Neuromorphic Engineering HW1

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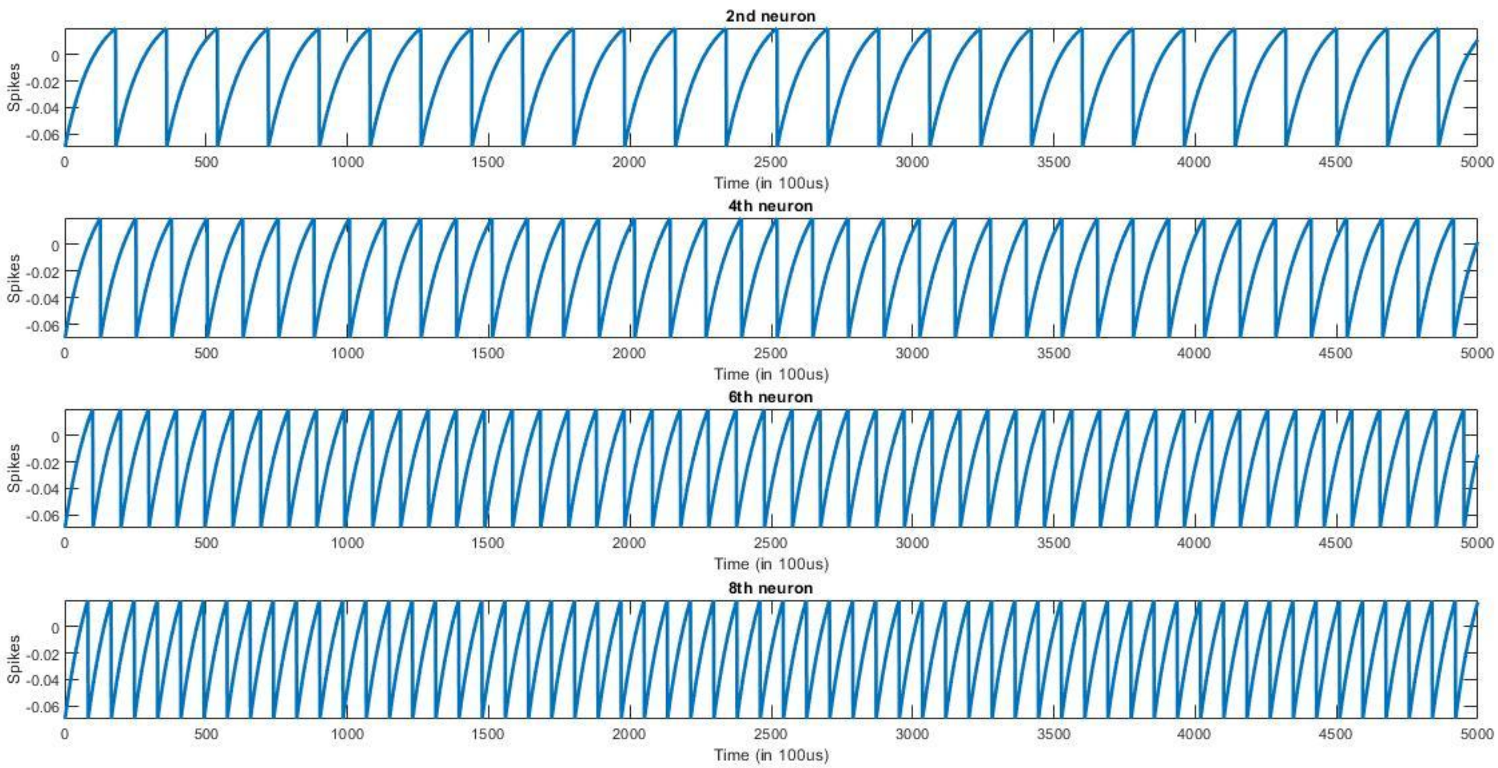
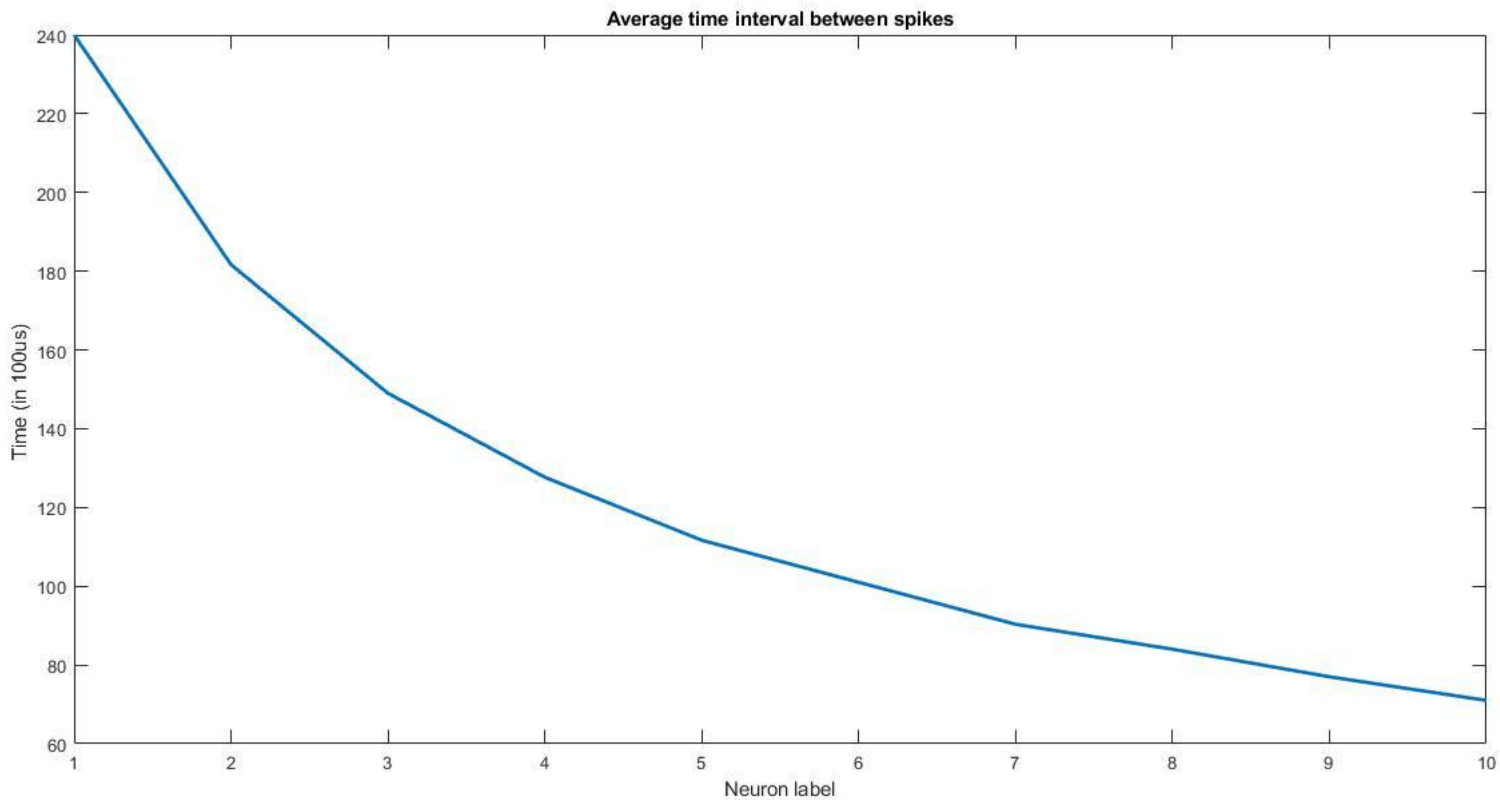
Q-1

