study3

April 9, 2022

1 Study 3 Magnetic trap for plasma with Helmholtz coil

1.0.1 Data used

100 particles of Hydrogen

Fields:

1. Magnetic field due to a Helmholtz coil: 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]
2. Electric field is set to 0 throughout

Sampling:

1. Speeds parabolic distribution sampled with Maxwellian distribution equivalent of plasma temperature 10000 K
2. Velocity directions uniform random sampled
3. Positions all sampled to start at 0.5m from the center [0,0,0] (Particles injected from the walls, or reflected, may be considered (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)

Updating:

1. Duration of 1 step of update: 0.001 microseconds
2. Number of steps: 3 x 100 = 300
3. Total duration of simulation = 0.3 microseconds

Imports and Requirements

[1]:
```
# Make imports
import import_ipynb
from run import Run
from constants import Constants
from field import Field
import numpy as np
import matplotlib.pyplot as plt
import matplotlib as mpl
#import matplotlib.animation as animation
from mpl_toolkits.mplot3d import Axes3D
```

```
from tempfile import NamedTemporaryFile
import base64
from matplotlib import animation
from IPython.display import HTML
```

```
importing Jupyter notebook from run.ipynb
importing Jupyter notebook from batch.ipynb
importing Jupyter notebook from particle.ipynb
importing Jupyter notebook from field.ipynb
importing Jupyter notebook from constants.ipynb
```

[2]:
```
#Create a constants object instance to access the constants from constants.
↪ipynb file
constants = Constants()
```

[3]:
```
# Functions for animations
VIDEO_TAG = """<video controls>
     <source src="data:video/x-m4v;base64,{0}" type="video/mp4">
     Your browser does not support the video tag.
    </video>"""

def anim_to_html(anim):
    if not hasattr(anim, '_encoded_video'):
        f = NamedTemporaryFile(suffix='.mp4', delete=False)
        anim.save(f.name, fps=20, extra_args=['-vcodec', 'libx264', '-pix_fmt',␣
↪'yuv420p'])
        f.flush()
        video = open(f.name, "rb").read()
        f.close()
        anim._encoded_video = base64.b64encode(video).decode('utf-8')

    return VIDEO_TAG.format(anim._encoded_video)



def display_animation(anim):
    plt.close(anim._fig)
    return HTML(anim_to_html(anim))

def plot_animation_3d(positions):
    '''
    This function can plot both positions and velocities
    '''

    #positions = np.array([xdata, ydata, zdata])
    FRAMES = np.shape(positions)[0]
```

```
    # Here positions has shape (198, 3) where each entry is a position which is␣
↪an array of x,y,z coordinates
    fig = plt.figure()
    ax = fig.add_subplot(111, projection='3d')

    def init():
        ax.view_init(elev=10., azim=0)
        ax.set_xlabel('x')
        ax.set_ylabel('y')
        ax.set_zlabel('z')

    # animation function.  This is called sequentially
    def animate(i):
        current_index = int(positions.shape[0] / FRAMES * i)
        ax.cla()
        ax.view_init(elev=10., azim=i)
        ax.set_xlabel('x')
        ax.set_ylabel('y')
        ax.set_zlabel('z')
        # For line plot uncomment the following line
        # ax.plot3D(positions[:current_index, 0], positions[:current_index, 1],␣
↪positions[:current_index, 2])
        ax.scatter3D(positions[:current_index, 0], positions[:current_index,␣
↪1], positions[:current_index, 2])

    # call the animator.
    anim = animation.FuncAnimation(fig, animate, init_func=init, frames=FRAMES,␣
↪interval=100)

    return anim

def plot_animation_2d(positions, exclude):
    '''
    This function can plot both positions and velocities
    exclude can be 0, 1 or 2:
    if exclude = 2, this means exclude the z data of the given array and plot␣
↪the x and y data
    '''

    available = [0,1,2]
    available.remove(exclude)

    #positions = np.array([xdata, ydata, zdata])
    FRAMES = np.shape(positions)[0]
    # Here positions has shape (198, 3) where each entry is a position which is␣
↪an array of x,y,z coordinates
```

```
    fig = plt.figure()
    ax = fig.add_subplot(111)

    def init():
        ax.set_xlabel(chr(available[0] + 120))
        ax.set_ylabel(chr(available[1] + 120))

    # animation function.  This is called sequentially
    def animate(i):
        current_index = int(positions.shape[0] / FRAMES * i)
        ax.cla()
        ax.set_xlabel(chr(available[0] + 120))
        ax.set_ylabel(chr(available[1] + 120))
        # For line plot uncomment the following line
        # ax.plot3D(positions[:current_index, 0], positions[:current_index, 1],␣
 ↪positions[:current_index, 2])
        ax.scatter(positions[:current_index, available[0]], positions[:
 ↪current_index, available[1]])

    # call the animator.
    anim = animation.FuncAnimation(fig, animate, init_func=init, frames=FRAMES,␣
 ↪interval=100)

    return anim

def plot_animation_1d(positions, include):
    '''
    This function can plot both positions and velocities
    include can be 0, 1 or 2.
    if include = 2, this means plot the z data of the array
    '''

    #positions = np.array([xdata, ydata, zdata])
    FRAMES = np.shape(positions)[0]
    # Here positions has shape (198, 3) where each entry is a position which is␣
 ↪an array of x,y,z coordinates
    fig = plt.figure()
    ax = fig.add_subplot(111)

    def init():
        ax.set_xlabel('step')
        ax.set_ylabel(chr(include + 120))

    # animation function.  This is called sequentially
    def animate(i):
        current_index = int(positions.shape[0] / FRAMES * i)
        ax.cla()
```

```
        ax.set_xlabel('step')
        ax.set_ylabel(chr(include + 120))
        # For line plot uncomment the following line
        # ax.plot3D(positions[:current_index, 0], positions[:current_index, 1],␣
↪positions[:current_index, 2])
        ax.scatter(np.arange(len(positions))[:current_index], positions[:
↪current_index, include])

    # call the animator.
    anim = animation.FuncAnimation(fig, animate, init_func=init, frames=FRAMES,␣
↪interval=100)

    return anim

def multiplot_animation_3d(positions):
    '''
    Here each element of positions is data for 1 particle that one would give␣
↪as input to
    plot_animation_3d function, i.e. position or velocity update history of 1␣
↪particle

    This function can plot both positions and velocities
    '''

    #positions = np.array(np.array([xdata, ydata, zdata]))
    FRAMES = np.shape(positions)[1]
    # Here positions has shape (10, 1089, 3)
    fig = plt.figure()
    ax = fig.add_subplot(111, projection='3d')

    def init():
        ax.view_init(elev=20., azim=0)
        ax.set_xlabel('x')
        ax.set_ylabel('y')
        ax.set_zlabel('z')

    # animation function.  This is called sequentially
    def animate(i):
        current_index = int(positions.shape[1] / FRAMES * i)
        ax.cla()
        ax.view_init(elev=20., azim=i)
        ax.set_xlabel('x')
        ax.set_ylabel('y')
        ax.set_zlabel('z')
        # For line plot uncomment the following line
        # ax.plot3D(positions[:current_index, 0], positions[:current_index, 1],␣
↪positions[:current_index, 2])
```

```
        for position in positions:
            ax.scatter3D(position[:current_index, 0], position[:current_index,␣
↪1], position[:current_index, 2])

    # call the animator.
    anim = animation.FuncAnimation(fig, animate, init_func=init, frames=FRAMES,␣
↪interval=100)

    return anim

# Currently plots x and y positions
def multiplot_animation_2d(positions, exclude):
    '''
    Here each element of positions is data for 1 particle that one would give␣
↪as input to
    plot_animation_3d function, i.e. position or velocity update history of 1␣
↪particle

    This function can plot both positions and velocities
    exclude can be 0, 1 or 2:
    if exclude = 2, this means exclude the z data of the given array and plot␣
↪the x and y data
    '''

    available = [0,1,2]
    available.remove(exclude)

    #positions = np.array(np.array([xdata, ydata, zdata]))
    FRAMES = np.shape(positions)[1]
    # Here positions has shape (10, 1089, 3)
    fig = plt.figure()
    ax = fig.add_subplot(111)

    def init():
        ax.set_xlabel(chr(available[0] + 120))
        ax.set_ylabel(chr(available[1] + 120))

    # animation function.  This is called sequentially
    def animate(i):
        current_index = int(positions.shape[1] / FRAMES * i)
        ax.cla()
        ax.set_xlabel(chr(available[0] + 120))
        ax.set_ylabel(chr(available[1] + 120))
        # For line plot uncomment the following line
        # ax.plot3D(positions[:current_index, 0], positions[:current_index, 1],␣
↪positions[:current_index, 2])
```

```
        for position in positions:
            ax.scatter(position[:current_index, available[0]], position[:
↪current_index, available[1]])

    # call the animator.
    anim = animation.FuncAnimation(fig, animate, init_func=init, frames=FRAMES,␣
↪interval=100)

    return anim

def multiplot_animation_1d(positions, include):
    '''Here each element of positions is data for 1 particle that one would␣
↪give as input to
    plot_animation_3d function, i.e. position or velocity update history of 1␣
↪particle

    This function can plot both positions and velocities
    include can be 0, 1 or 2.
    if include = 2, this means plot the z data of the array
    '''

    #positions = np.array(np.array([xdata, ydata, zdata]))
    FRAMES = np.shape(positions)[1]
    # Here positions has shape (10, 1089, 3)
    fig = plt.figure()
    ax = fig.add_subplot(111)

    def init():
        ax.set_xlabel('step')
        ax.set_ylabel(chr(include + 120))

    # animation function.  This is called sequentially
    def animate(i):
        current_index = int(positions.shape[1] / FRAMES * i)
        ax.cla()
        ax.set_xlabel('step')
        ax.set_ylabel(chr(include + 120))
        # For line plot uncomment the following line
        # ax.plot3D(positions[:current_index, 0], positions[:current_index, 1],␣
↪positions[:current_index, 2])
        for position in positions:
            ax.scatter(np.arange(len(position))[:current_index], position[:
↪current_index, include])

    # call the animator.
```

```
    anim = animation.FuncAnimation(fig, animate, init_func=init, frames=FRAMES,␣
 ↪interval=100)

    return anim
```

Create the system and run the simulation

[4]:
```
# Create a run object instance
s2 = Run()
```

[5]:
```
#### Same as study 1 for now

# Create 100 Hydrogen ions whose:
# speeds are Maxwellian sampled, velocity directions are uniform randomly␣
 ↪sampled
# positions are all sampled such that particles start at [-0.5, 0, 0]
# a chamber 1m x 1m x 1m with extreme points [-0.5, -0.5, -0.5] and [0.5, 0.5,␣
 ↪0.5] considered
s2.create_batch_with_file_initialization('H+', constants.constants['e'][0],\
                                         constants.constants['m_H'][0] *␣
 ↪constants.constants['amu'][0], \
                                         100, 100, 'H ions', r_index=1,␣
 ↪v_index=3)
#r_index=1 means initialize positions with particles sampled 0.5m from the␣
 ↪center
#v_index=3 means initialize velocities with speeds sampled from parabolic␣
 ↪distribution
```

[7]:
```
s2_index_update = 0 # Update the first batch in this Run instance
s2_particle_track_indices = [i for i in range(100)] # Track all 100 particles
s2_dT = 10**(-7) # 0.1 microseconds
s2_stepT = 10**(-9) # 0.001 microseconds time step
s2_Nsteps = int(s2_dT/s2_stepT)+1

s2_batch_ps_and_vs = dict()
for i in range(100): # 100 is number of particles
    s2_batch_ps_and_vs[i] = []

s2_batch1 = s2.batches[0]['H ions'] # take current batch
s2_field = Field()

# Electric field is set to zero
# Magnetic field along z axis
for i in range(s2_Nsteps):
    for j in range(len(s2_batch1.particles)):
        #argsE = s2_field.radial_E_field(s2_batch1.particles[j].r, V=100,␣
 ↪center = [0,0,0])
```

```
        argsE=0
        argsB = s2_field.helmholtz_coil_B_field(n=1000, I=20, R=0.1,␣
↪B_hat=[0,0,1], mu_0=constants.constants['mu_0'][0])
        # I was 100 along z axis or 20 along z axis
        args = (s2_field, s2_stepT, argsE, argsB)
        s2_batch1.particles[j].update(args)
        ithUpdateForAParticle = (i, s2_batch1.particles[j].r, s2_batch1.
↪particles[j].v)
        s2_batch_ps_and_vs[j].append(ithUpdateForAParticle)

# Electric field is set to zero
# Magnetic field along x axis
for i in range(s2_Nsteps):
    for j in range(len(s2_batch1.particles)):
        argsE=0
        #argsE = s2_field.radial_E_field(s2_batch1.particles[j].r, V=100,␣
↪center = [0,0,0])
        argsB = s2_field.helmholtz_coil_B_field(n=1000, I=-20, R=0.1,␣
↪B_hat=[0,0,1], mu_0=constants.constants['mu_0'][0])
        # I was -20 along x axis or -20 along z axis
        args = (s2_field, s2_stepT, argsE, argsB)
        s2_batch1.particles[j].update(args)
        ithUpdateForAParticle = (i, s2_batch1.particles[j].r, s2_batch1.
↪particles[j].v)
        s2_batch_ps_and_vs[j].append(ithUpdateForAParticle)

# Electric field is set to zero
# Magnetic field along y axis
for i in range(s2_Nsteps):
    for j in range(len(s2_batch1.particles)):
        argsE=0
        #argsE = s2_field.radial_E_field(s2_batch1.particles[j].r, V=100,␣
↪center = [0,0,0])
        argsB = s2_field.helmholtz_coil_B_field(n=1000, I=20, R=0.1,␣
↪B_hat=[0,0,1], mu_0=constants.constants['mu_0'][0])
        # I was 50 along y axis or 20 along z axis
        args = (s2_field, s2_stepT, argsE, argsB)
        s2_batch1.particles[j].update(args)
        ithUpdateForAParticle = (i, s2_batch1.particles[j].r, s2_batch1.
↪particles[j].v)
        s2_batch_ps_and_vs[j].append(ithUpdateForAParticle)


'''
s2_batch_ps_and_vs will be of the form :
```

```
{ 0 (means 0th particle): [(0 (means 0th timestep), array of position, array of␣
↪velocity)]
     }

so it is a dictionary whose keys are strings particle numbers and
values are particles update history which is:
        [list of tuples (time step, position, velocity) ]
'''
```

[7]:

```
'\ns2_batch_ps_and_vs will be of the form : \n{ 0 (means 0th particle): [(0
(means 0th timestep), array of position, array of velocity)]\n     }\n\nso it is
a dictionary whose keys are strings particle numbers and \nvalues are particles
update history which is:\n        [list of tuples (time step, position,
velocity) ]\n'
```

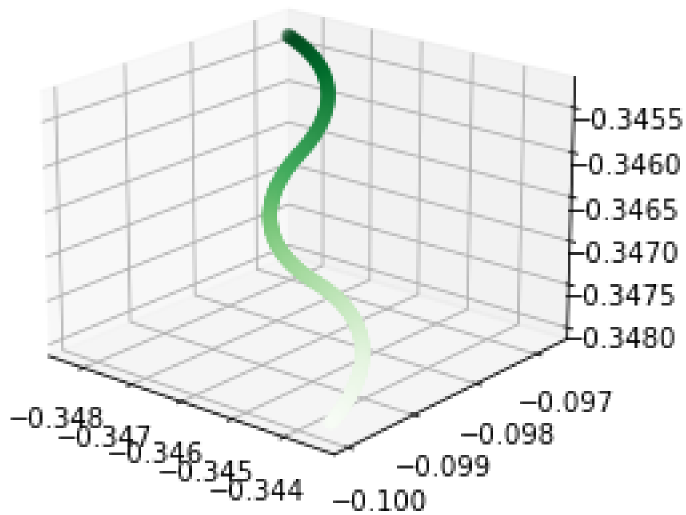
Plots and Animations

[8]:

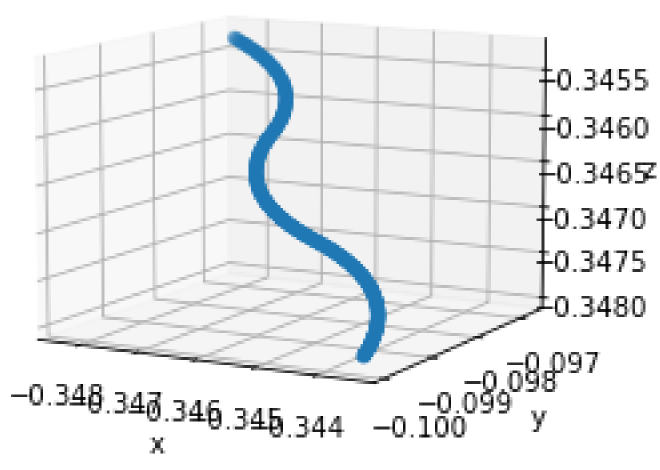
```python
# Take positions and velocities of the particle at index 0
s2_allfield_p0_ps = []
s2_allfield_p0_vs = []
s2_p0 = s2_batch_ps_and_vs[0]
for i in range(len(s2_p0)):
        s2_allfield_p0_ps.append(s2_p0[i][1])
        s2_allfield_p0_vs.append(s2_p0[i][2])
s2_allfield_p0_ps = np.array(s2_allfield_p0_ps)
s2_allfield_p0_vs = np.array(s2_allfield_p0_vs)
```

[9]:

```python
# Plot the positions of the particle at index 0
s2_allfield_p0_ps_fig = plt.figure()
s2_allfield_p0_ps_ax = plt.axes(projection='3d')
s2_allfield_p0_ps_ax.view_init(20, -50)

# Data for three-dimensional scattered points
# for position update history of particle 0 during all field configurations
s2_allfield_p0_ps_zdata = [elem[2] for elem in s2_allfield_p0_ps] # Animate␣
↪this plot as well.
s2_allfield_p0_ps_xdata = [elem[0] for elem in s2_allfield_p0_ps]
s2_allfield_p0_ps_ydata = [elem[1] for elem in s2_allfield_p0_ps]
s2_allfield_p0_ps_ax.scatter3D(s2_allfield_p0_ps_xdata,␣
↪s2_allfield_p0_ps_ydata, s2_allfield_p0_ps_zdata,\
                            c=s2_allfield_p0_ps_zdata, cmap='Greens');
#plt.savefig('ps3', dpi='figure', format='png')
```

