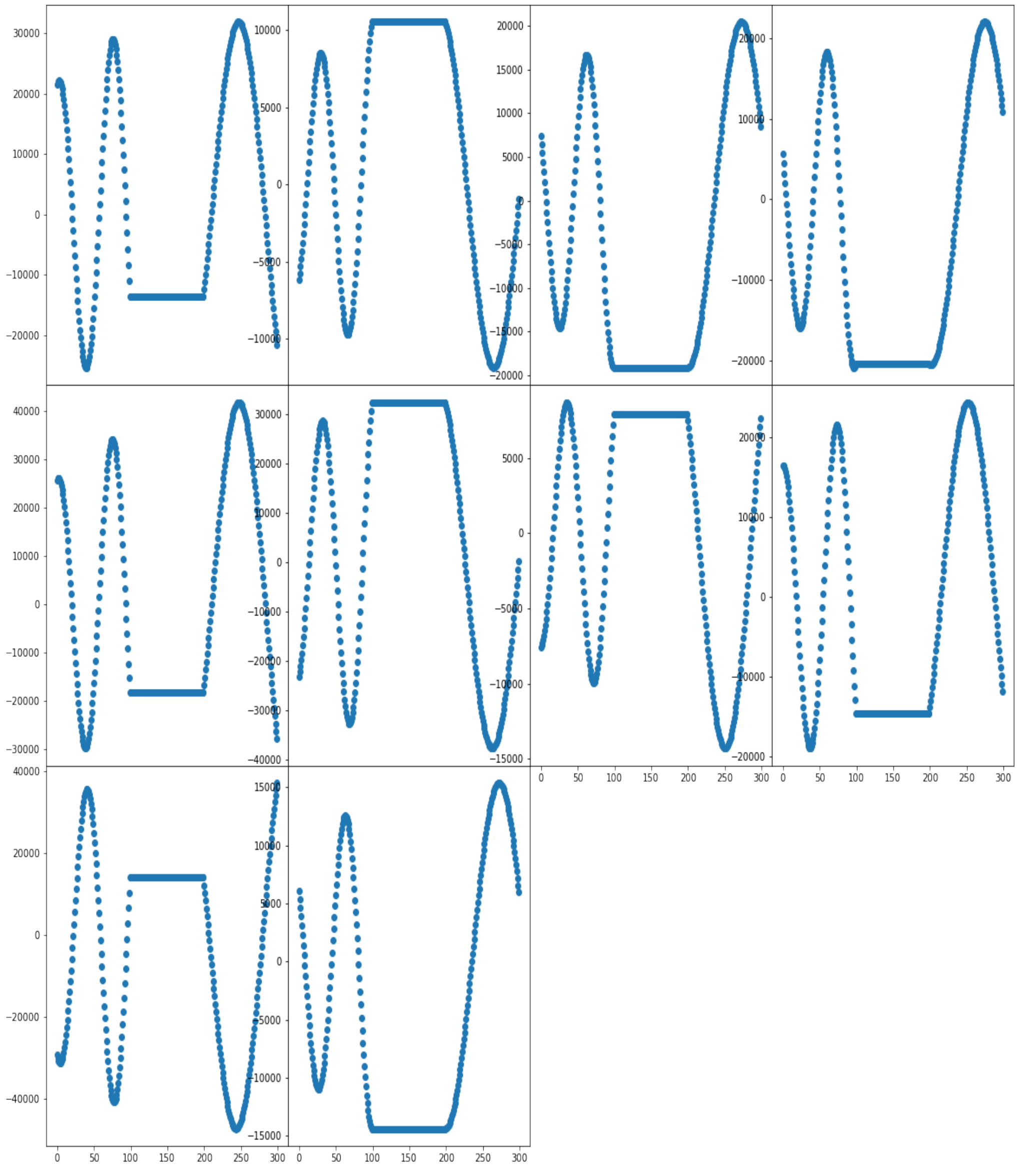

Figure 64: x-components of velocities

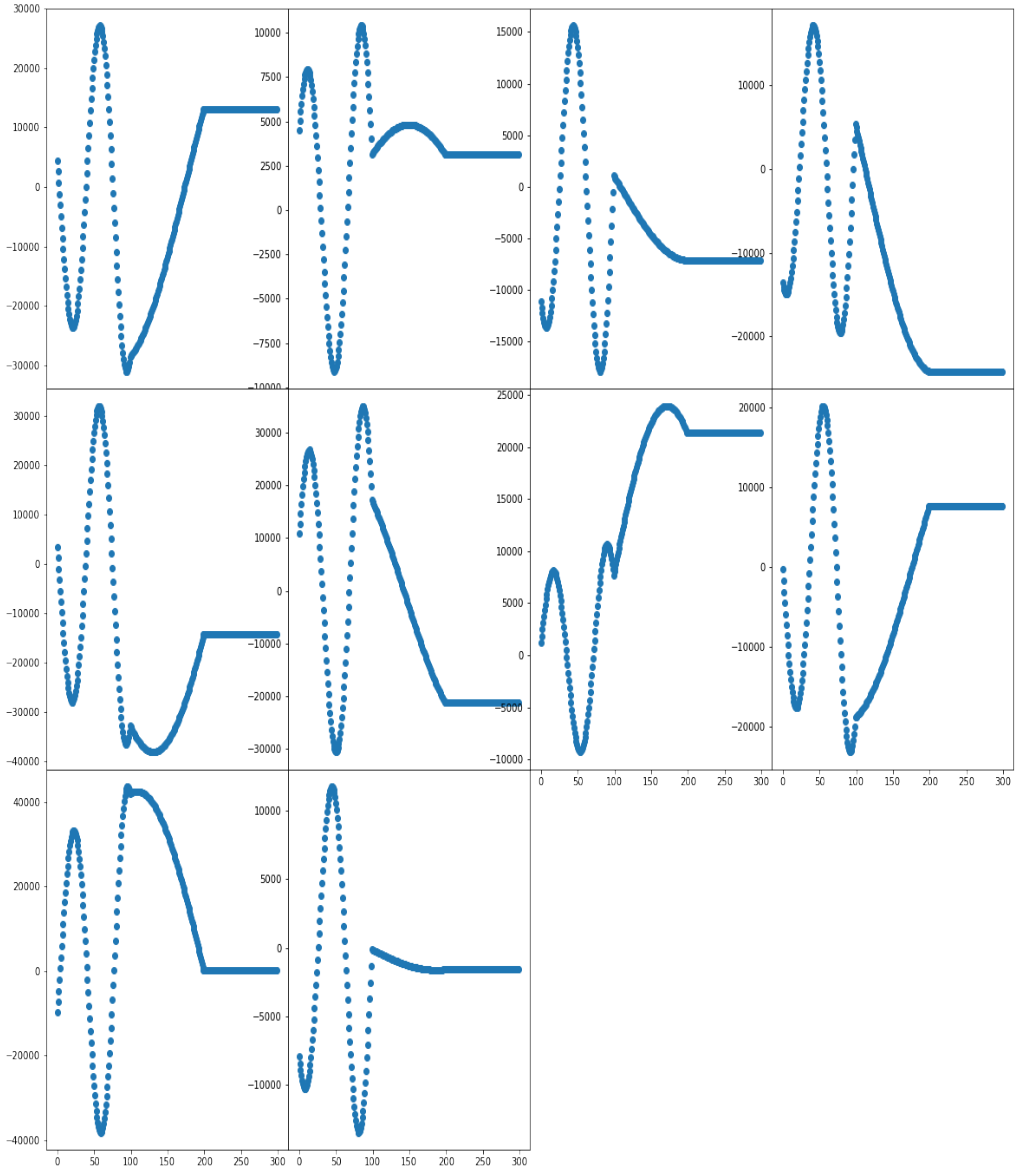

Figure 65: y-components of velocities

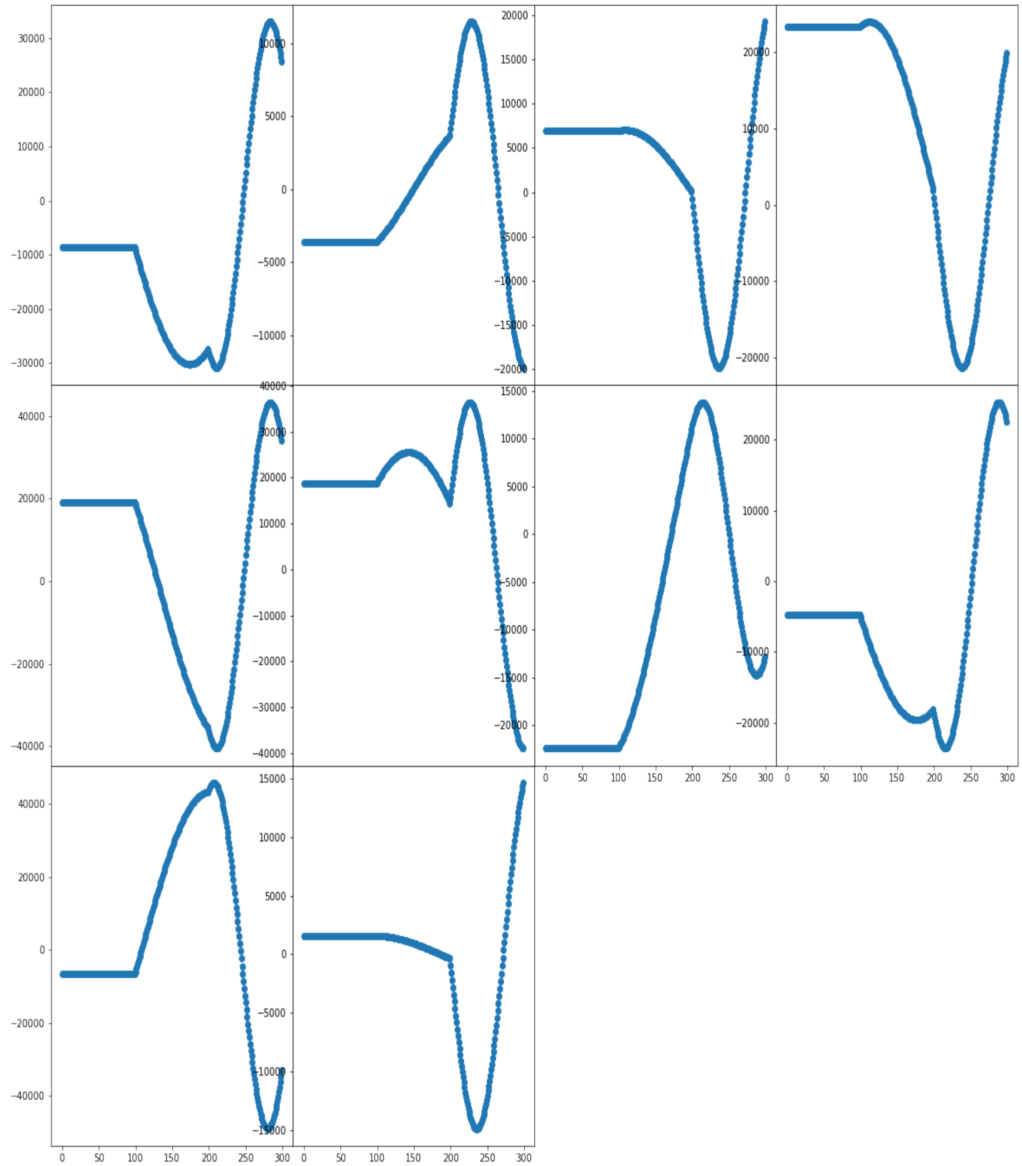

Figure 66: z-components of velocities

Like we discussed in the first part of study 3, it is difficult to tell that the initial distribution of positions and velocities are very different from those in study 2, especially having different particles in different figures. However, one can notice in figures (59) and (63) that the evolution paths look more diverse among themselves than those in study 2; which is suggestive that initial particle position and velocity distribution is different in study 3 than in study 2.

3 Prospects for such studies

We have also made animations for the plots which help us understand the evolution of the particles in the plasma even better. Due to the limitation of time, we were only able to perform these studies. Should one spend a few more months on such a project, many interesting studies could be done, including studies that really help one use plasma devices better during plasma processes such as those in surface engineering practices.
Some interesting studies that could be done, by building on the available resources could be:

- Define new field configurations; either analytical or based on expressions that mimic coils or instruments used to create fields.
- Vary the fields (either slowly or abruptly)and see how the particles evolve.
- Define new distributions to sample the initial position and velocity distributions.
- Use different distributions in the same study to mimic particles entering the chamber through multiple routes.