(c)

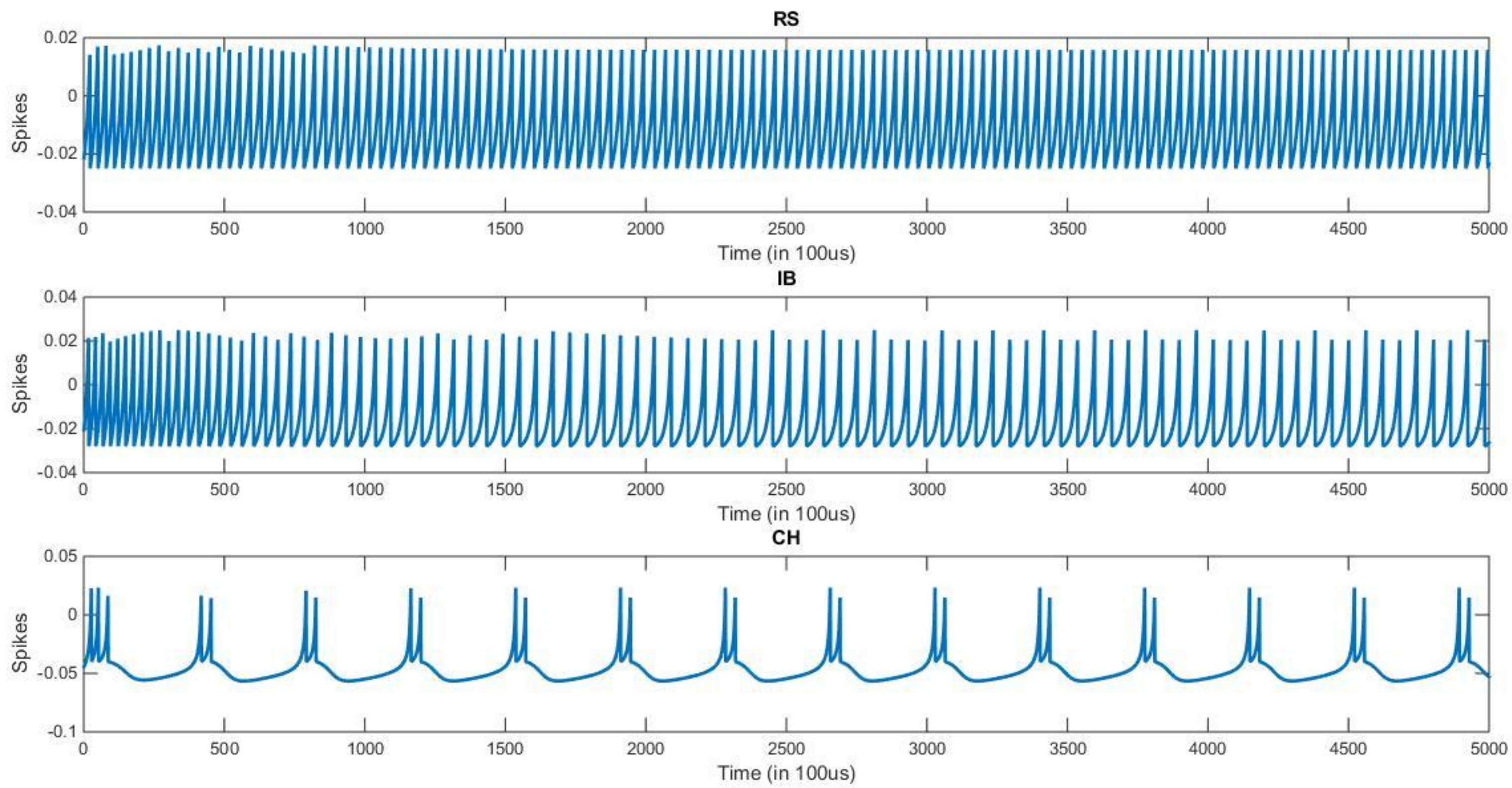


(d)


Average time interval between spikes
Time (in 100us)
240
220
200
180
160
140
120
100
80
60
1
2
3
4
5
6
7
8
9
10
Neuron label