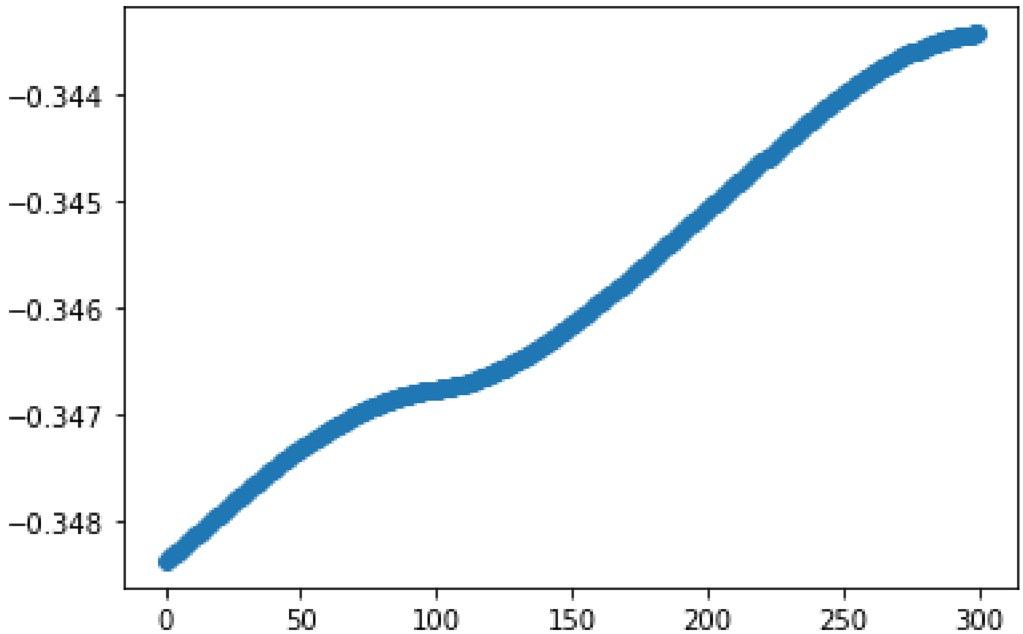


[10]:
```
# Animate the position of the particle at index 0
s2_allfield_p0_ps_anim = plot_animation_3d(s2_allfield_p0_ps)
#display_animation(s2_allfield_p0_ps_anim)
#s2_allfield_p0_ps_anim.save(r'ps3.mp4')
```



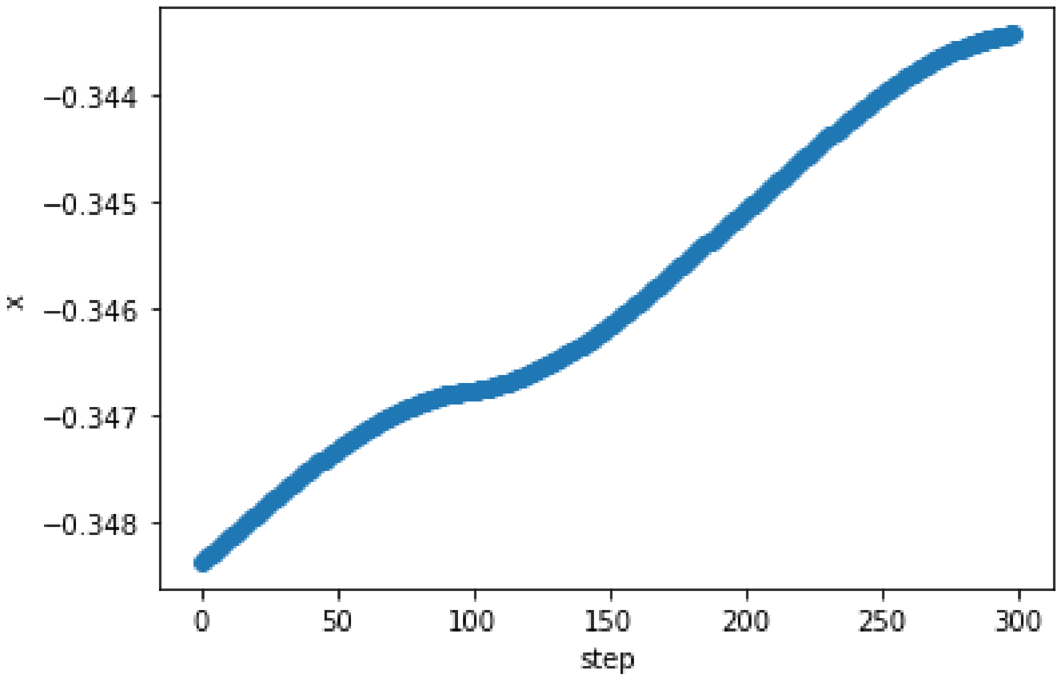
[10]:

```
# Plot x position
s2_allfield_p0_ps_x_fig = plt.figure()
s2_allfield_p0_ps_x_ax = plt.axes()
s2_allfield_p0_ps_x_ax.scatter(np.arange(len(s2_allfield_p0_ps_xdata)),␣
↪s2_allfield_p0_ps_xdata);
#plt.savefig('psx3', dpi='figure', format='png')
```

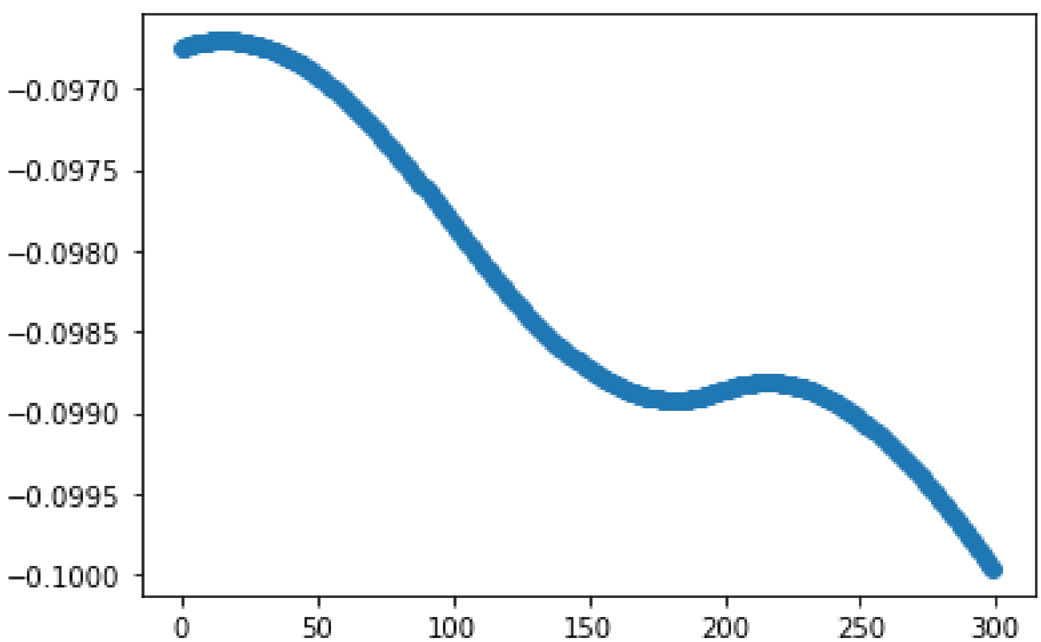


[12]:

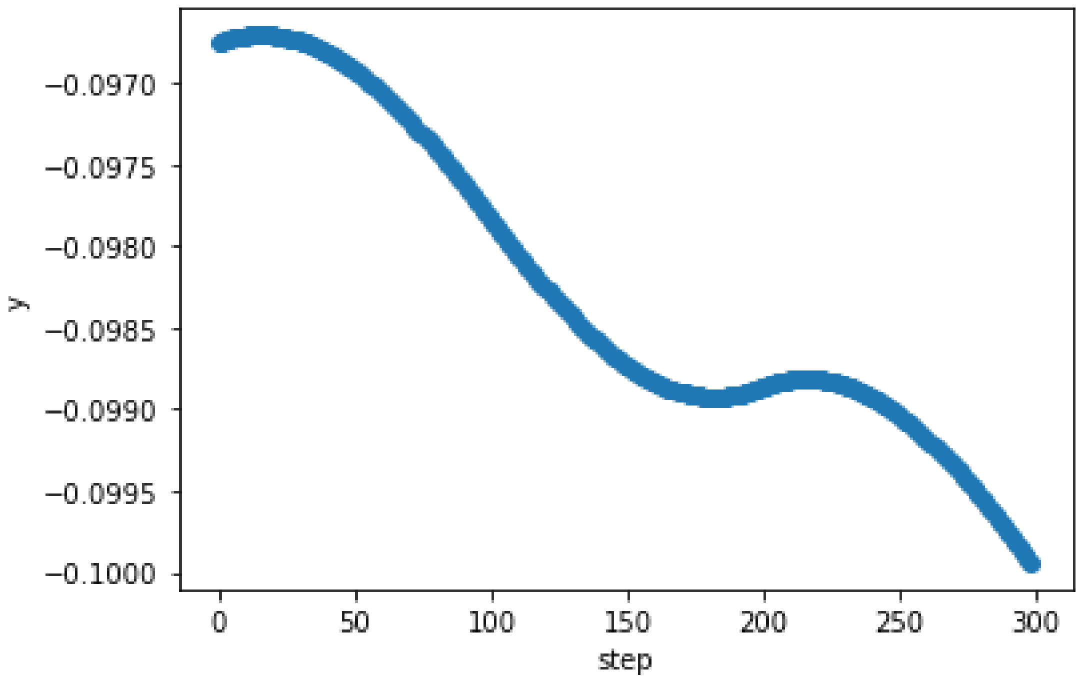
```
# Animate x position
s2_allfield_p0_ps_x_anim = plot_animation_1d(s2_allfield_p0_ps, include=0)
#display_animation(s2_allfield_p0_ps_x_anim)
#s2_allfield_p0_ps_x_anim.save(r'psx3.mp4')
```



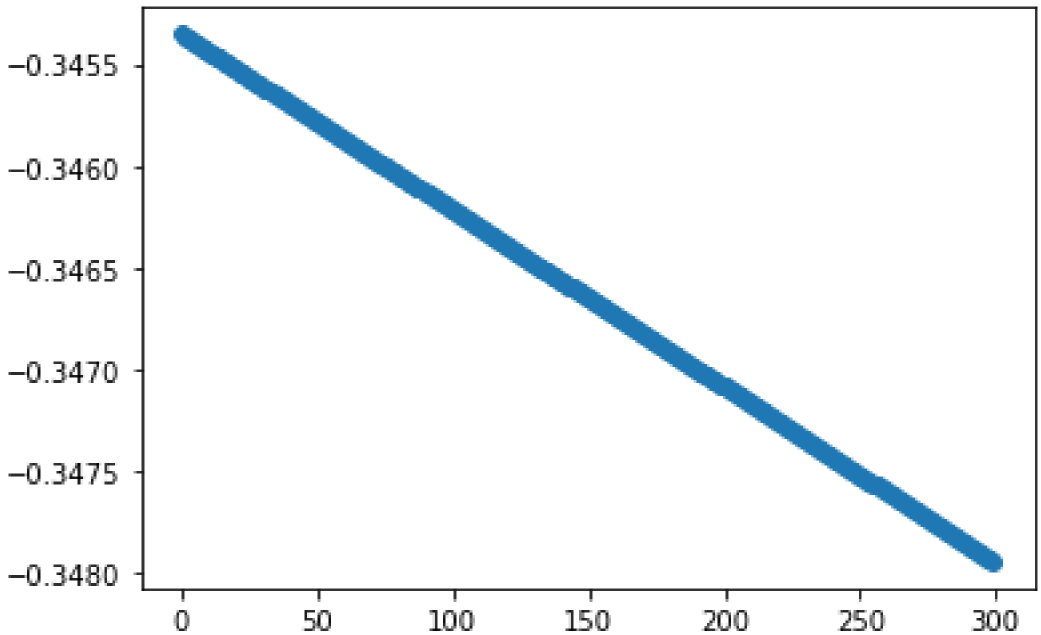
[11]:
```
# Plot y position
s2_allfield_p0_ps_y_fig = plt.figure()
s2_allfield_p0_ps_y_ax = plt.axes()
s2_allfield_p0_ps_y_ax.scatter(np.arange(len(s2_allfield_p0_ps_ydata)),␣
↪s2_allfield_p0_ps_ydata);
#plt.savefig('psy3', dpi='figure', format='png')
```



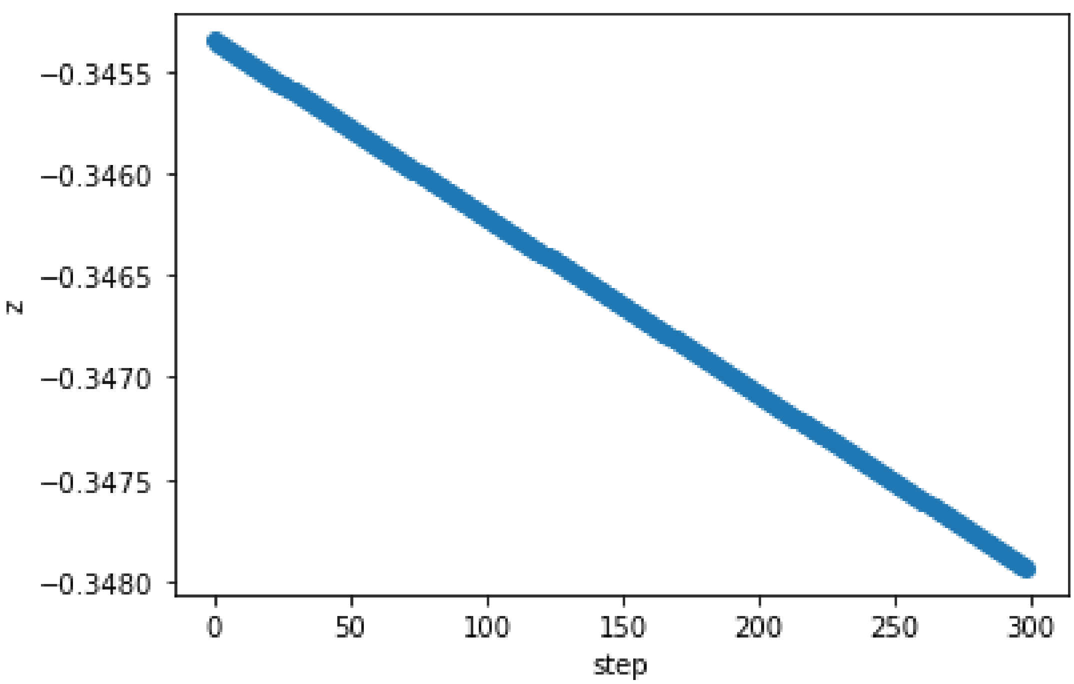
[14]:
```
# Animate y position
s2_allfield_p0_ps_y_anim = plot_animation_1d(s2_allfield_p0_ps, include=1)
#display_animation(s2_allfield_p0_ps_y_anim)
#s2_allfield_p0_ps_y_anim.save(r'psy3.mp4')
```



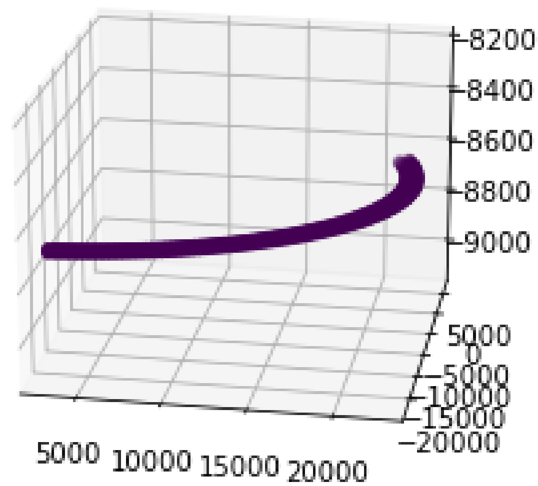
[12]:
```
# Plot z position
s2_allfield_p0_ps_z_fig = plt.figure()
s2_allfield_p0_ps_z_ax = plt.axes()
s2_allfield_p0_ps_z_ax.scatter(np.arange(len(s2_allfield_p0_ps_zdata)),␣
 ↪s2_allfield_p0_ps_zdata);
#plt.savefig('psz3', dpi='figure', format='png')
```



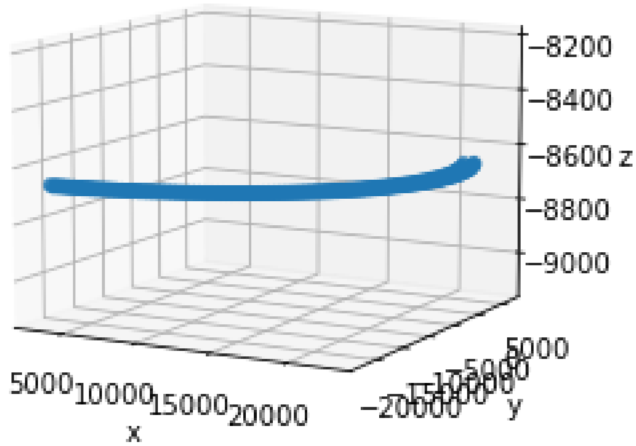
[16]:
```
# Animate z position
s2_allfield_p0_ps_z_anim = plot_animation_1d(s2_allfield_p0_ps, include=2)
#display_animation(s2_allfield_p0_ps_z_anim)
#s2_allfield_p0_ps_z_anim.save(r'psz3.mp4')
```