- Save the states of the particles at some point in the study and use that as initial distribution for another study.
- Allow functionality to absorb particles (in coating processes) or eject particles from the chamber.
- Define interactions between the particles.
- Create an interactive plasma simulation which keeps running on a computer and the user input can change the particles, fields and other properties of the simulation.
- Study the effect of plasma temperature on certain plasma processes.

Study 1 mostly served the purpose of showing that the program works well. In study 1, we kept the magnetic field to be constant, while we changed the electric field. In study 2 we set out to study how we can control particles in a plasma by controlling the magnetic field, as that closely follows the aim of our project. We first see that we can completely trap the particles along the magnetic field. In the second part of study 2, we see that by changing the direction of the magnetic field, we can trap the particles in any direction we want to. In summary, possibly using a coil whose orientation we can change, we can create a magnetic trap for a plasma chamber. By controlling the current in the coil and its orientation, we can control plasma very well. And we can also do studies based on such a setup. Although we did not the study specifically the magnetic mirror effect, we were able to study magnetic traps for plasma. In study 3, we used a different initial distribution of the velocities and positions for particles when they enter the chamber. Initial distribution of positions describes where the particles are injected into the chamber. For example, maybe they are all injected at the same position through a port or valve like in study 2, or maybe they are sprayed through the walls or maybe we study the flux of particles reflected off of the wall of the chamber like in study 3. The velocity distribution of the particles entering the chamber also help us understand parameters like plasma temperature. We have changed fields in a few epochs in these studies so that we can clearly notice these changes in the plots. Other strategies like changing the fields smoothly or slowly, would be difficult to observe well in the plots; although they would be very interesting from computational perspective. We did not do any computational study in our project, due to the limitation of time. We were only able to understand basic ideas about controlling plasma with electric and magnetic fields through plots. But with some extensions to a project like ours, one could perform computational studies and understand optimization techniques to model and operate the behavior or a real plasma device; which would be very useful in understanding plasma processes in surface engineering techniques. This was our motivation for the project. But we were only able to accomplish this in the time we had. However, we feel very excited about the possibilities offered by such a project. One might even find it interesting to work on such a project, during the course of one's Phd or professional academic research; and many people around the world have done so.

References

[1] Florian LB (GitHub user). *Charged Particle Trajectories in Electric and Magnetic Fields*. Thu, 28 Jan 2016. *https://flothesof.github.io/charged-particle-trajectories-E-and-B-fields.html*

[2] Scipy library rdist distribution documentation. *https://docs.scipy.org/doc/scipy/reference/generated/scipy.stats.rdist.html*