ASSIGNMENT 3

Contents

Question 1

a) The Electric field for 0.1V applied at one end is:

```
global C
global Em T
global BoundX BoundY
global Pxp Px Pyp Py Vx Vy
global Vtherm
global nElectrons
global t_mn

C.q_0 = 1.60217653e-19;             % electron charge
C.hb = 1.054571596e-34;             % Dirac constant
C.h = C.hb * 2 * pi;                    % Planck constant
C.m_0 = 9.10938215e-31;             % electron mass
C.kb = 1.3806504e-23;               % Boltzmann constant
C.eps_0 = 8.854187817e-12;          % vacuum permittivity
C.mu_0 = 1.2566370614e-6;           % vacuum permeability
C.c = 299792458;                    % speed of light
C.g = 9.80665;                      % metres (32.1740 ft) per s²


Em = 0.26 * C.m_0;                    % Mass of the Electron
BoundX = 200e-9;                    % X boundary
BoundY = 100e-9;                    % Y boundary
T = 300;                            % Semiconductor temperature

t_mn = 0.2e-12;                     % Mean time between collisions

TimeSteps = 300;                   % Number of time steps

nElectrons = 1000;                    % Number of electrons

dt = 1e-14;                         % Time Step


Efield = 0.1/BoundX
```

```
Efield =

   5.0000e+05
```

b) The force is given by

```
Force = Efield * C.q_0
```

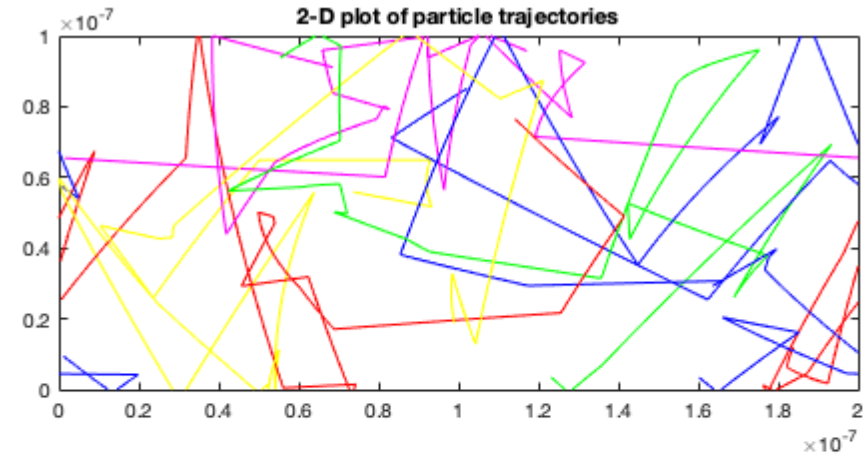
```
Force =

   8.0109e-14
```

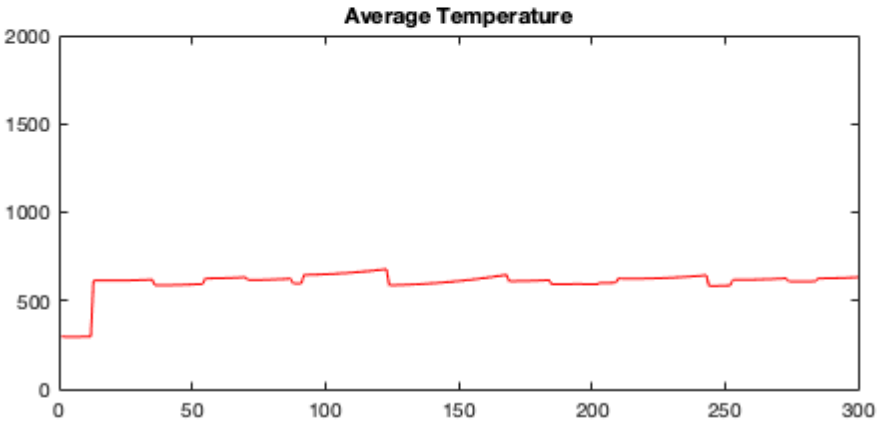
c) Acceleration and 2-D plot of particle trajectory.

```
Accel = Force/Em

Pxp(1: nElectrons) = rand(nElectrons, 1) * BoundX;
Pyp(1: nElectrons) = rand(nElectrons, 1) * BoundY;

Vtherm = sqrt(2 * C.kb * T/Em);

Vx(1: nElectrons) = randn(nElectrons, 1) * (Vtherm/sqrt(2));
Vy(1: nElectrons) = randn(nElectrons, 1) * (Vtherm/sqrt(2));

myColors = ['r' 'b' 'g' 'y' 'm' ];
myColorTyp = 1;

Pscat = 1 - exp(-(dt/t_mn));

a = randi(nElectrons,5,1);

% Current Density
J = zeros(1,TimeSteps - 1);
% I(1) = nElectrons * mean(abs(Vx)) * C.q_0 * BoundX * BoundY;
TAvgp = 300;
for i=2:TimeSteps

   Px(1: nElectrons) = Pxp(1: nElectrons) + (Vx .* dt);
   Py(1: nElectrons) = Pyp(1: nElectrons) + (Vy .* dt);

      %Apply 0.1V at one end
   Vx = Vx + ((1/2) * Accel * dt);

   if(Pscat > rand())
     Vx(1: nElectrons) = randn(nElectrons, 1) * Vtherm;
     Vy(1: nElectrons) = randn(nElectrons, 1) * Vtherm;
   end

   Vy((Py>BoundY) | (Py<0)) = -Vy((Py>BoundY) | (Py<0));

   for j=1:5
       subplot(2,1,1);
       plot([Pxp(a(j)) Px(a(j))], [Pyp(a(j)) Py(a(j))],myColors(j));
       xlim([0 BoundX]);
       ylim([0 BoundY]);
   end
   pause(0.1)
   hold on
   title('2-D plot of particle trajectories');

   VxAbs = abs(Vx);
```

```
    VyAbs = abs(Vy);

    TAvg = (mean((VxAbs.^2)+ (VyAbs.^2)) * Em)/(2 * C.kb);

    subplot(2,1,2);
    plot([i-1 i],[TAvgp TAvg],'r');
    xlim([0 TimeSteps]);
    ylim([0 2000]);
    pause(0.1)
    hold on
    title('Average Temperature');

    Px(Px>BoundX) = Px(Px>BoundX)-BoundX;
    Px(Px<0) = BoundX;

    Pxp = Px;
    Pyp = Py;
    TAvgp = TAvg;
    J(i) = nElectrons * mean(abs(Vx)) * C.q_0;
end
```

```
Accel =

    3.3823e+17
```