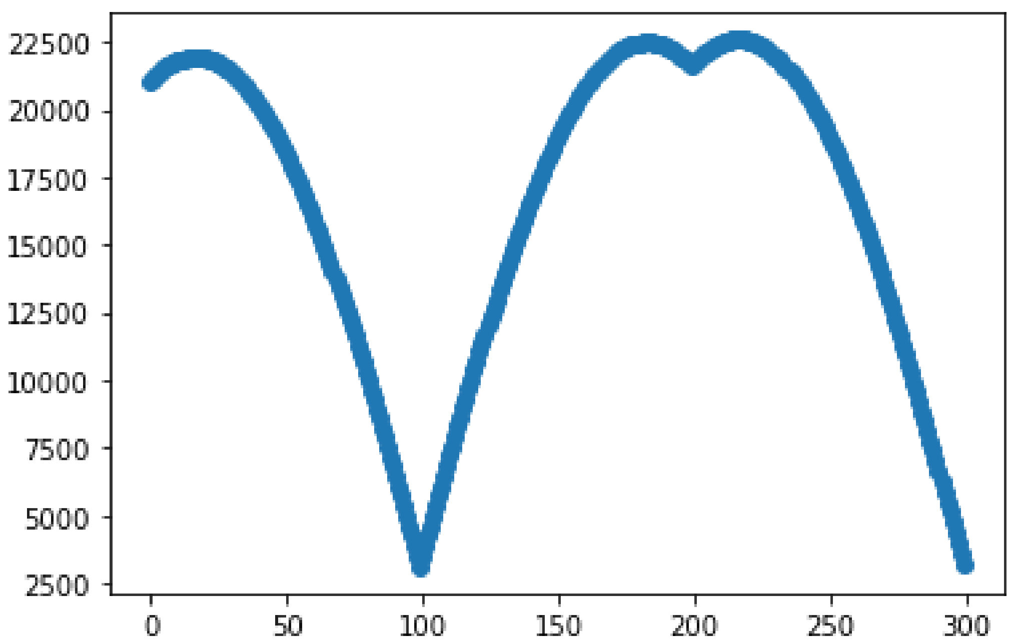
[13]:
```
# Plot the velocity of the particle at index 0
s2_allfield_p0_vs_fig = plt.figure()
s2_allfield_p0_vs_ax = plt.axes(projection='3d')
s2_allfield_p0_vs_ax.view_init(20, -80)

# Data for three-dimensional scattered points
# for position update history of particle 0 during all field configurations
s2_allfield_p0_vs_zdata = [elem[2] for elem in s2_allfield_p0_vs] # Animate␣
↪this plot as well.
s2_allfield_p0_vs_xdata = [elem[0] for elem in s2_allfield_p0_vs]
s2_allfield_p0_vs_ydata = [elem[1] for elem in s2_allfield_p0_vs]
s2_allfield_p0_vs_ax.scatter3D(s2_allfield_p0_vs_xdata,␣
↪s2_allfield_p0_vs_ydata, s2_allfield_p0_vs_zdata,\
                            c=s2_allfield_p0_vs_zdata);
#plt.savefig('vs3', dpi='figure', format='png')
```



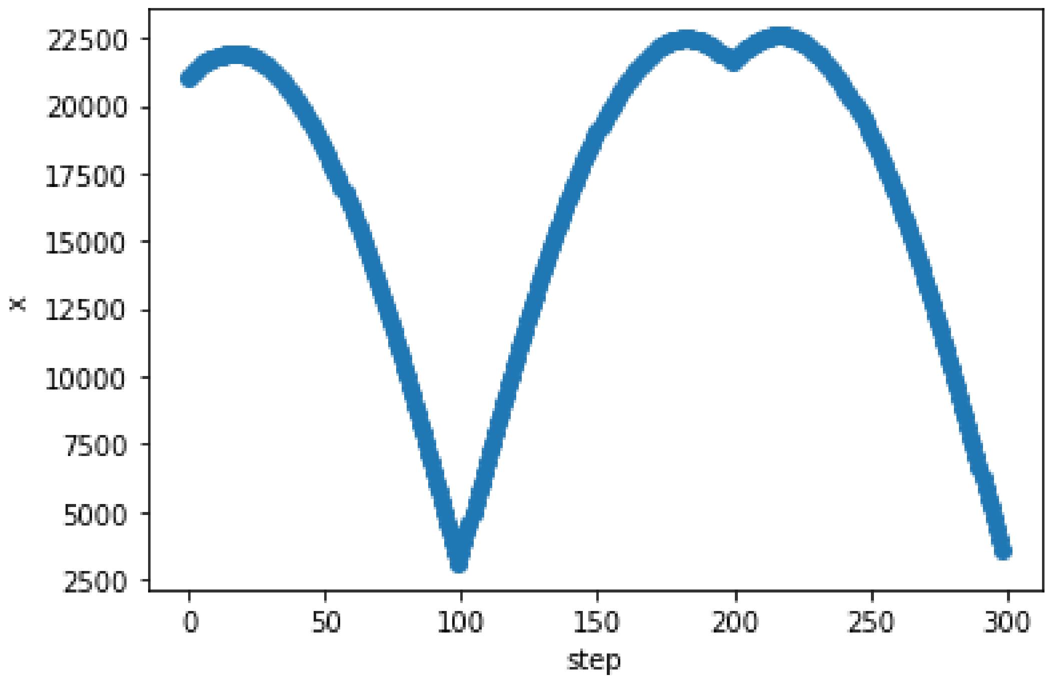
[18]:
```
# Animate the velocity
s2_allfield_p0_vs_anim = plot_animation_3d(s2_allfield_p0_vs)
#display_animation(s2_allfield_p0_vs_anim)
#s2_allfield_p0_vs_anim.save(r'vs3.mp4')
```



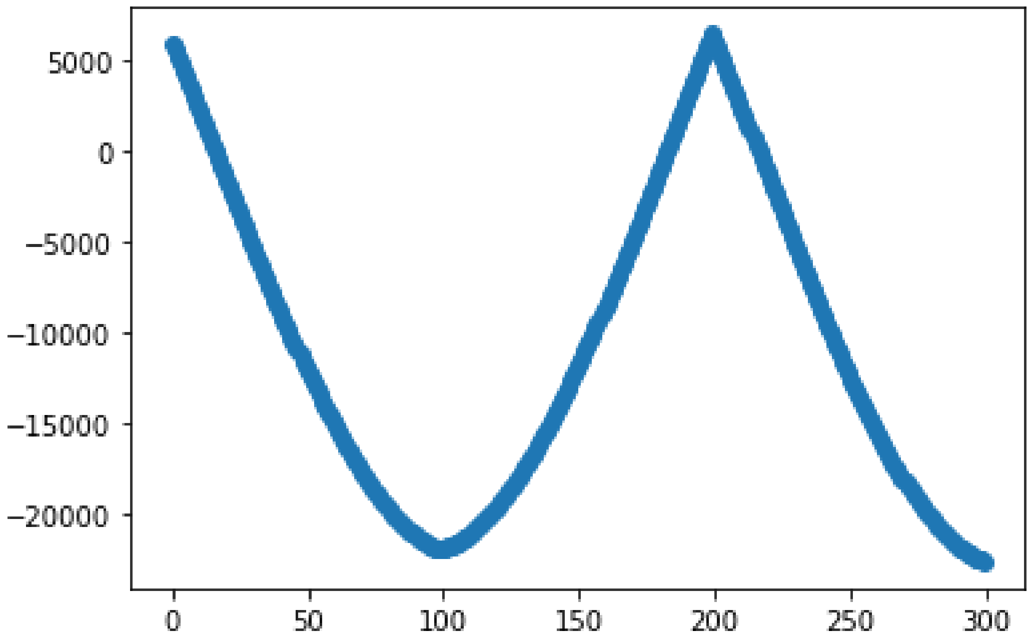

```
[14]: # Plot x velocity
s2_allfield_p0_vs_x_fig = plt.figure()
s2_allfield_p0_vs_x_ax = plt.axes()
s2_allfield_p0_vs_x_ax.scatter(np.arange(len(s2_allfield_p0_vs_xdata)),
 ↪s2_allfield_p0_vs_xdata);
#plt.savefig('vsx3', dpi='figure', format='png')
```



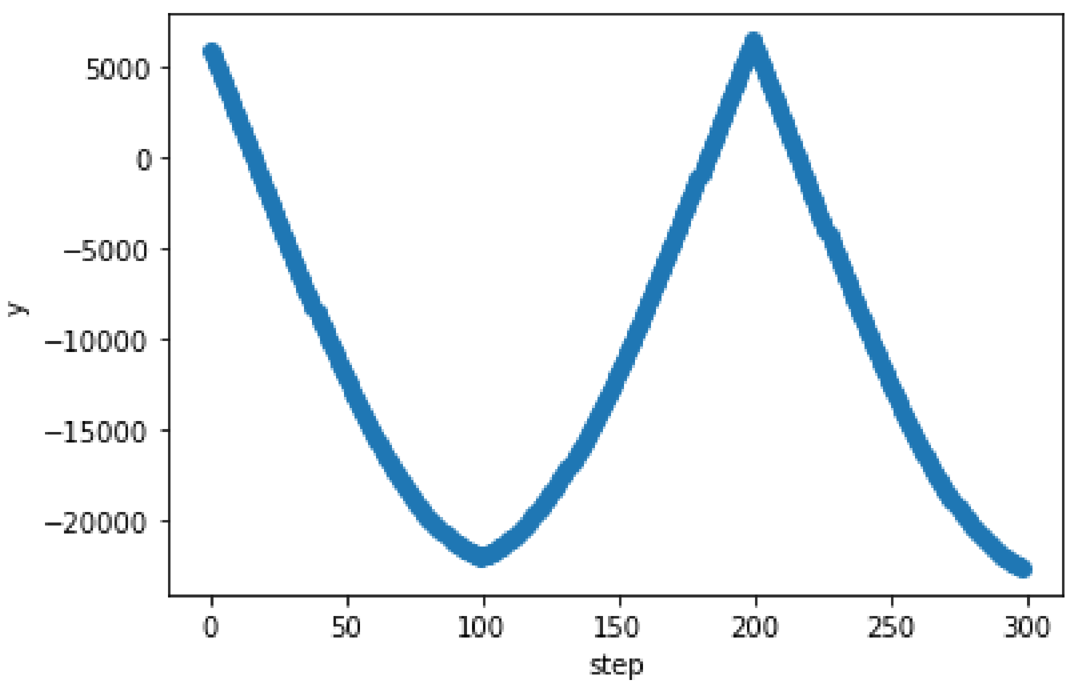
[21]:
```
# Animate x velocity
s2_allfield_p0_vs_x_anim = plot_animation_1d(s2_allfield_p0_vs, include=0)
#display_animation(s2_allfield_p0_vs_x_anim)
#s2_allfield_p0_vs_x_anim.save(r'vsx3.mp4')
```



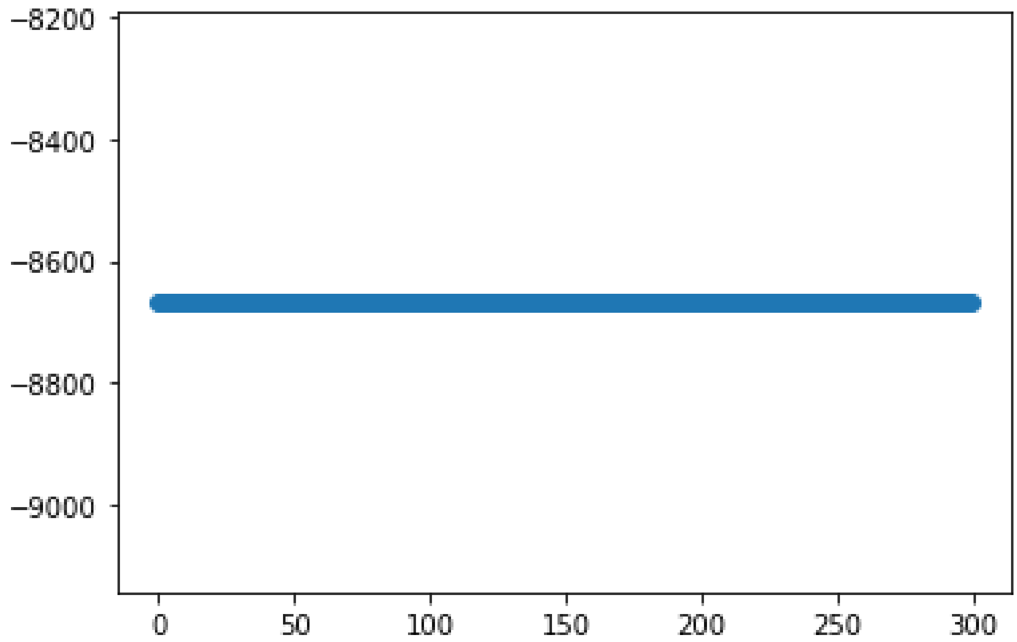
[15]:
```
# Plot y velocity
s2_allfield_p0_vs_y_fig = plt.figure()
s2_allfield_p0_vs_y_ax = plt.axes()
s2_allfield_p0_vs_y_ax.scatter(np.arange(len(s2_allfield_p0_vs_ydata)),␣
 ↪s2_allfield_p0_vs_ydata);
#plt.savefig('vsy3', dpi='figure', format='png')
```



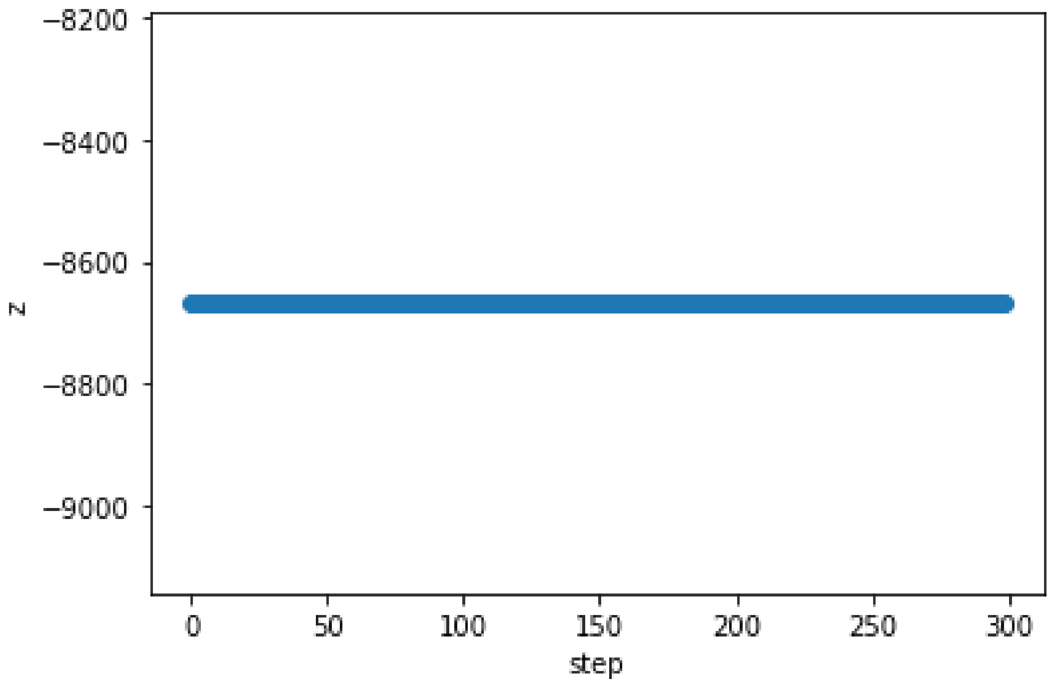

```
[23]: # Animate y velocity
s2_allfield_p0_vs_y_anim = plot_animation_1d(s2_allfield_p0_vs, include=1)
#display_animation(s2_allfield_p0_vs_y_anim)
#s2_allfield_p0_vs_y_anim.save(r'vsy3.mp4')
```



[16]:
```
# Plot z velocity
s2_allfield_p0_vs_z_fig = plt.figure()
s2_allfield_p0_vs_z_ax = plt.axes()
s2_allfield_p0_vs_z_ax.scatter(np.arange(len(s2_allfield_p0_vs_zdata)),␣
 ↪s2_allfield_p0_vs_zdata);
#plt.savefig('vsz3', dpi='figure', format='png')
```

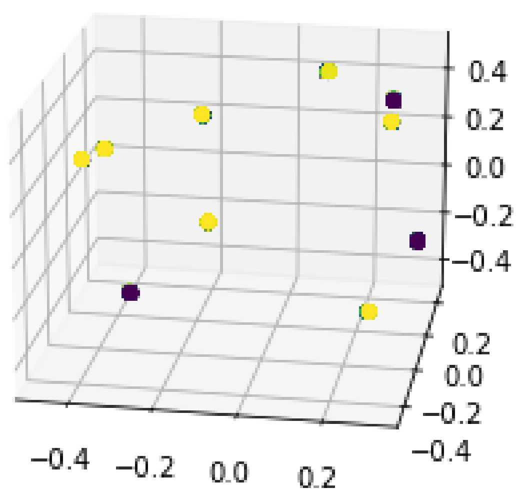


[25]:
```
# Animate z velocity
s2_allfield_p0_vs_z_anim = plot_animation_1d(s2_allfield_p0_vs, include=2)
#display_animation(s2_allfield_p0_vs_z_anim)
#s2_allfield_p0_vs_z_anim.save(r'vsz3.mp4')
```



[17]:
```
# Take positions and velocities for 10 particles
s2_particles = [0, 10, 20, 30, 40, 50, 60, 70, 80, 90] # take particles at␣
↪these indices
s2_allfield_10p_ps = []
s2_allfield_10p_vs = []

for aparticle in s2_particles:
    # Same procedure for as a single particle
    s2_allfield_ap_ps = []
    s2_allfield_ap_vs = []
    s2_ap = s2_batch_ps_and_vs[aparticle]
    for i in range(len(s2_ap)):
            s2_allfield_ap_ps.append(s2_ap[i][1])
            s2_allfield_ap_vs.append(s2_ap[i][2])
    s2_allfield_ap_ps = np.array(s2_allfield_ap_ps)
    s2_allfield_ap_vs = np.array(s2_allfield_ap_vs)

    s2_allfield_10p_ps.append(s2_allfield_ap_ps)
    s2_allfield_10p_vs.append(s2_allfield_ap_vs)

s2_allfield_10p_ps = np.array(s2_allfield_10p_ps)
s2_allfield_10p_vs = np.array(s2_allfield_10p_vs)
```

[21]:
```
####### THIS doesnot work in this notebook.
# Plot the positions for the particles
s2_allfield_10p_ps_fig = plt.figure()
s2_allfield_10p_ps_ax = plt.axes(projection='3d')
s2_allfield_10p_ps_ax.view_init(20, -80)

# Data for three-dimensional scattered points
for j in range(len(s2_particles)):
    s2_allfield_ap_ps_zdata = [elem[2] for elem in s2_allfield_10p_ps[j]] #␣
 ↪Animate this plot as well.
    s2_allfield_ap_ps_xdata = [elem[0] for elem in s2_allfield_10p_ps[j]]
    s2_allfield_ap_ps_ydata = [elem[1] for elem in s2_allfield_10p_ps[j]]
    s2_allfield_10p_ps_ax.scatter3D(s2_allfield_ap_ps_xdata,␣
 ↪s2_allfield_ap_ps_ydata, s2_allfield_ap_ps_zdata,\
                            c=s2_allfield_ap_ps_zdata);
#plt.savefig('multips2', dpi='figure', format='png')
```

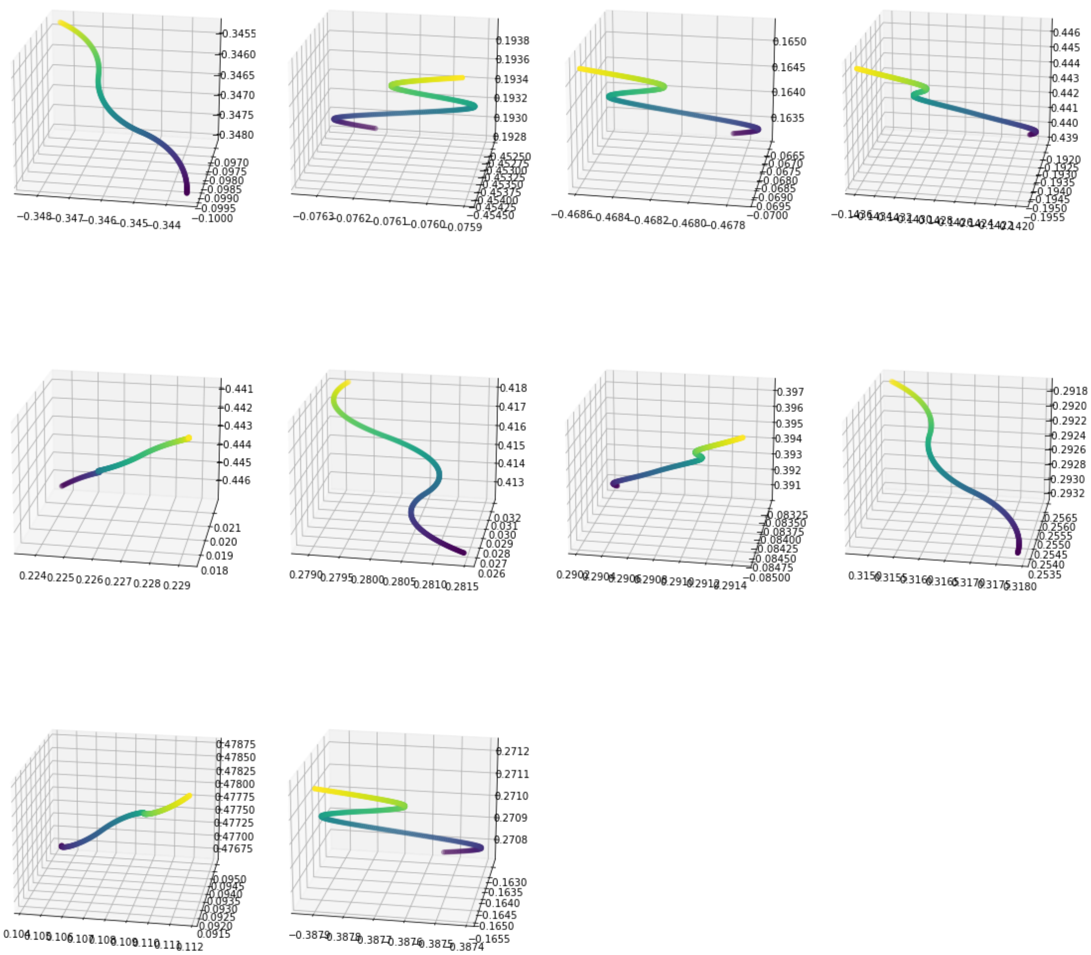


[22]:
```
def subplots_3d(s2_allfield_10p_ps, s2_particles):
    s2_allfield_10p_ps_fig = plt.figure()
    s2_allfield_10p_ps_fig.set_figheight(20)
    s2_allfield_10p_ps_fig.set_figwidth(20)
    spec = mpl.gridspec.GridSpec(ncols=4, nrows=3,
                          width_ratios=[1, 1, 1, 1], wspace=0,
                          hspace=0, height_ratios=[1,1,1])
    for i in range(len(s2_particles)):
        #s2_allfield_10p_ps_ax = s2_allfield_10p_ps_fig.add_subplot(5, 2, i+1,␣
 ↪projection='3d')
```

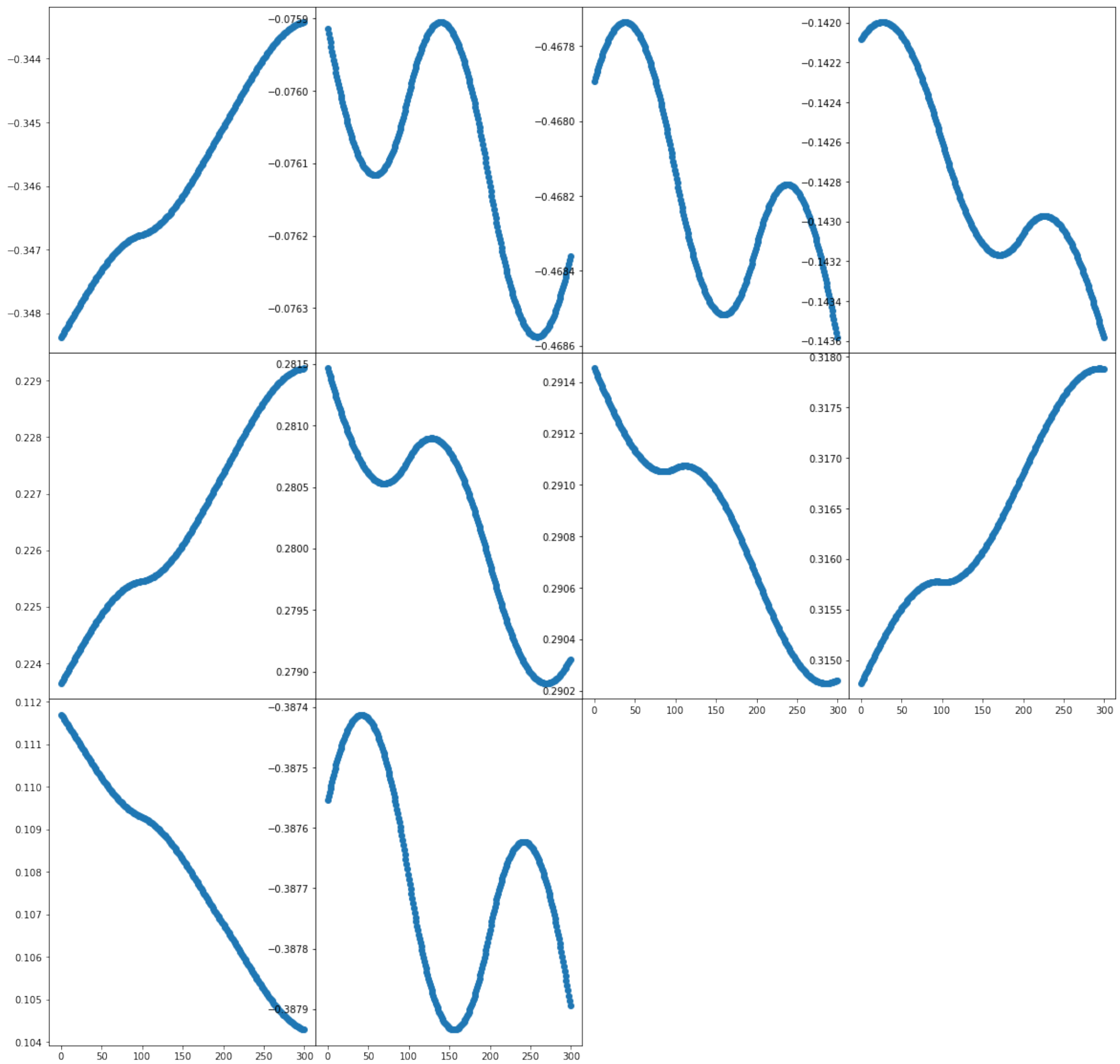
```
        s2_allfield_10p_ps_ax = s2_allfield_10p_ps_fig.add_subplot(spec[i],␣
↪projection='3d')
        s2_allfield_10p_ps_ax.view_init(20, -80)

        s2_allfield_ap_ps_zdata = [elem[2] for elem in s2_allfield_10p_ps[i]] #␣
↪Animate this plot as well.
        s2_allfield_ap_ps_xdata = [elem[0] for elem in s2_allfield_10p_ps[i]]
        s2_allfield_ap_ps_ydata = [elem[1] for elem in s2_allfield_10p_ps[i]]
        s2_allfield_10p_ps_ax.scatter3D(s2_allfield_ap_ps_xdata,␣
↪s2_allfield_ap_ps_ydata, s2_allfield_ap_ps_zdata,\
                            c=s2_allfield_ap_ps_zdata);
```

[23]:
```
def subplots_1d(s2_allfield_10p_ps, s2_particles, include):
    '''
    include can be 0 (meaning x), 1 (meaning y) or 2 (meaning z)
    '''

    s2_allfield_10p_ps_fig = plt.figure()
    s2_allfield_10p_ps_fig.set_figheight(20)
    s2_allfield_10p_ps_fig.set_figwidth(20)
    spec = mpl.gridspec.GridSpec(ncols=4, nrows=3,
                         width_ratios=[1, 1, 1, 1], wspace=0,
                         hspace=0, height_ratios=[1,1,1])
    for i in range(len(s2_particles)):
        #s2_allfield_10p_ps_ax = s2_allfield_10p_ps_fig.add_subplot(3, 4, i+1,␣
↪projection='3d')
        s2_allfield_10p_ps_ax = s2_allfield_10p_ps_fig.add_subplot(spec[i])
        #s2_allfield_10p_ps_ax.view_init(20, -80)
        s2_allfield_ap_ps_xyOrzdata = [elem[include] for elem in␣
↪s2_allfield_10p_ps[i]]
        s2_allfield_10p_ps_ax.scatter(np.
↪arange(len(s2_allfield_ap_ps_xyOrzdata)), s2_allfield_ap_ps_xyOrzdata);
```

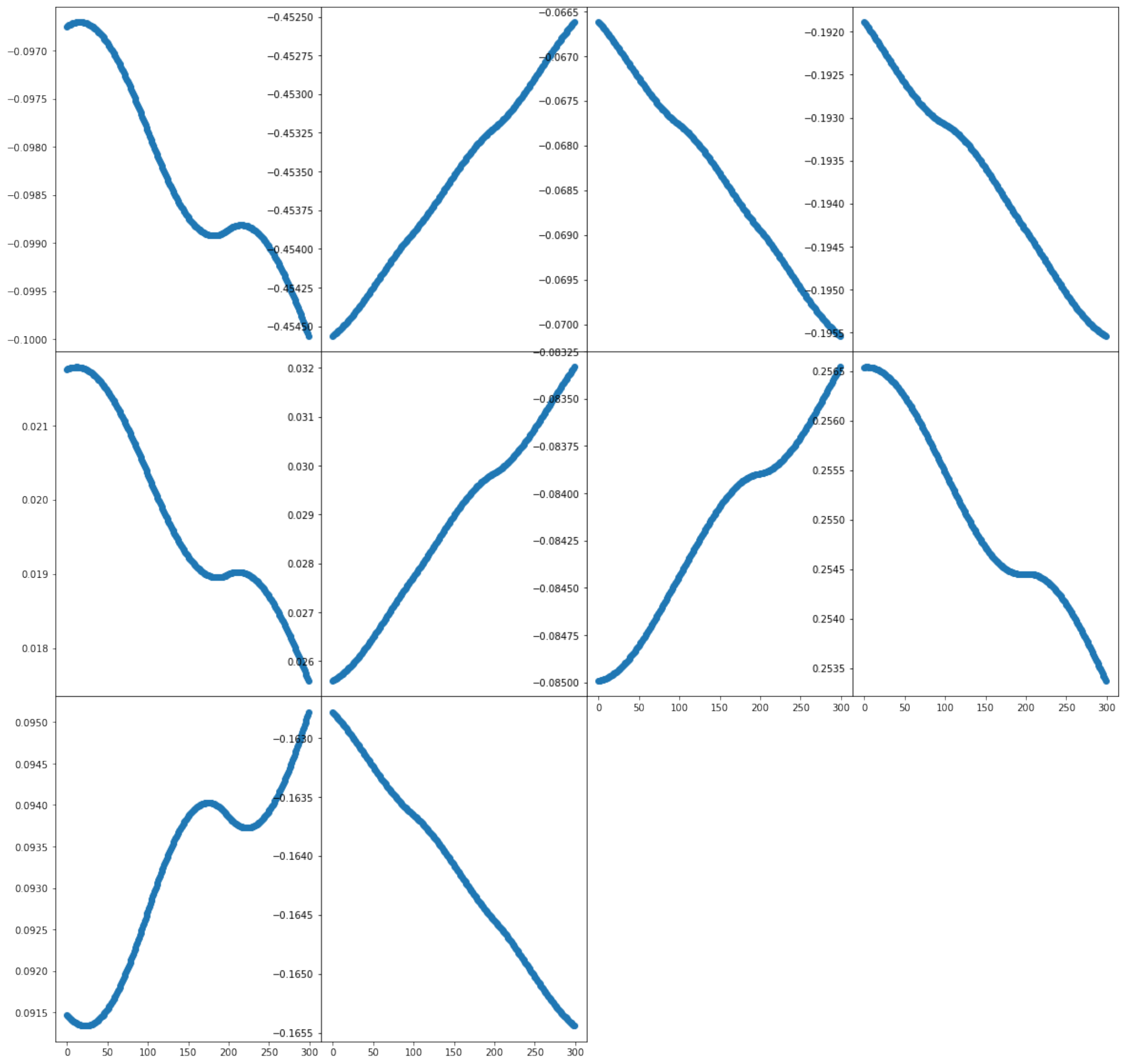
[24]:
```
# Plot the positions
subplots_3d(s2_allfield_10p_ps, s2_particles)
#plt.savefig('subps3', dpi='figure', format='png')
```



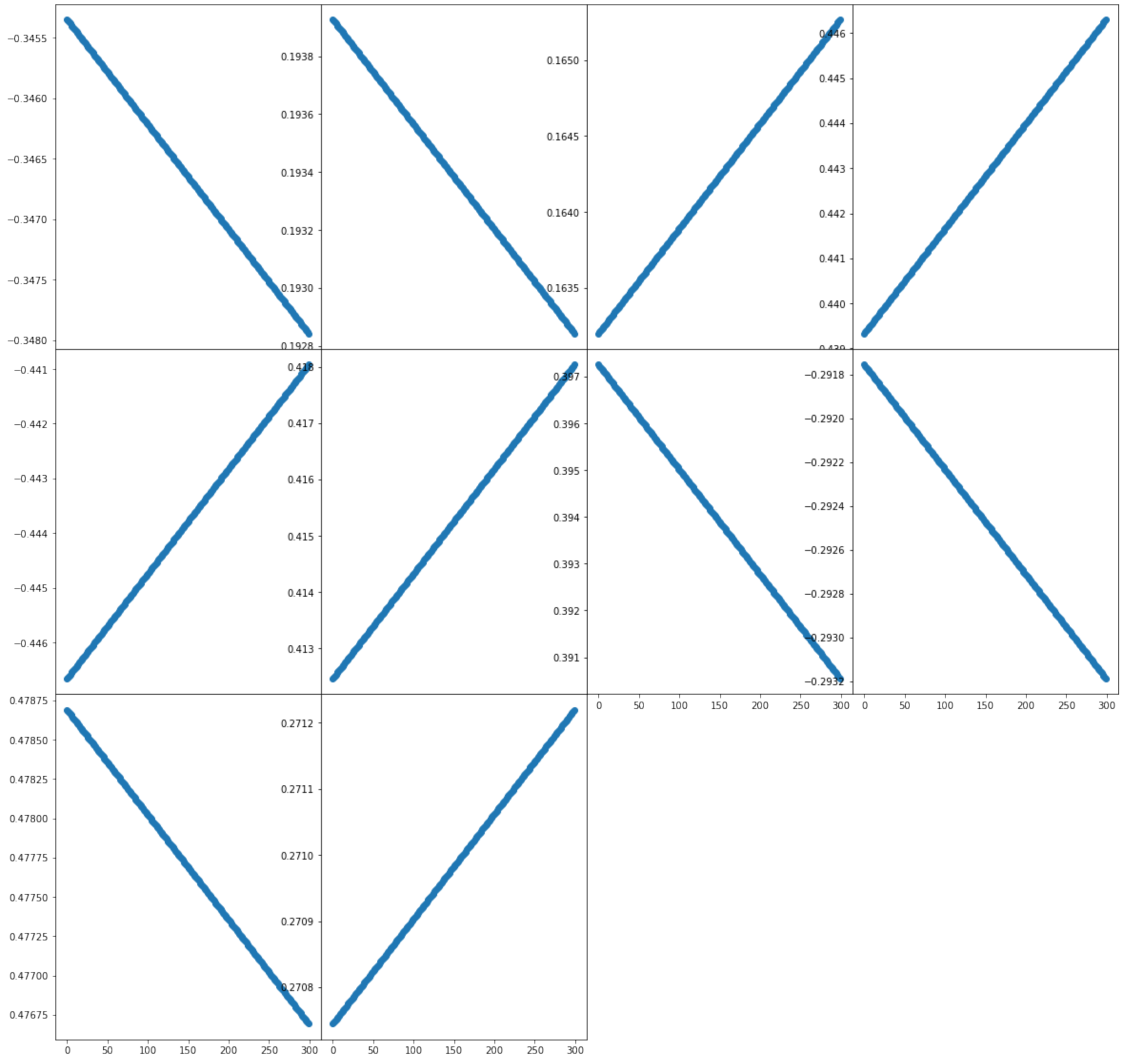
[25]:
```
# Plot the x positions
subplots_1d(s2_allfield_10p_ps, s2_particles, include=0)
#plt.savefig('subpsx3', dpi='figure', format='png')
```