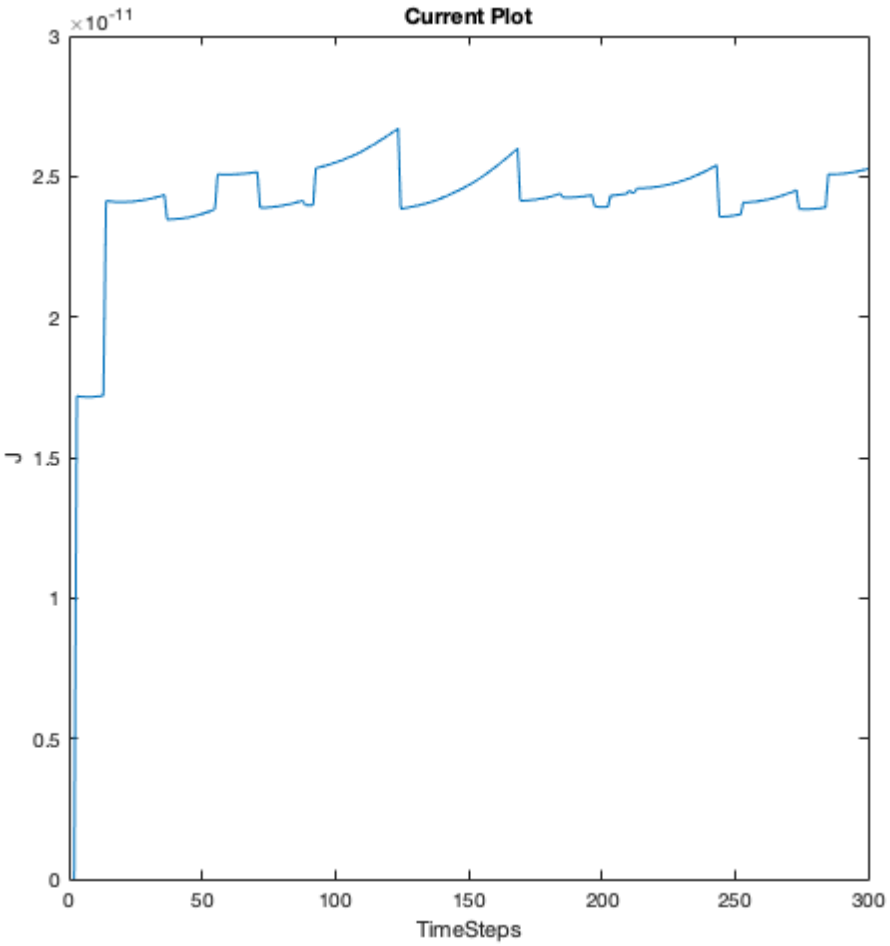
d) The equation to calculate the current in a given region is:

J = n * V * Q

Where J is the current density, n is the number of electrons in the region and Q is the charge in Coulombs.

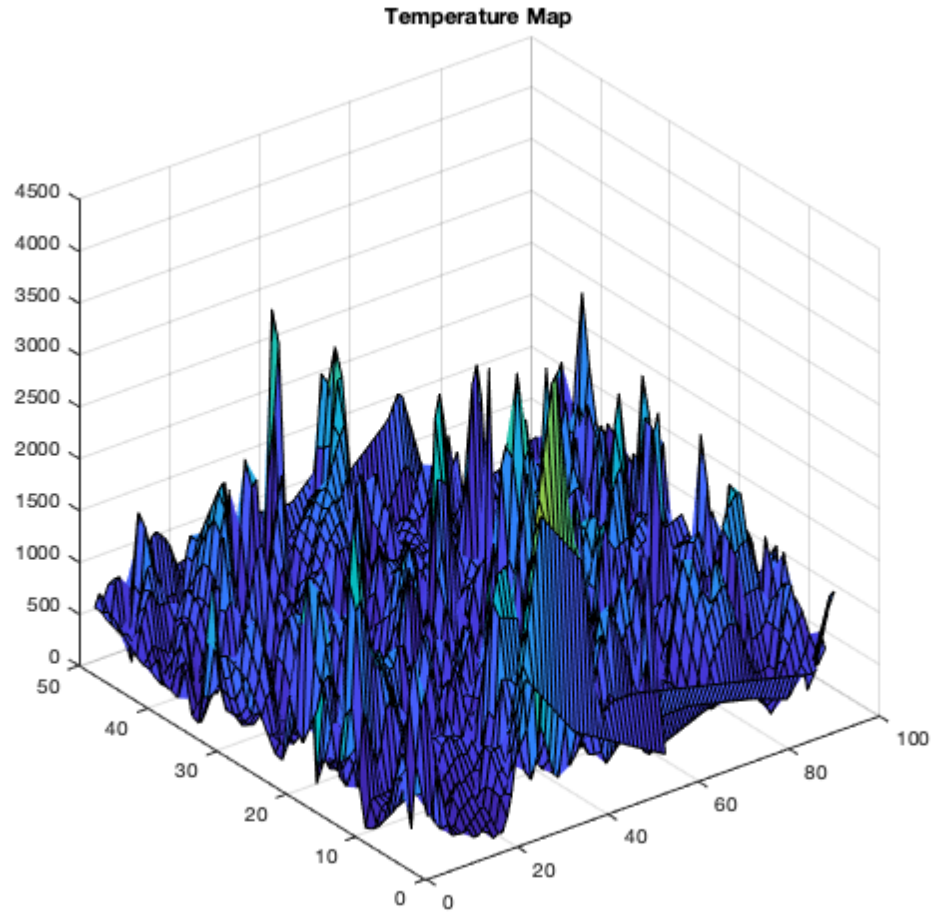
The figure below shows the current map in the region:

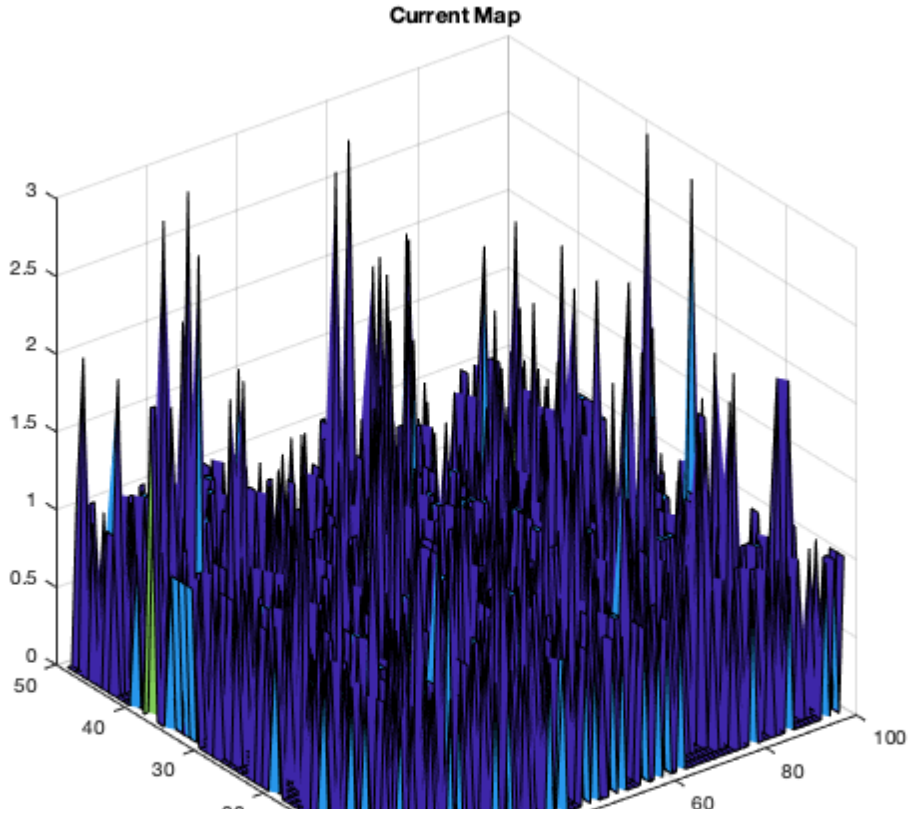
```
figure
plot(linspace(2,TimeSteps,TimeSteps),J);
title('Current Plot');
ylabel('J');
xlabel('TimeSteps');
```