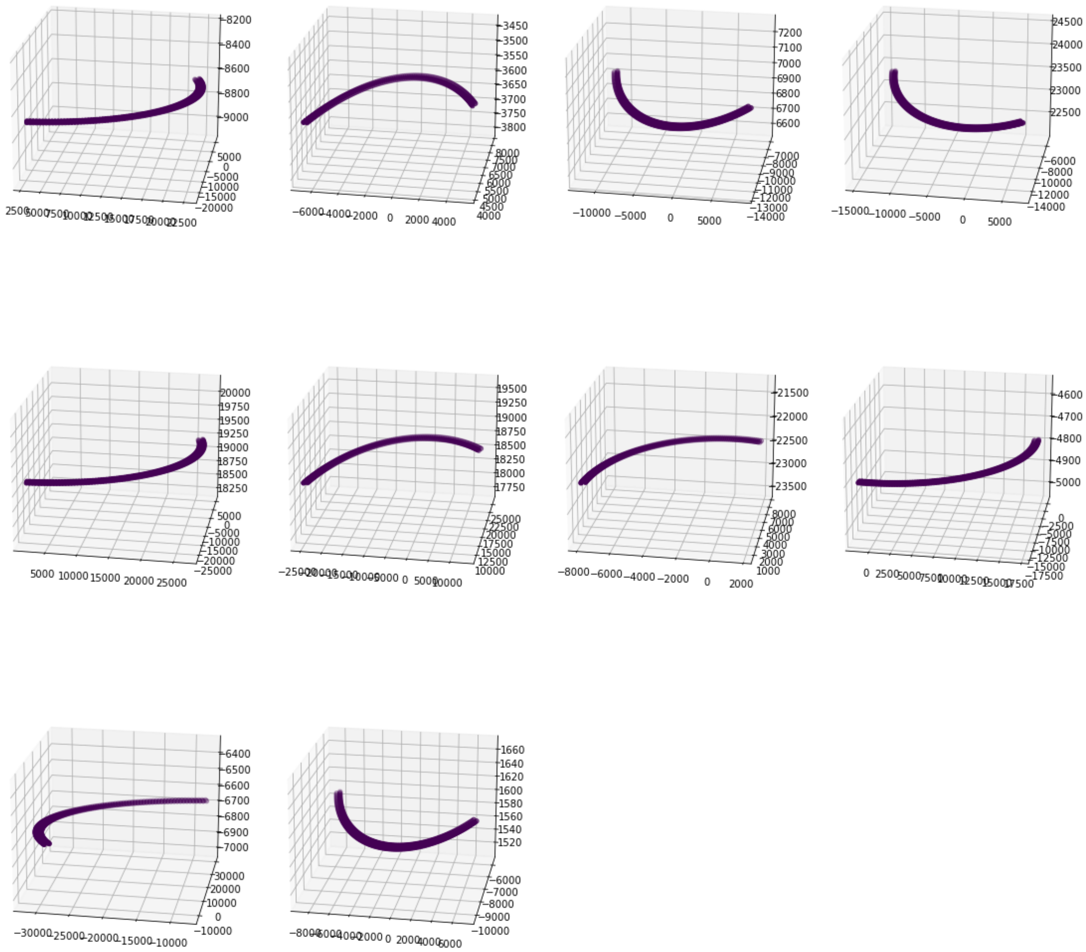
[26]:
```
# Plot the y positions
subplots_1d(s2_allfield_10p_ps, s2_particles, include=1)
#plt.savefig('subpsy3', dpi='figure', format='png')
```



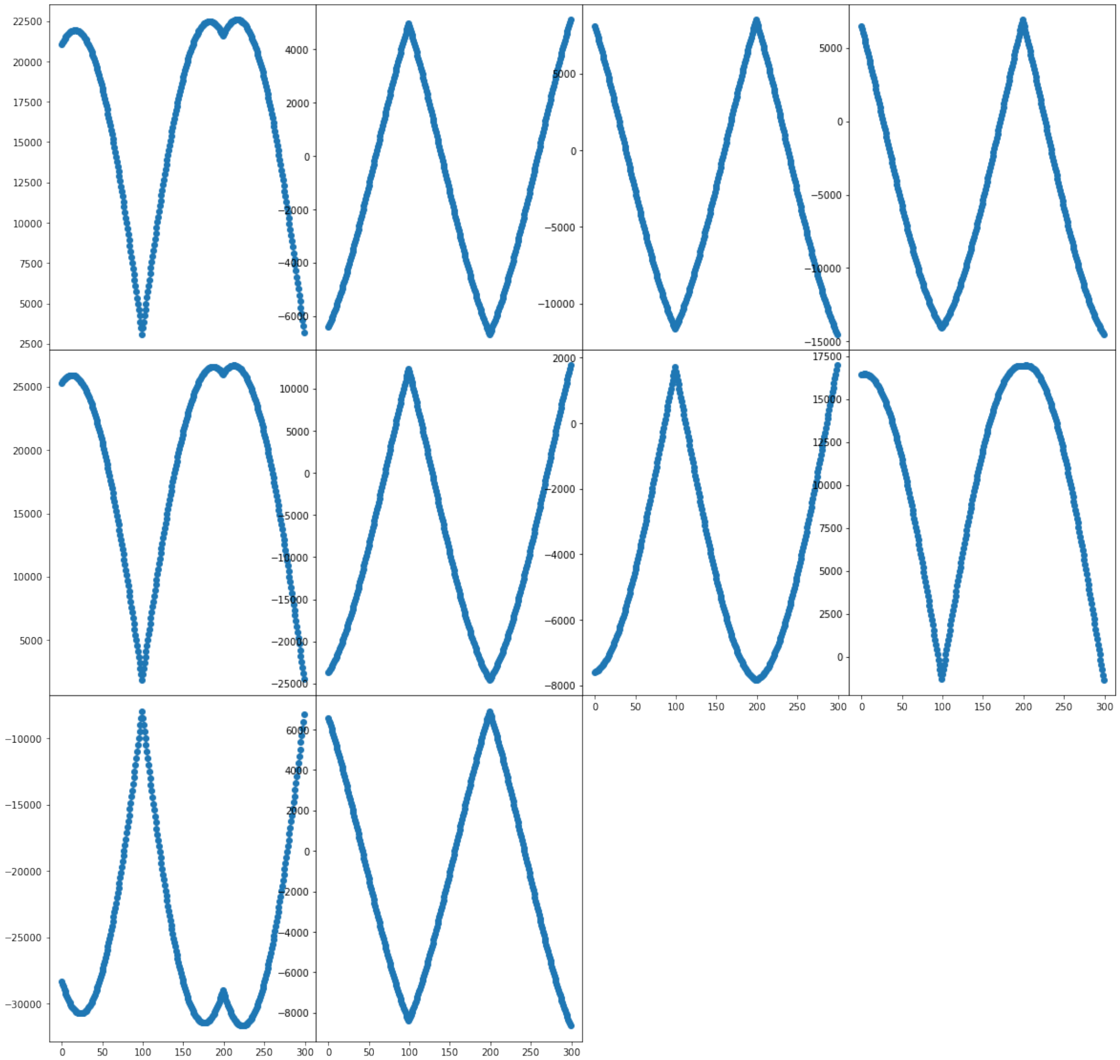
```
[27]: # Plot the z positions
      subplots_1d(s2_allfield_10p_ps, s2_particles, include=2)
      #plt.savefig('subpsz3', dpi='figure', format='png')
```



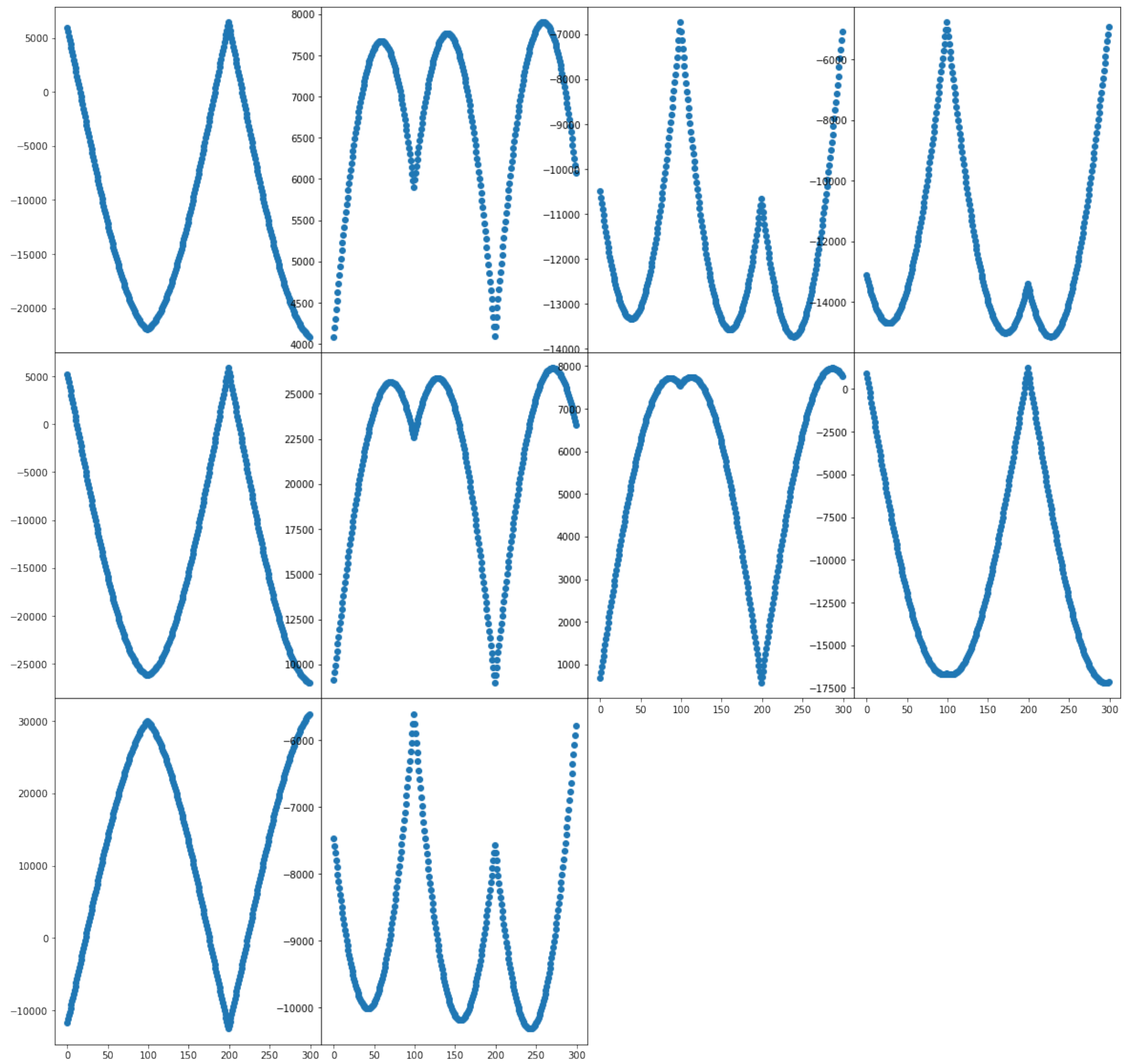
[28]:
```
# Plot the velocities
subplots_3d(s2_allfield_10p_vs, s2_particles)
#plt.savefig('subvs3', dpi='figure', format='png')
```



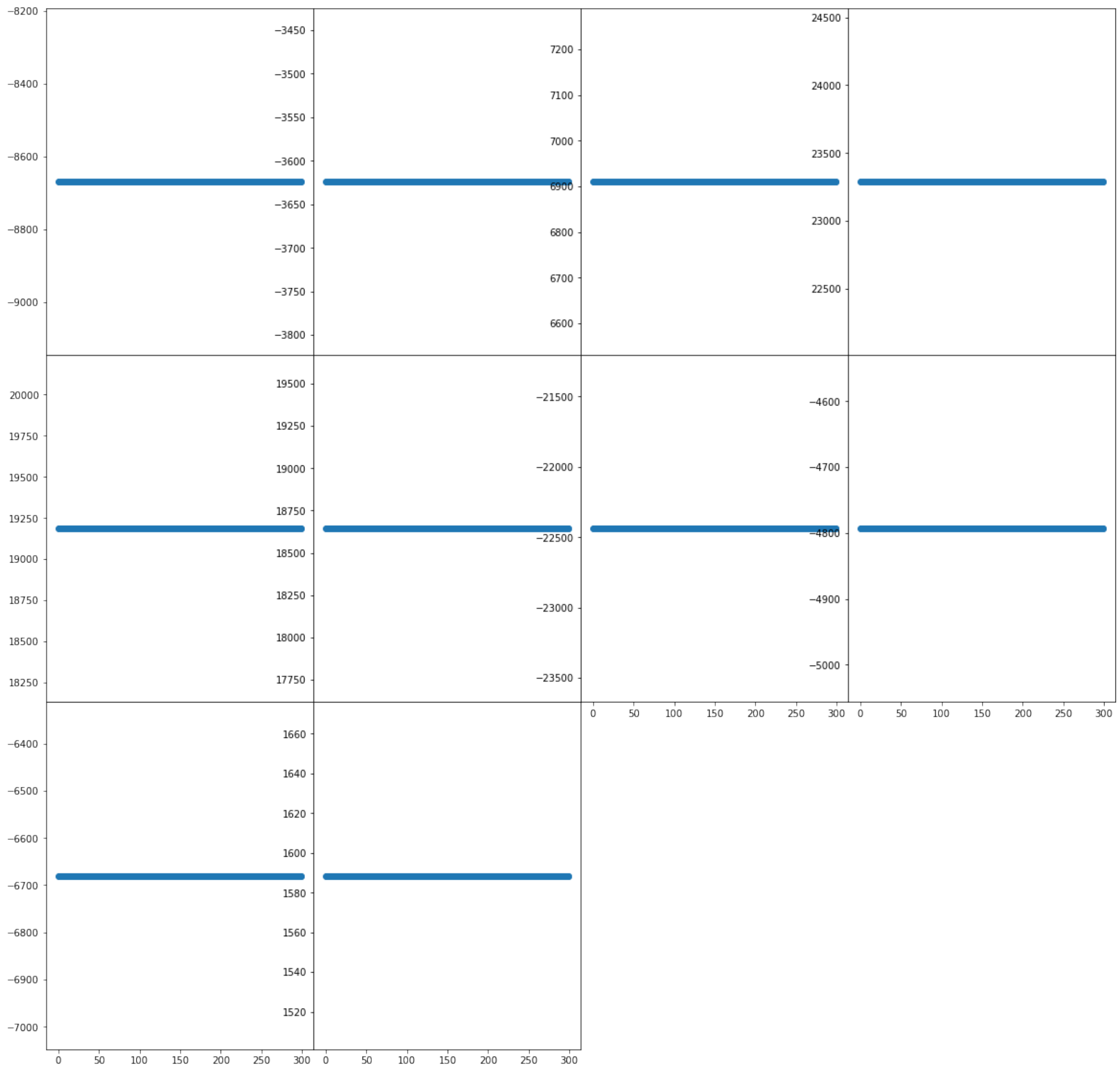
[29]:
```
# Plot the x velocities
subplots_1d(s2_allfield_10p_vs, s2_particles, include=0)
#plt.savefig('subvsx3', dpi='figure', format='png')
```



[30]:
```python
# Plot the y velocities
subplots_1d(s2_allfield_10p_vs, s2_particles, include=1)
#plt.savefig('subvsy3', dpi='figure', format='png')
```



[31]:
```
# Plot the z velocities
subplots_1d(s2_allfield_10p_vs, s2_particles, include=2)
#plt.savefig('subvsz3', dpi='figure', format='png')
```



[39]:
```
def subplot_animation_3d(positions, s2_particles):
    '''
    Here each element of positions is data for 1 particle that one would give as input to
    plot_animation_3d function, i.e. position or velocity update history of 1 particle

    This function can plot both positions and velocities
    '''

    #positions = np.array(np.array([xdata, ydata, zdata]))
    FRAMES = np.shape(positions)[1]
    # Here positions has shape (10, 1089, 3)
    s2_allfield_10p_ps_axes = []
```

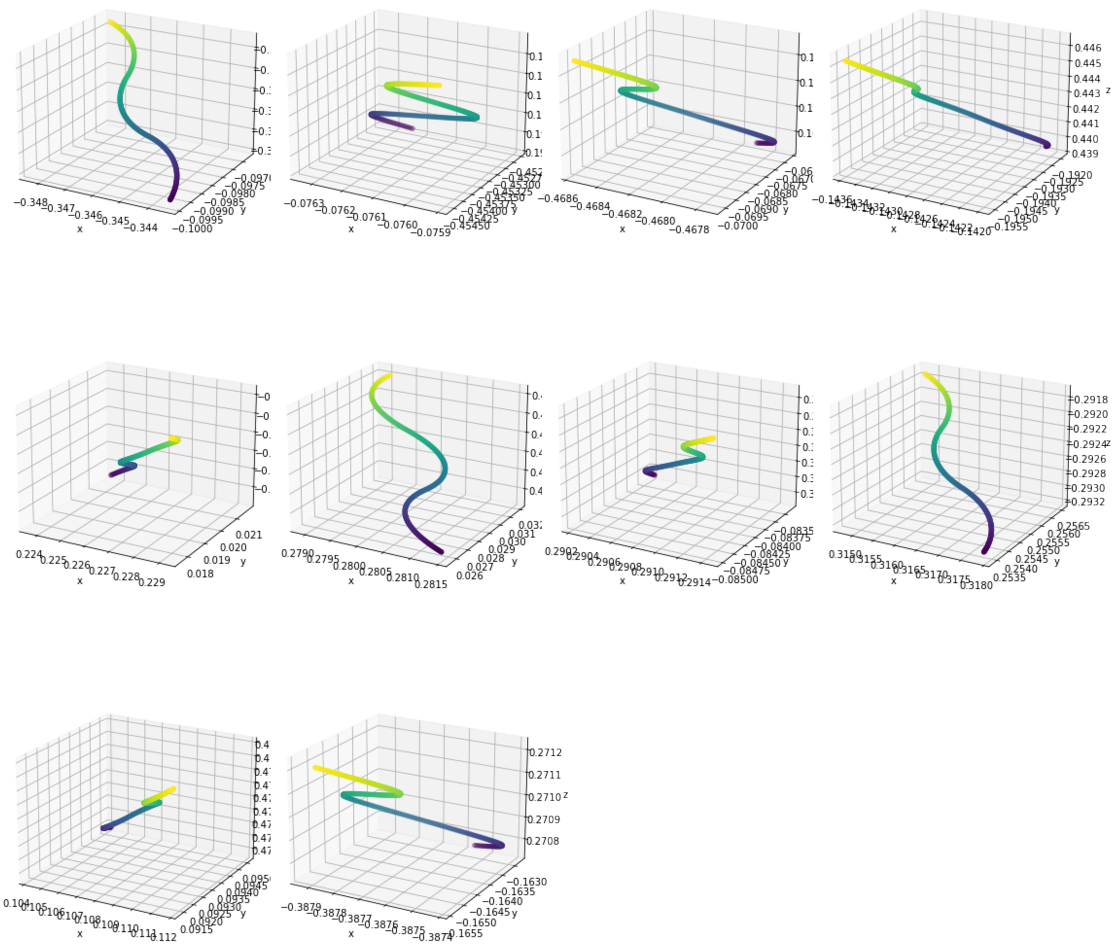
```
    s2_allfield_10p_ps_fig = plt.figure()
    s2_allfield_10p_ps_fig.set_figheight(20)
    s2_allfield_10p_ps_fig.set_figwidth(20)
    spec = mpl.gridspec.GridSpec(ncols=4, nrows=3,
                         width_ratios=[1, 1, 1, 1], wspace=0,
                         hspace=0, height_ratios=[1,1,1])
    #ax = fig.add_subplot(111, projection='3d')
    for i in range(len(s2_particles)):
        #s2_allfield_10p_ps_ax = s2_allfield_10p_ps_fig.add_subplot(3, 4, i+1,␣
↪projection='3d')
        s2_allfield_10p_ps_ax = s2_allfield_10p_ps_fig.add_subplot(spec[i],␣
↪projection='3d')
        s2_allfield_10p_ps_axes.append(s2_allfield_10p_ps_ax)

    def init():
        for i in range(len(s2_particles)):

            s2_allfield_10p_ps_axes[i].view_init(elev=20., azim=0)
            s2_allfield_10p_ps_axes[i].set_xlabel('x')
            s2_allfield_10p_ps_axes[i].set_ylabel('y')
            s2_allfield_10p_ps_axes[i].set_zlabel('z')

    # animation function.  This is called sequentially
    def animate(i):
        current_index = int(positions.shape[1] / FRAMES * i)
        # For line plot uncomment the following line
        # ax.plot3D(positions[:current_index, 0], positions[:current_index, 1],␣
↪positions[:current_index, 2])

        for j in range(len(s2_particles)):
            s2_allfield_10p_ps_axes[j].cla()
            s2_allfield_10p_ps_axes[j].view_init(elev=20., azim=i)
            s2_allfield_10p_ps_axes[j].set_xlabel('x')
            s2_allfield_10p_ps_axes[j].set_ylabel('y')
            s2_allfield_10p_ps_axes[j].set_zlabel('z')
            position = positions[j]
            s2_allfield_ap_ps_zdata = position[:current_index, 2] # Animate␣
↪this plot as well.
            s2_allfield_ap_ps_xdata = position[:current_index, 0]
            s2_allfield_ap_ps_ydata = position[:current_index, 1]
            s2_allfield_10p_ps_axes[j].scatter3D(s2_allfield_ap_ps_xdata,␣
↪s2_allfield_ap_ps_ydata, s2_allfield_ap_ps_zdata,\
                                    c=s2_allfield_ap_ps_zdata);

    # call the animator.
    anim = animation.FuncAnimation(s2_allfield_10p_ps_fig, animate,␣
↪init_func=init, frames=FRAMES, interval=100)
```

```
    return anim
```