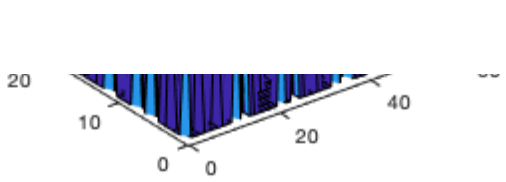


e) Density and temperature plots

```
Vmag = sqrt(Vx.^2 + Vy.^2);
Tmap = (Em * (Vmag.^2))./(2 * C.kb);
mapX = linspace(min(Px), max(Px), 100);
mapY = linspace(min(Py), max(Py), 50);
[X,Y] = meshgrid(mapX, mapY);
Tsurf = griddata(Px,Py,Tmap,X,Y);
figure
surf(Tsurf);
title('Temperature Map');

Jx = linspace(0, BoundX, 100);
Jy = linspace(0, BoundY, 50);
CurrJ = histcounts2(Py, Px, Jy, Jx);
figure
surf(CurrJ);
title('Current Map');
```


Temperature Map
4500
4000
3500
3000
2500
2000
1500
1000
500
0
50
40
30
20
10
0
0
20
40
60
80
100


Current Map
3
2.5
2
1.5
1
0.5
0
50
40
30
100
80
60



Question 2

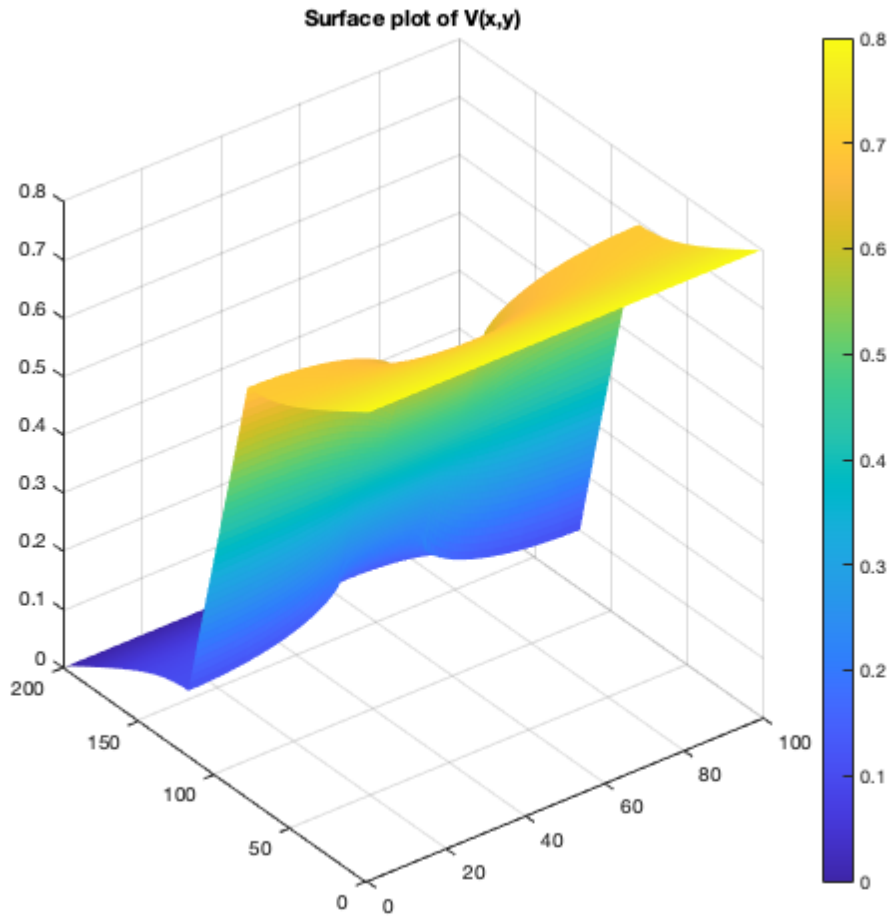
clearvars

```
clearvars -GLOBAL
close all
set(0,'DefaultFigureWindowStyle', 'docked')

%CONSTANTS AND VARIABLES

global C
global Em T
global BoundX BoundY
global Pxp Px Pyp Py Vx Vy
global Vtherm
global nElectrons
global t_mn



C.q_0 = 1.60217653e-19;             % electron charge
C.hb = 1.054571596e-34;             % Dirac constant
C.h = C.hb * 2 * pi;                    % Planck constant
C.m_0 = 9.10938215e-31;             % electron mass
C.kb = 1.3806504e-23;               % Boltzmann constant
C.eps_0 = 8.854187817e-12;          % vacuum permittivity
C.mu_0 = 1.2566370614e-6;           % vacuum permeability
C.c = 299792458;                    % speed of light
C.g = 9.80665;                      % metres (32.1740 ft) per s²


Em = 0.26 * C.m_0;                    % Mass of the Electron
BoundX = 200e-9;                    % X boundary
BoundY = 100e-9;                    % Y boundary
T = 300;                            % Semiconductor temperature

t_mn = 0.2e-12;                     % Mean time between collisions

TimeSteps = 1000;                   % Number of time steps

nElectrons = 1000;                   % Number of electrons

dt = 1e-14;                         % Time Step

[Ex, Ey, Vmap] = Efield_FD(0.8);
```

a) Surface plot of V(x,y)

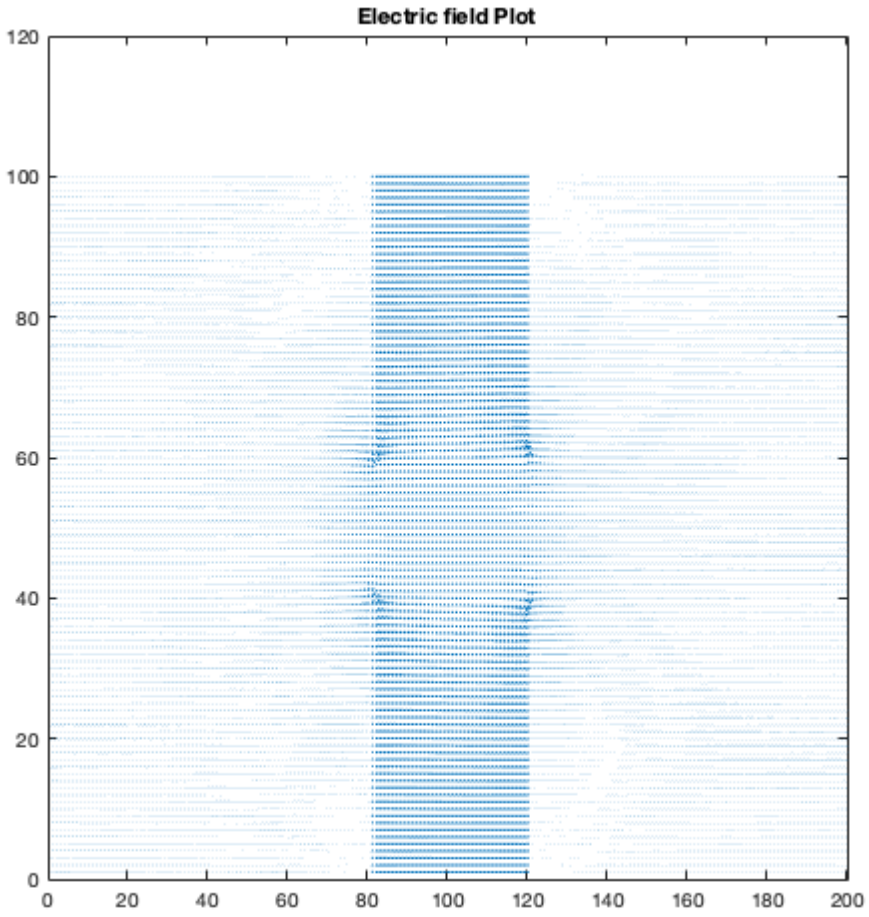
```
figure
set(surf(Vmap),'linestyle', 'none');
```

```
colorbar;
title('Surface plot of V(x,y)');
```



b) 2-D electric field vector plot

```
figure
quiver(Ex', Ey');
title('Electric field Plot');
```