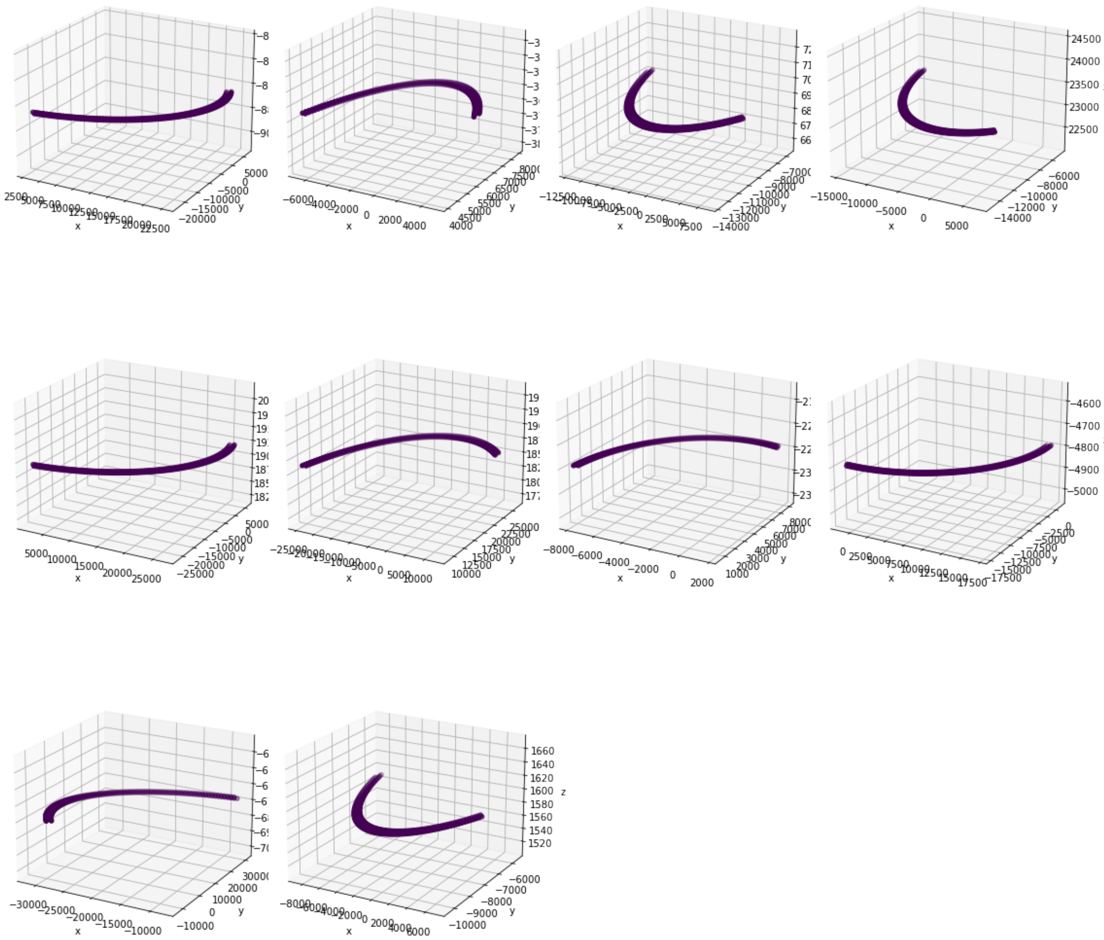
[40]:
```
def subplot_animation_1d(positions, s2_particles, include):

    #positions = np.array(np.array([xdata, ydata, zdata]))
    FRAMES = np.shape(positions)[1]
    # Here positions has shape (10, 1089, 3)

    s2_allfield_10p_ps_axes = []
    s2_allfield_10p_ps_fig = plt.figure()
    s2_allfield_10p_ps_fig.set_figheight(20)
    s2_allfield_10p_ps_fig.set_figwidth(20)
    spec = mpl.gridspec.GridSpec(ncols=4, nrows=3,
                         width_ratios=[1, 1, 1, 1], wspace=0,
                         hspace=0, height_ratios=[1,1,1])
    for i in range(len(s2_particles)):
        #s2_allfield_10p_ps_ax = s2_allfield_10p_ps_fig.add_subplot(4,3,i+1)
        s2_allfield_10p_ps_ax = s2_allfield_10p_ps_fig.add_subplot(spec[i])
        s2_allfield_10p_ps_axes.append(s2_allfield_10p_ps_ax)

    def init():
    # tab here: the for loop is inside the init function if the init function␣
↪is used
        for j in range(len(s2_particles)):
            s2_allfield_10p_ps_axes[j].set_xlabel('steps')
            s2_allfield_10p_ps_axes[j].set_ylabel(chr(include + 120))

    # animation function.  This is called sequentially
    def animate(i):
        current_index = int(positions.shape[1] / FRAMES * i)

        for j in range(len(s2_particles)):
            s2_allfield_10p_ps_axes[j].cla()
            s2_allfield_10p_ps_axes[j].set_xlabel('steps')
            s2_allfield_10p_ps_axes[j].set_ylabel(chr(include + 120))

            position = positions[j]
            s2_allfield_ap_ps_xyOrzdata = position[:current_index, include]
            s2_allfield_10p_ps_axes[j].scatter(np.
↪arange(len(s2_allfield_ap_ps_xyOrzdata)), s2_allfield_ap_ps_xyOrzdata);

    # call the animator.
    #anim = animation.FuncAnimation(s2_allfield_10p_ps_fig, animate,␣
↪frames=FRAMES, interval=100)
    anim = animation.FuncAnimation(s2_allfield_10p_ps_fig, animate,␣
↪init_func=init, frames=FRAMES, interval=100)
```

```
    return anim
```

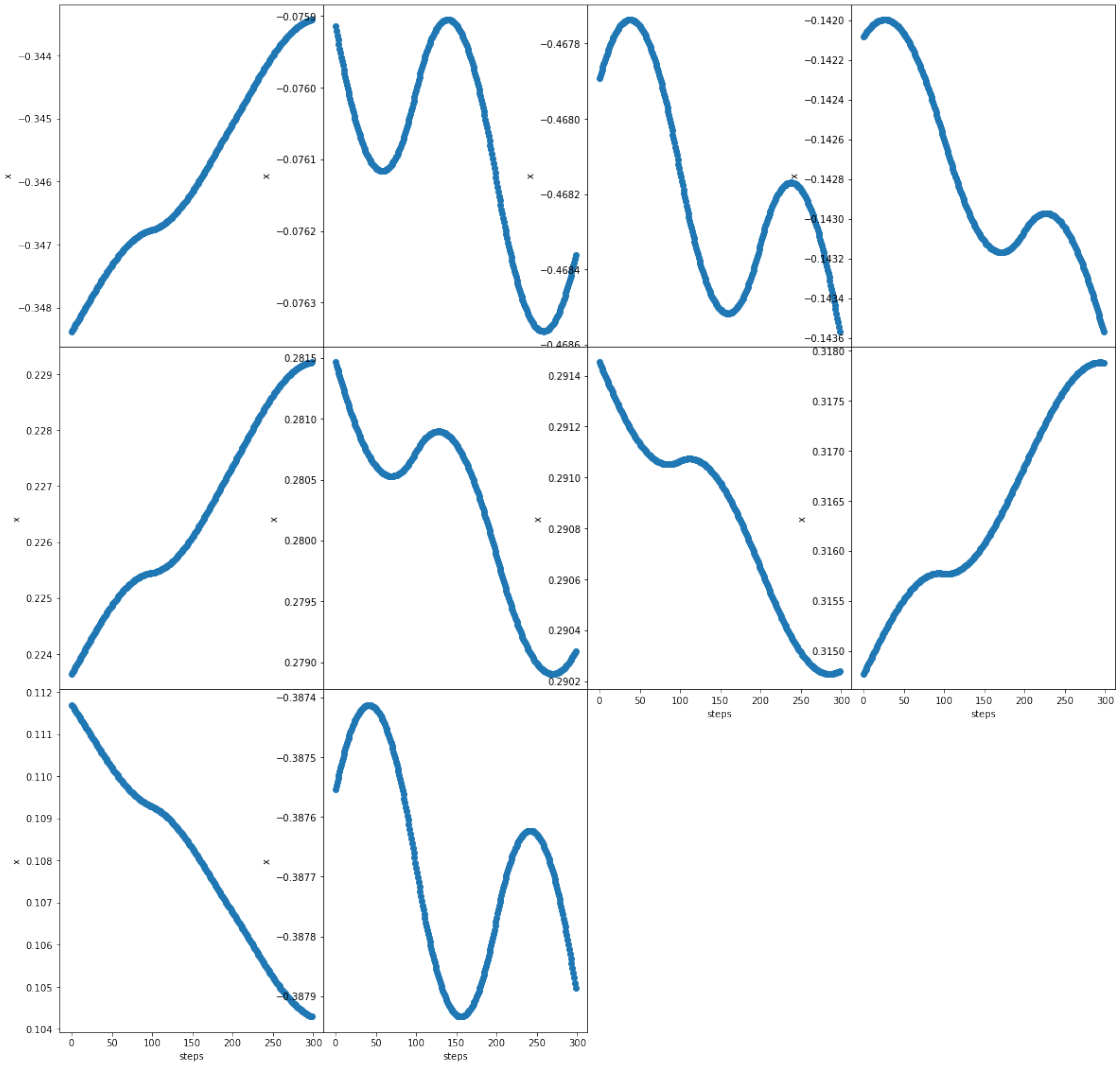
[41]:
```
# Subplot Animate the positions
s2_allfield_10p_ps_anim = subplot_animation_3d(s2_allfield_10p_ps, s2_particles)
#display_animation(s2_allfield_10p_ps_anim)
#s2_allfield_10p_ps_anim.save(r'subps3.mp4')
```



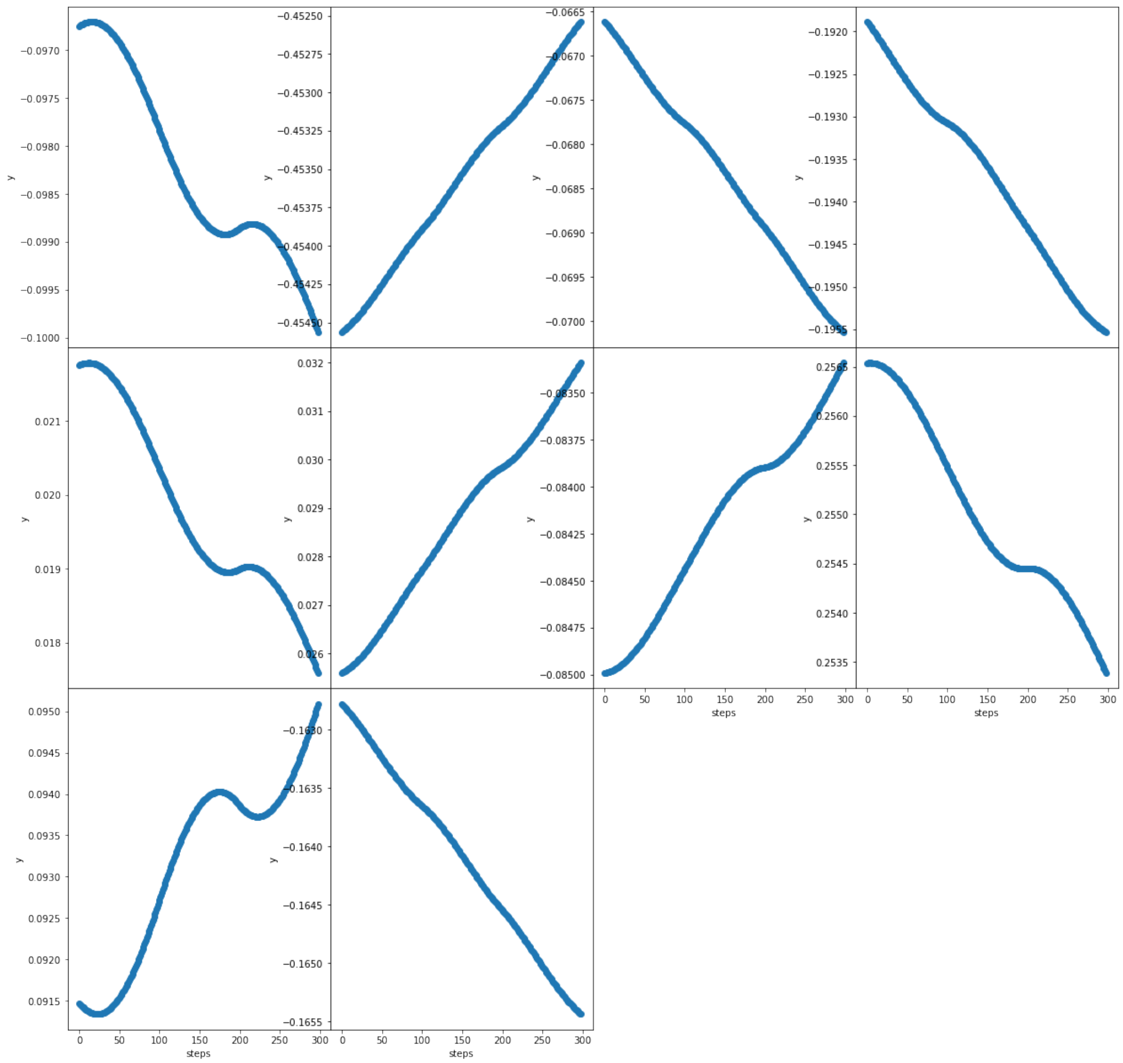
[42]:
```
# Subplot Animate the velocities
s2_allfield_10p_vs_anim = subplot_animation_3d(s2_allfield_10p_vs, s2_particles)
#display_animation(s2_allfield_10p_vs_anim)
#s2_allfield_10p_vs_anim.save(r'subvs3.mp4')
```