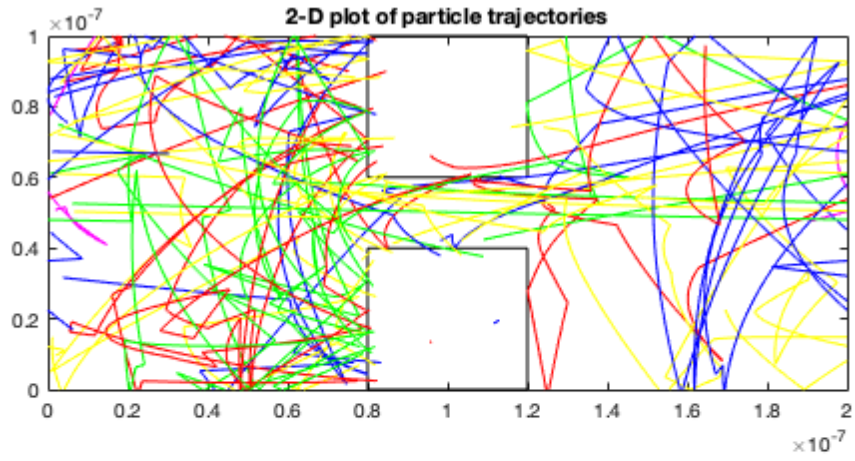


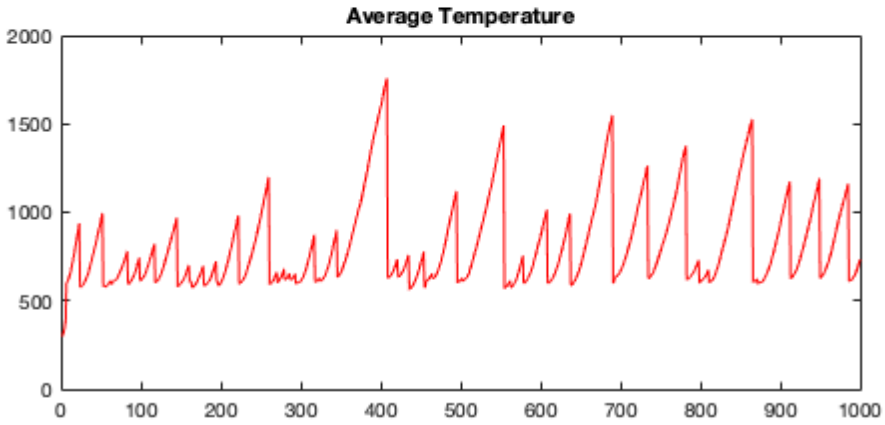
c) 2-D particle trajectories

```
ForceX = (1e9)* Ex * C.q_0;
ForceY = (1e9)* Ey * C.q_0;
AccelX = ForceX/Em;
AccelY = ForceY/Em;

% BOX 1 Boundaries

Box1Bnd1x = 0.8e-7;
Box1Bnd1y = 1e-7;
Box1Bnd2x = 1.2e-7;
Box1Bnd2y = 1e-7;
Box1Bnd3x = 1.2e-7;
Box1Bnd3y = 0.6e-7;
Box1Bnd4x = 0.8e-7;
Box1Bnd4y = 0.6e-7;

% BOX 2 Boundaries

Box2Bnd1x = 0.8e-7;
Box2Bnd1y = 0.4e-7;
Box2Bnd2x = 1.2e-7;
Box2Bnd2y = 0.4e-7;
Box2Bnd3x = 1.2e-7;
```

```
Box2Bnd3y = 0;
Box2Bnd4x = 0.8e-7;
Box2Bnd4y = 0;

subplot(2,1,1);
myBoxes(Box1Bnd1x, Box1Bnd1y, Box1Bnd2x, Box1Bnd2y, Box1Bnd3x, Box1Bnd3y, Box1Bnd4x, Box1Bnd4y);
myBoxes(Box2Bnd1x, Box2Bnd1y, Box2Bnd2x, Box2Bnd2y, Box2Bnd3x, Box2Bnd3y, Box2Bnd4x, Box2Bnd4y);
hold on

%Check if electrons are within Box 1 and Box 2

x = randi(nElectrons,1);
Pxp(1: x) = ((Box2Bnd4x - 0).*rand(x, 1))* BoundX;
Pxp(x+1: nElectrons) = ((BoundX - Box2Bnd3x).*rand(nElectrons - x, 1) + Box2Bnd3x )* BoundX;

Pxp(1: nElectrons) = rand(nElectrons, 1) * BoundX;
Pyp(1: nElectrons) = rand(nElectrons, 1) * BoundY;

Vtherm = sqrt(2 * C.kb * T/Em);

Vx(1: nElectrons) = randn(nElectrons, 1) * (Vtherm/sqrt(2));
Vy(1: nElectrons) = randn(nElectrons, 1) * (Vtherm/sqrt(2));

myColors = ['r' 'b' 'g' 'y' 'm' ];
myColorTyp = 1;

Pscat = 1 - exp(-(dt/t_mn));

a = randi(nElectrons,5,1);


% Current Density
J = zeros(1,TimeSteps - 1);
% I(1) = nElectrons * mean(abs(Vx)) * C.q_0 * BoundX * BoundY;

TAvgp = 300;
for i=2:TimeSteps

    Px(1: nElectrons) = Pxp(1: nElectrons) + (Vx .* dt);
    Py(1: nElectrons) = Pyp(1: nElectrons) + (Vy .* dt);

   %Apply 0.1V at one end

   [x_bin, edge_x] = discretize(Px,200);
   [y_bin, edge_y] = discretize(Py,100);


   Vx = Vx + (1/2) * AccelX(sub2ind(size(AccelX),x_bin,y_bin))*dt;
   Vy = Vy + (1/2) * AccelY(sub2ind(size(AccelY),x_bin,y_bin))*dt;

   if(Pscat > rand())
     Vx(1: nElectrons) = randn(nElectrons, 1) * Vtherm;
     Vy(1: nElectrons) = randn(nElectrons, 1) * Vtherm;
   end

   Vy((Py>BoundY) | (Py<0)) = -Vy((Py>BoundY) | (Py<0));

   for j=1:5
       subplot(2,1,1);
       plot([Pxp(a(j)) Px(a(j))], [Pyp(a(j)) Py(a(j))],myColors(j));
```

```
        xlim([0 BoundX]);
        ylim([0 BoundY]);
    end
    pause(0.1)
    hold on
    title('2-D plot of particle trajectories');

    VxAbs = abs(Vx);
    VyAbs = abs(Vy);

    TAvg = (mean((VxAbs.^2)+ (VyAbs.^2)) * Em)/(2 * C.kb);

    subplot(2,1,2);
    plot([i-1 i],[TAvgp TAvg],'r');
    xlim([0 TimeSteps]);
    pause(0.1)
    hold on
    title('Average Temperature');


    for k = 1:nElectrons
        if (Py(k) > Box1Bnd3y) && (Px(k) > Box1Bnd1x) && (Px(k) < Box1Bnd2x)
             if Pxp(k) > Box1Bnd2x && Px(k) < Box1Bnd2x
                 Vx(k) = -Vx(k);
                 Px(k) = 2 * Box1Bnd2x - Px(k);
             elseif Pxp(k) < Box1Bnd1x && Px(k) > Box1Bnd1x
                 Vx(k) = -Vx(k);
                 Px(k) = 2*Box1Bnd1x-Px(k);
             elseif Pyp(k) < Box1Bnd3y && Py(i) > Box1Bnd3y
                 Vy(k) = -Vy(i);
                 Py(k) = 2 * Box1Bnd3y - Py(k);
             end
         elseif (Py(k) <= Box2Bnd1y) && (Px(k) > Box2Bnd1x) && (Px(k) < Box2Bnd3x)
             if Pxp(k) > Box2Bnd3x && Px(k) < Box2Bnd3x
                 Vx(k) = -Vx(k);
                 Px(k) = 2 * Box2Bnd3x - Px(k);
             elseif Pxp(k) < Box2Bnd1x && Px(k) > Box2Bnd1x
                 Vx(k) = -Vx(k);
                 Px(k) = 2 * Box2Bnd1x - Px(k);
             elseif Pyp(i) > Box2Bnd1y && Py(k) < Box2Bnd1y
                 Vy(k) = -Vy(k);
                 Py(k) = 2 * Box2Bnd1y - Py(k);
             end
        end
     end
    Px(Px>BoundX) = Px(Px>BoundX)-BoundX;
    Px(Px<0) = BoundX;

    Pxp = Px;
    Pyp = Py;
    TAvgp = TAvg;

    J(i) = nElectrons * mean(abs(Vx)) * C.q_0;

end
```