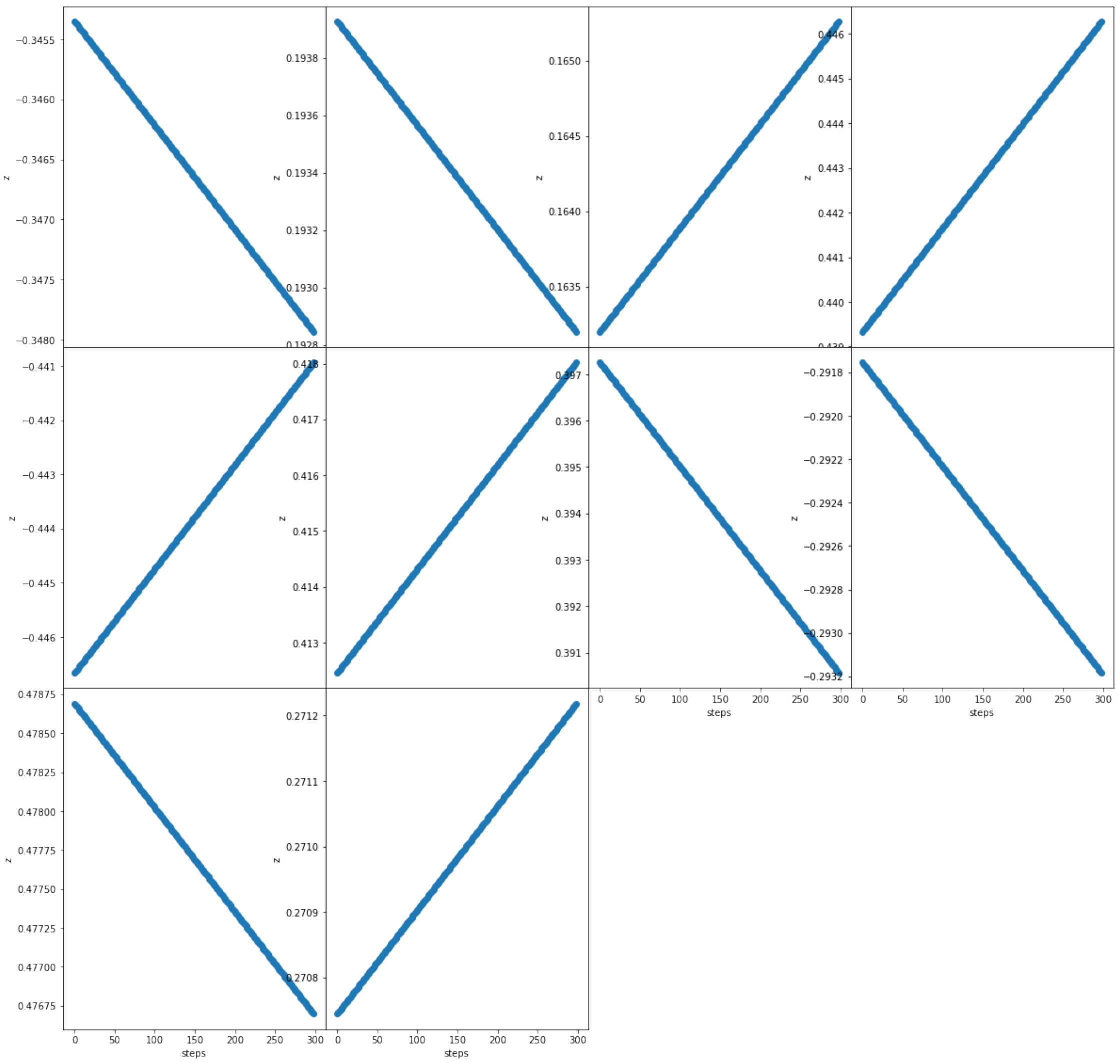
[43]:
```
# Subplot Animate the x positions
s2_allfield_10p_ps_x_anim = subplot_animation_1d(s2_allfield_10p_ps,␣
    ↪s2_particles, include=0)
#display_animation(s2_allfield_10p_ps_x_anim)
#s2_allfield_10p_ps_x_anim.save(r'subpsx3.mp4')
```



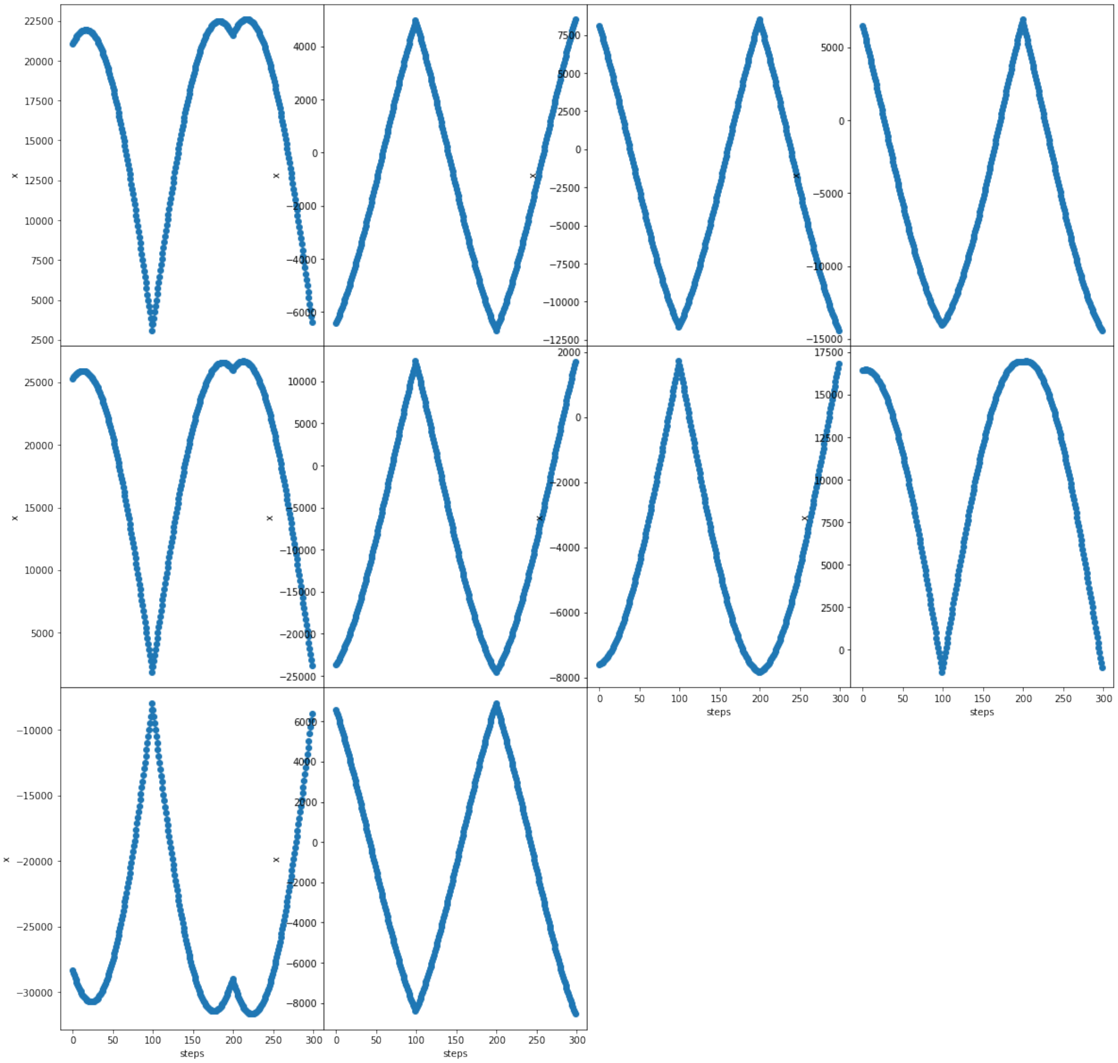
[44]:
```
# Subplot Animate the y positions
s2_allfield_10p_ps_y_anim = subplot_animation_1d(s2_allfield_10p_ps,␣
↪s2_particles, include=1)
#display_animation(s2_allfield_10p_ps_y_anim)
#s2_allfield_10p_ps_y_anim.save(r'subpsy3.mp4')
```



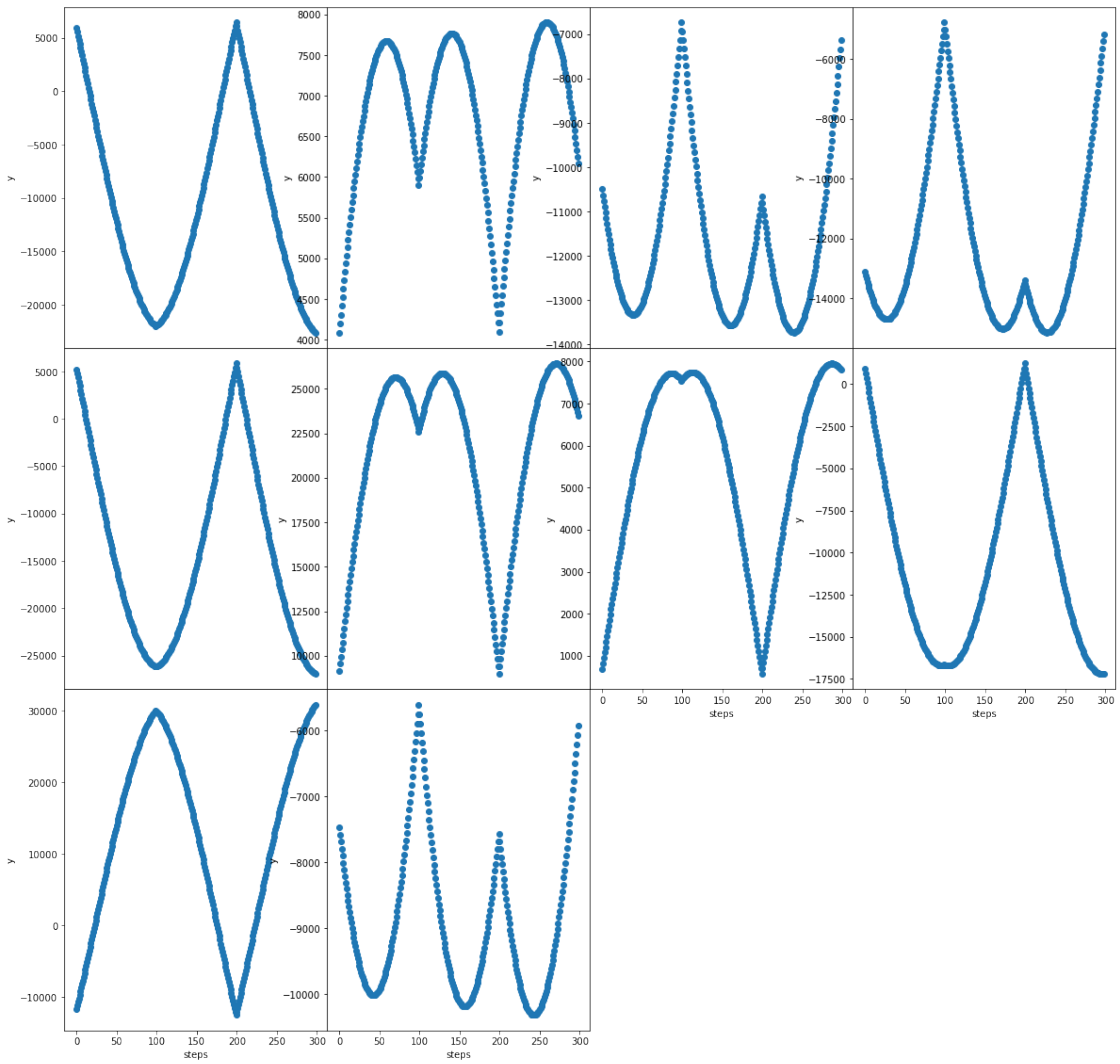
[45]:
```
# Subplot Animate the z positions
s2_allfield_10p_ps_z_anim = subplot_animation_1d(s2_allfield_10p_ps,␣
↪s2_particles, include=2)
#display_animation(s2_allfield_10p_ps_z_anim)
#s2_allfield_10p_ps_z_anim.save(r'subpsz3.mp4')
```



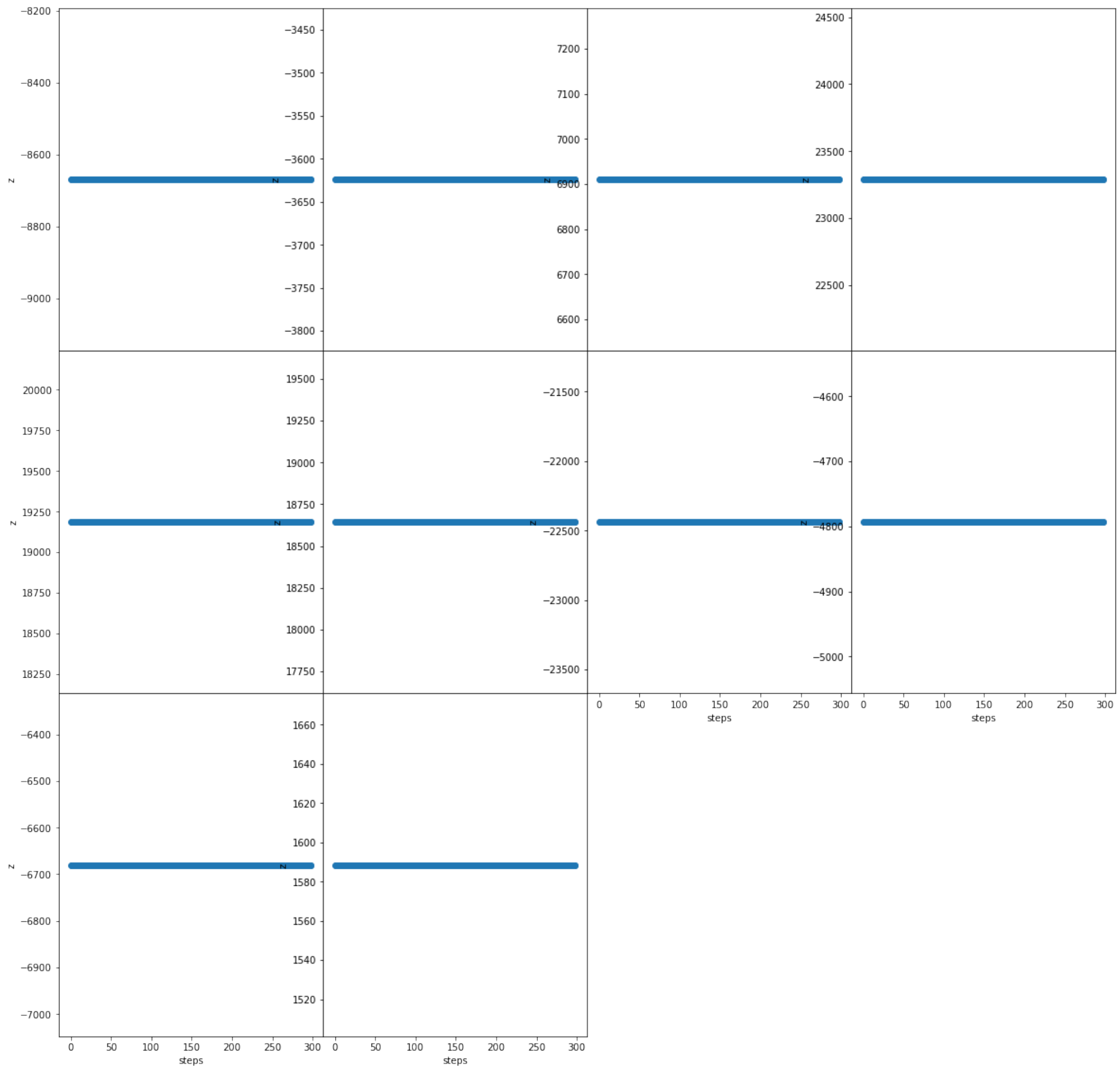
[46]:
```
# Subplot Animate the x velocities
s2_allfield_10p_vs_x_anim = subplot_animation_1d(s2_allfield_10p_vs,␣
↪s2_particles, include=0)
#display_animation(s2_allfield_10p_vs_x_anim)
#s2_allfield_10p_vs_x_anim.save(r'subvsx3.mp4')
```



[47]:
```
# Subplot Animate the y velocities
s2_allfield_10p_vs_y_anim = subplot_animation_1d(s2_allfield_10p_vs,␣
↪s2_particles, include=1)
#display_animation(s2_allfield_10p_vs_y_anim)
#s2_allfield_10p_vs_y_anim.save(r'subvsy3.mp4')
```



[48]:
```
# Subplot Animate the z velocities
s2_allfield_10p_vs_z_anim = subplot_animation_1d(s2_allfield_10p_vs,
 ↪s2_particles, include=2)
#display_animation(s2_allfield_10p_vs_z_anim)
#s2_allfield_10p_vs_z_anim.save(r'subvsz3.mp4')
```



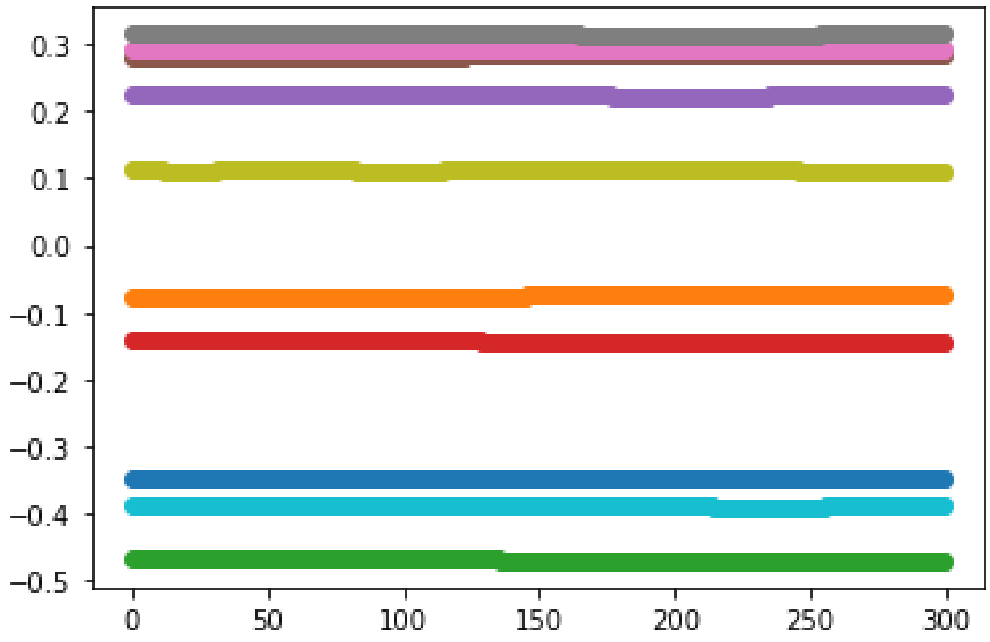
```
[ ]:
```

```
[56]: # Animate the positions
s2_allfield_10p_ps_anim = multiplot_animation_3d(s2_allfield_10p_ps)
display_animation(s2_allfield_10p_ps_anim)
#s2_allfield_10p_ps_anim.save(r'multips2.mp4')
```