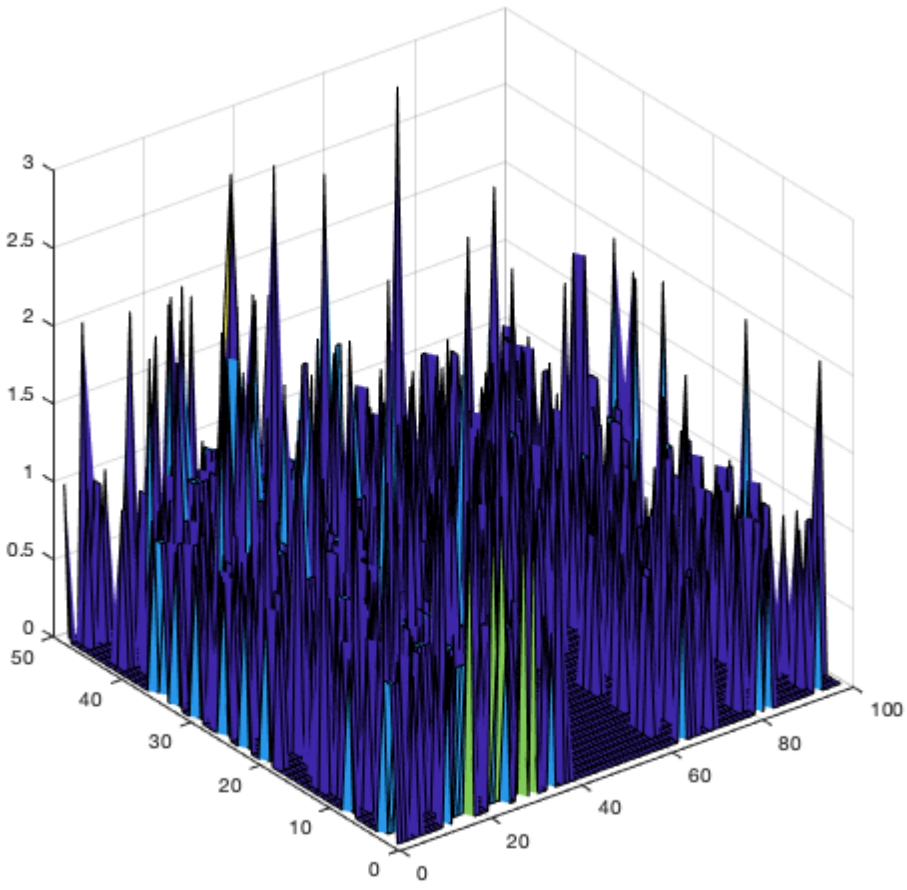




Question 3

a) Density plot Density Map

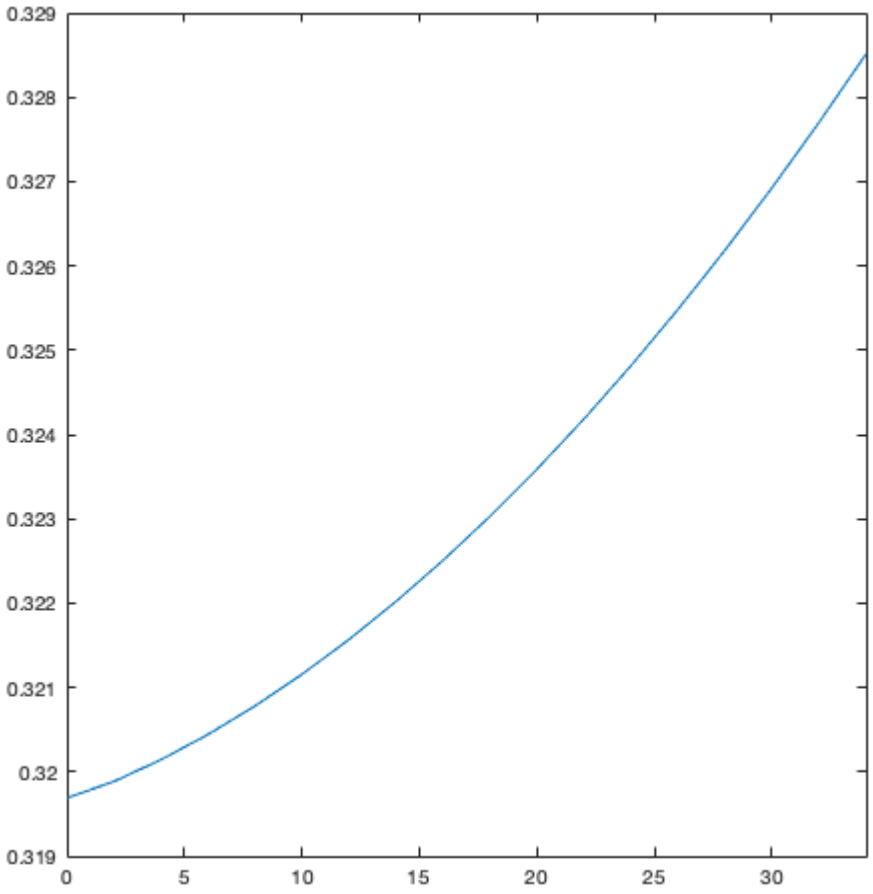
```
Jx = linspace(0, BoundX, 100);
Jy = linspace(0, BoundY, 50);
CurrJ = histcounts2(Py, Px, Jy, Jx);
figure
surf(CurrJ);
```



In the density map above, it can be observed that more electrons can be found on the side where the voltage was applied. Very few electrons get through the bottle neck as expected. this models resitance.

b) Plot of Current vs bottle neck

```
figure
plot(Necksizes, Curr);
xlim([0 max(Necksizes)])
```



c) One way to increase the accuracy of this simulation is to increase the amount of time and the number of electrons. Another way will be to increase the size or resoluton of the region being simulated.

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