[56]: <IPython.core.display.HTML object>

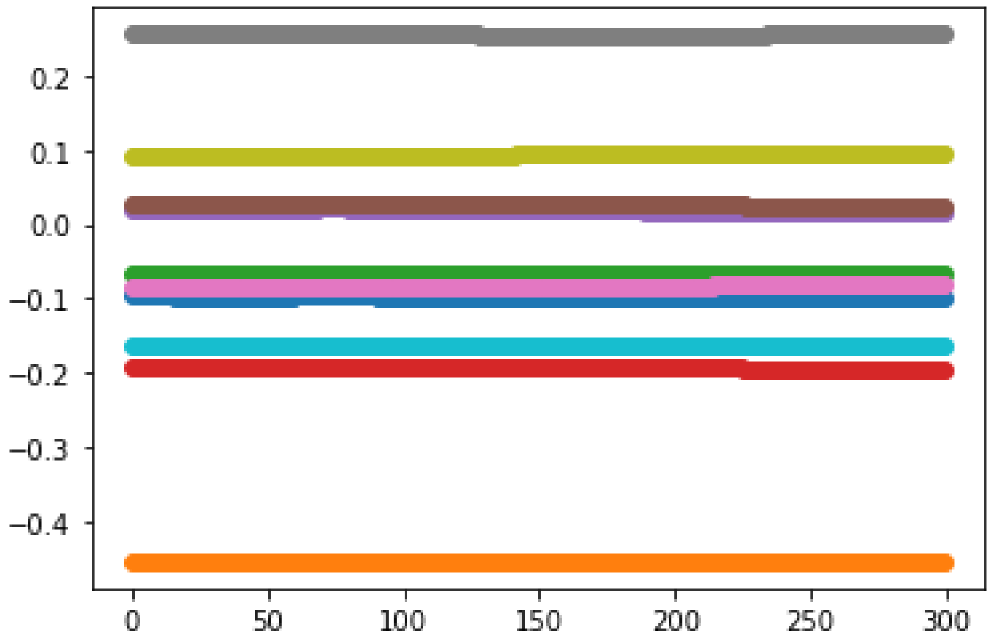
```
[71]: # Plot x positions
s2_allfield_10p_ps_x_fig = plt.figure()
s2_allfield_10p_ps_x_ax = plt.axes()
for i in range(len(s2_particles)):
```

```
    #s2_allfield_ap_ps_zdata = [elem[2] for elem in s2_allfield_10p_ps[i]] #␣
↪Animate this plot as well.
    s2_allfield_ap_ps_xdata = [elem[0] for elem in s2_allfield_10p_ps[i]]
    #s2_allfield_ap_ps_ydata = [elem[1] for elem in s2_allfield_10p_ps[i]]
    s2_allfield_10p_ps_x_ax.scatter(np.arange(len(s2_allfield_ap_ps_xdata)),␣
↪s2_allfield_ap_ps_xdata);
#plt.savefig('multipsx2', dpi='figure', format='png')
```



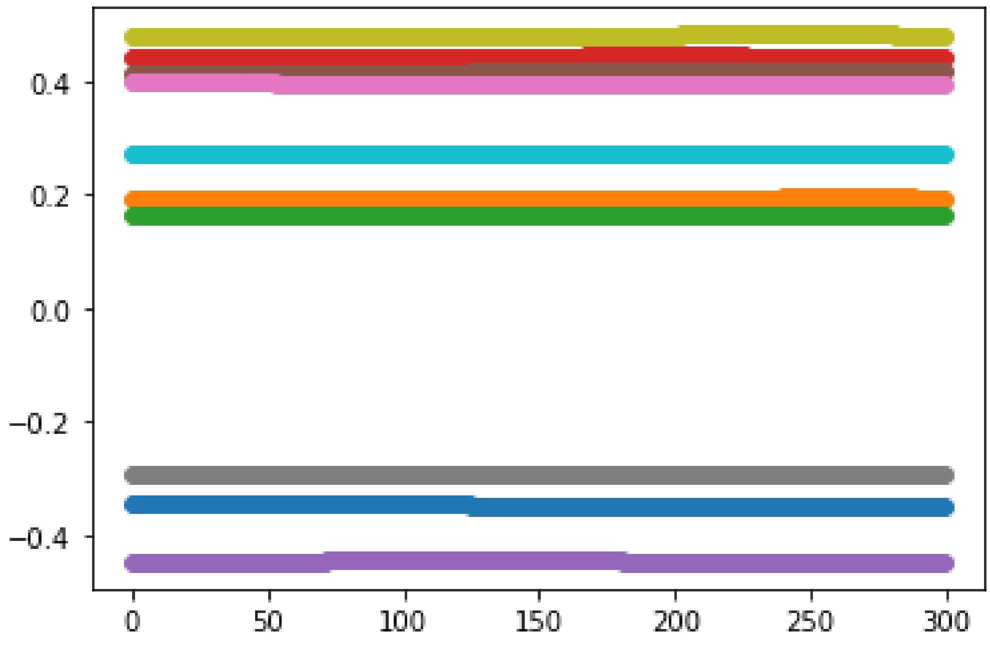
[41]:
```
# Animate x positions
s2_allfield_10p_ps_x_anim = multiplot_animation_1d(s2_allfield_10p_ps,␣
↪include=0)
display_animation(s2_allfield_10p_ps_x_anim)
#s2_allfield_10p_ps_x_anim.save(r'multipsx2.mp4')
```

[72]:
```
# Plot y positions
s2_allfield_10p_ps_y_fig = plt.figure()
s2_allfield_10p_ps_y_ax = plt.axes()
for i in range(len(s2_particles)):
    #s2_allfield_ap_ps_zdata = [elem[2] for elem in s2_allfield_10p_ps[i]] #␣
↪Animate this plot as well.
    #s2_allfield_ap_ps_xdata = [elem[0] for elem in s2_allfield_10p_ps[i]]
    s2_allfield_ap_ps_ydata = [elem[1] for elem in s2_allfield_10p_ps[i]]
    s2_allfield_10p_ps_y_ax.scatter(np.arange(len(s2_allfield_ap_ps_ydata)),␣
↪s2_allfield_ap_ps_ydata);
#plt.savefig('multipsy2', dpi='figure', format='png')
```



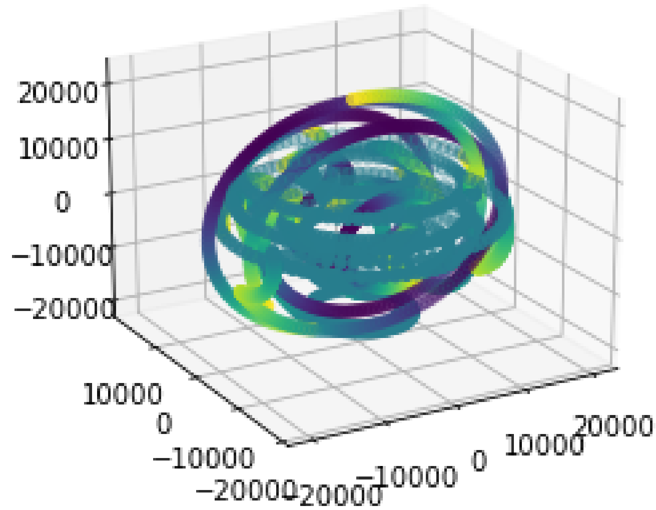
[47]:
```
# Animate y positions
s2_allfield_10p_ps_y_anim = multiplot_animation_1d(s2_allfield_10p_ps,␣
↪include=1)
display_animation(s2_allfield_10p_ps_y_anim)
#s2_allfield_10p_ps_y_anim.save(r'multipsy2.mp4')
```

[75]:
```
# Plot z positions
s2_allfield_10p_ps_z_fig = plt.figure()
s2_allfield_10p_ps_z_ax = plt.axes()
for i in range(len(s2_particles)):
    s2_allfield_ap_ps_zdata = [elem[2] for elem in s2_allfield_10p_ps[i]] #␣
↪Animate this plot as well.
    #s2_allfield_ap_ps_xdata = [elem[0] for elem in s2_allfield_10p_ps[i]]
    #s2_allfield_ap_ps_ydata = [elem[1] for elem in s2_allfield_10p_ps[i]]
    s2_allfield_10p_ps_z_ax.scatter(np.arange(len(s2_allfield_ap_ps_zdata)),␣
↪s2_allfield_ap_ps_zdata);
#plt.savefig('multipsz2', dpi='figure', format='png')
```



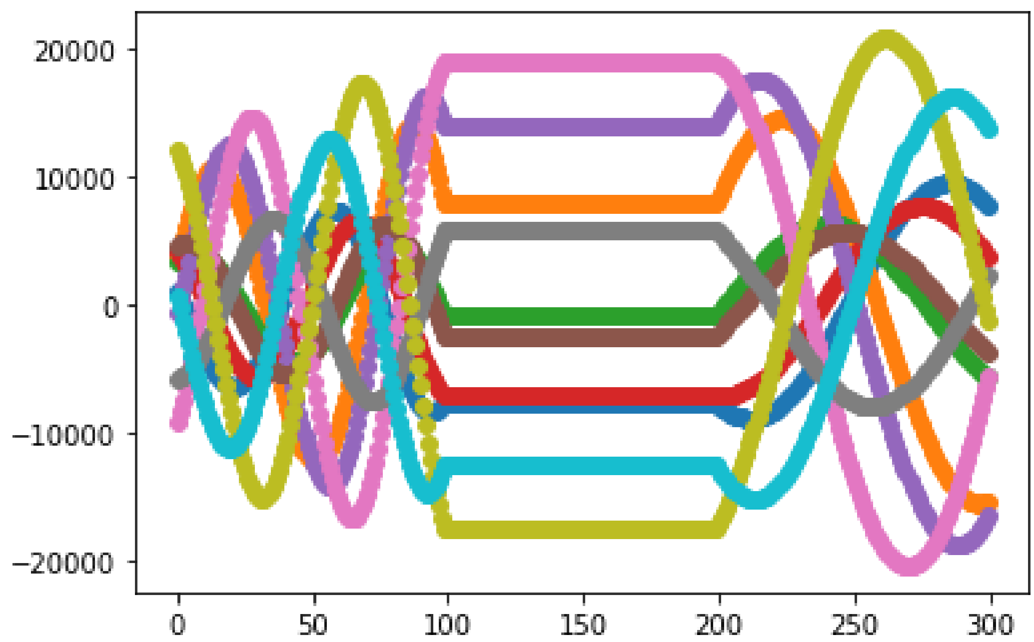
[55]:
```
# Animate z positions
s2_allfield_10p_ps_z_anim = multiplot_animation_1d(s2_allfield_10p_ps,␣
↪include=2)
display_animation(s2_allfield_10p_ps_z_anim)
#s2_allfield_10p_ps_z_anim.save(r'multipsz2.mp4')
```

[49]:
```
# Plot the velocities
s2_allfield_10p_vs_fig = plt.figure()
s2_allfield_10p_vs_ax = plt.axes(projection='3d')
s2_allfield_10p_vs_ax.view_init(20, -120)

# Data for three-dimensional scattered points
for i in range(len(s2_particles)):

    s2_allfield_ap_vs_zdata = [elem[2] for elem in s2_allfield_10p_vs[i]] #␣
↪Animate this plot as well.
    s2_allfield_ap_vs_xdata = [elem[0] for elem in s2_allfield_10p_vs[i]]
    s2_allfield_ap_vs_ydata = [elem[1] for elem in s2_allfield_10p_vs[i]]
    s2_allfield_10p_vs_ax.scatter3D(s2_allfield_ap_vs_xdata,␣
↪s2_allfield_ap_vs_ydata, s2_allfield_ap_vs_zdata,\
                                   c=s2_allfield_p0_vs_zdata);
#plt.savefig('multivs2', dpi='figure', format='png')
```



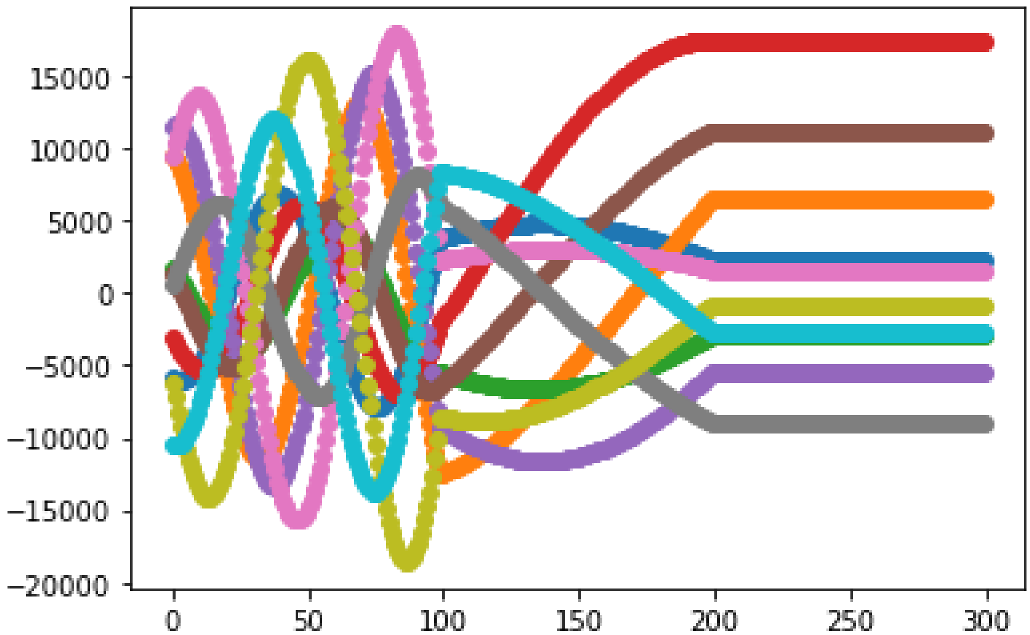

```
[52]: # Animate the velocities
s2_allfield_10p_vs_anim = multiplot_animation_3d(s2_allfield_10p_vs)
display_animation(s2_allfield_10p_vs_anim)
#s2_allfield_10p_vs_anim.save(r'multivs2.mp4')
```

```
[53]: # Plot x velocities
s2_allfield_10p_vs_x_fig = plt.figure()
s2_allfield_10p_vs_x_ax = plt.axes()
for i in range(len(s2_particles)):
    #s2_allfield_ap_vs_zdata = [elem[2] for elem in s2_allfield_10p_vs[i]] #␣
 ↪Animate this plot as well.
    s2_allfield_ap_vs_xdata = [elem[0] for elem in s2_allfield_10p_vs[i]]
    #s2_allfield_ap_vs_ydata = [elem[1] for elem in s2_allfield_10p_vs[i]]
    s2_allfield_10p_vs_x_ax.scatter(np.arange(len(s2_allfield_ap_vs_xdata)),␣
 ↪s2_allfield_ap_vs_xdata);
#plt.savefig('multivsx2', dpi='figure', format='png')
```



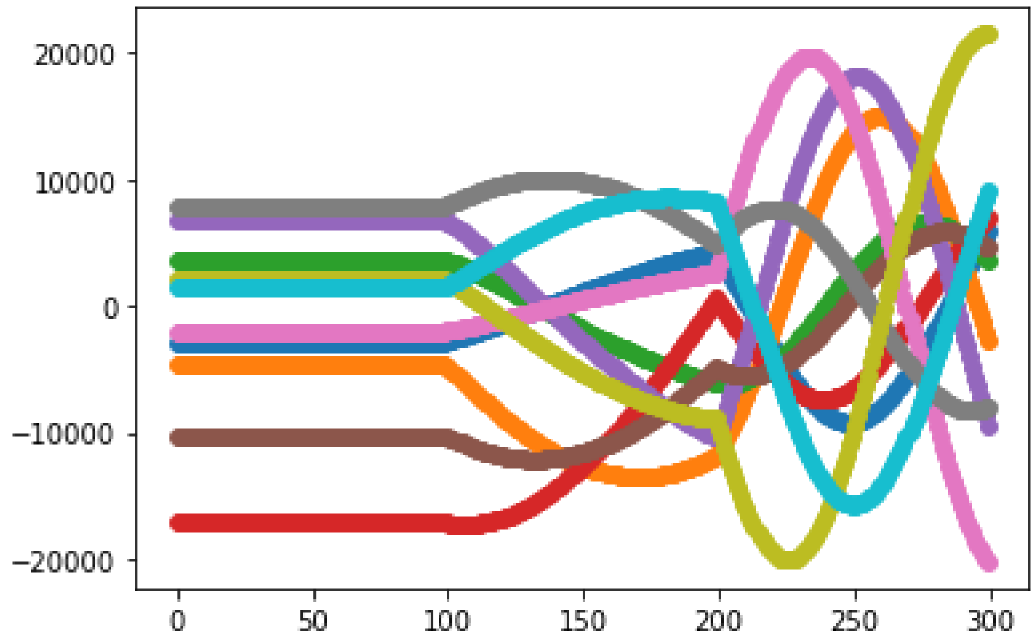
[56]:
```
# Animate x velocities
s2_allfield_10p_vs_x_anim = multiplot_animation_1d(s2_allfield_10p_vs,␣
↪include=0)
display_animation(s2_allfield_10p_vs_x_anim)
#s2_allfield_10p_vs_x_anim.save(r'multivsx2.mp4')
```

[57]:
```
# Plot y velocities
s2_allfield_10p_vs_y_fig = plt.figure()
s2_allfield_10p_vs_y_ax = plt.axes()
for i in range(len(s2_particles)):
    #s2_allfield_ap_vs_zdata = [elem[2] for elem in s2_allfield_10p_vs[i]] #␣
↪Animate this plot as well.
    #s2_allfield_ap_vs_xdata = [elem[0] for elem in s2_allfield_10p_vs[i]]
    s2_allfield_ap_vs_ydata = [elem[1] for elem in s2_allfield_10p_vs[i]]
    s2_allfield_10p_vs_y_ax.scatter(np.arange(len(s2_allfield_ap_vs_ydata)),␣
↪s2_allfield_ap_vs_ydata);
#plt.savefig('multivsy2', dpi='figure', format='png')
```




```
[61]: # Animate y velocities
s2_allfield_10p_vs_y_anim = multiplot_animation_1d(s2_allfield_10p_vs,␣
 ↪include=1)
display_animation(s2_allfield_10p_vs_y_anim)
#s2_allfield_10p_vs_y_anim.save(r'multivsy2.mp4')
```

```
[59]: # Plot z velocities
s2_allfield_10p_vs_z_fig = plt.figure()
s2_allfield_10p_vs_z_ax = plt.axes()
for i in range(len(s2_particles)):
    s2_allfield_ap_vs_zdata = [elem[2] for elem in s2_allfield_10p_vs[i]] #␣
 ↪Animate this plot as well.
    #s2_allfield_ap_vs_xdata = [elem[0] for elem in s2_allfield_10p_vs[i]]
    #s2_allfield_ap_vs_ydata = [elem[1] for elem in s2_allfield_10p_vs[i]]
    s2_allfield_10p_vs_z_ax.scatter(np.arange(len(s2_allfield_ap_vs_zdata)),␣
 ↪s2_allfield_ap_vs_zdata);
#plt.savefig('multivsz2', dpi='figure', format='png')
```



[62]:
```
# Animate z velocities
s2_allfield_10p_vs_z_anim = multiplot_animation_1d(s2_allfield_10p_vs,␣
↪include=2)

# call our new function to display the animation
display_animation(s2_allfield_10p_vs_z_anim)
#s2_allfield_10p_vs_z_anim.save(r'multivsz2.mp4')
```

[ ]:
```
```