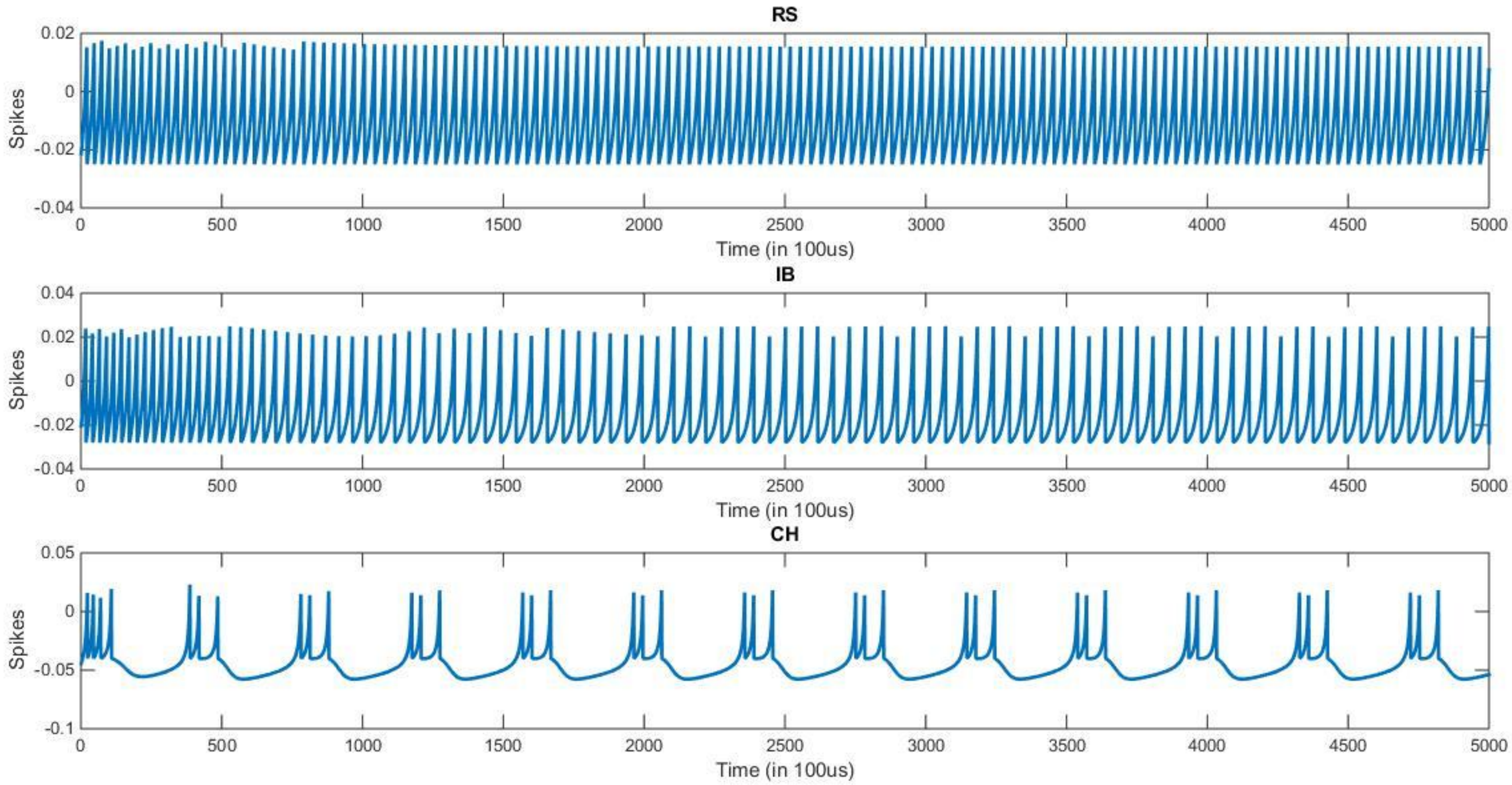
Q-2

(c) At 400pA



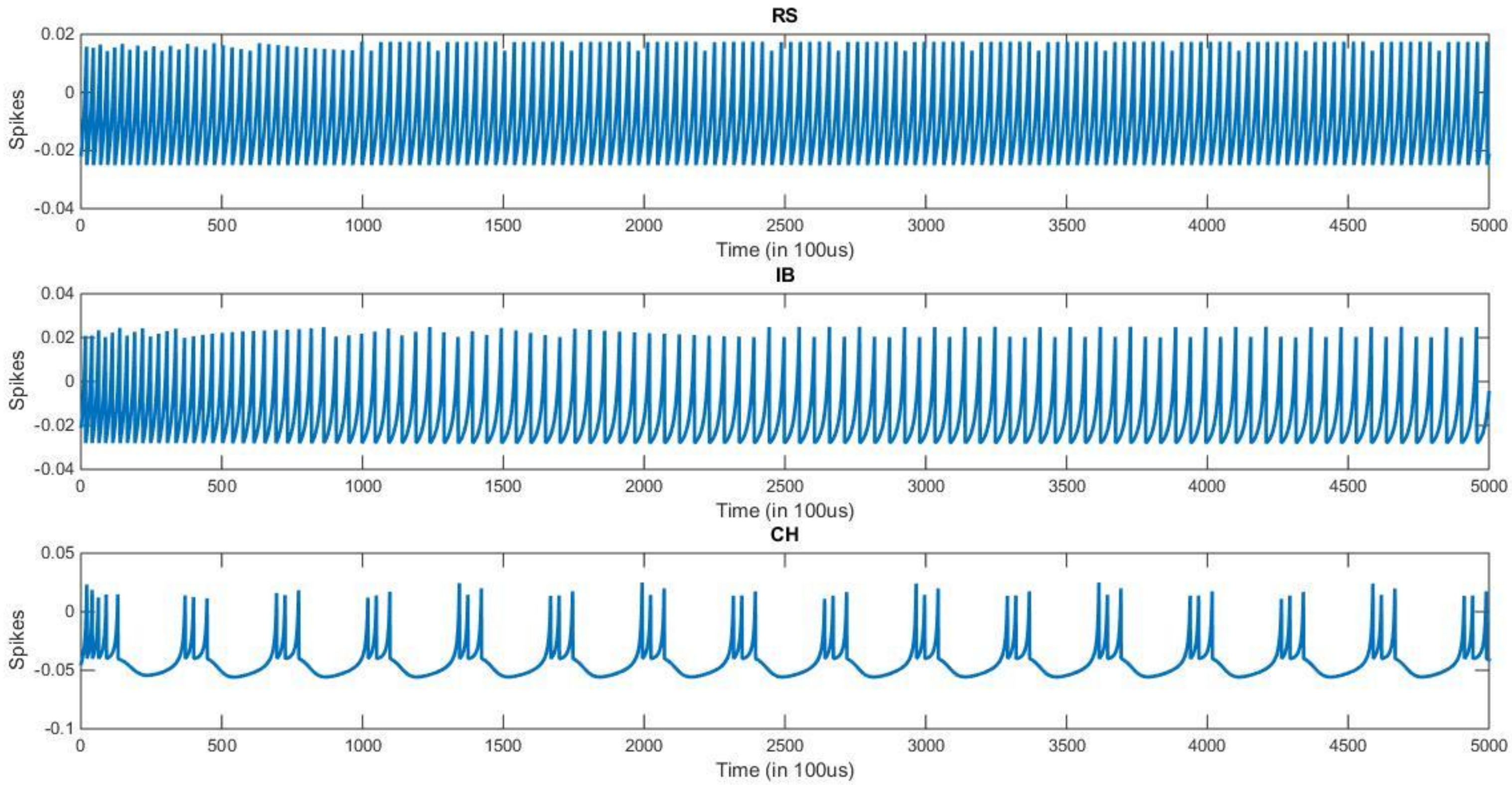
RS
Spikes
0.02
0
-0.02
-0.04
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Time (in 100us)
IB
Spikes
0.04
0.02
0
-0.02
-0.04
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Time (in 100us)
CH
Spikes
0.05
0
-0.05
-0.1
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Time (in 100us)

At 500pA

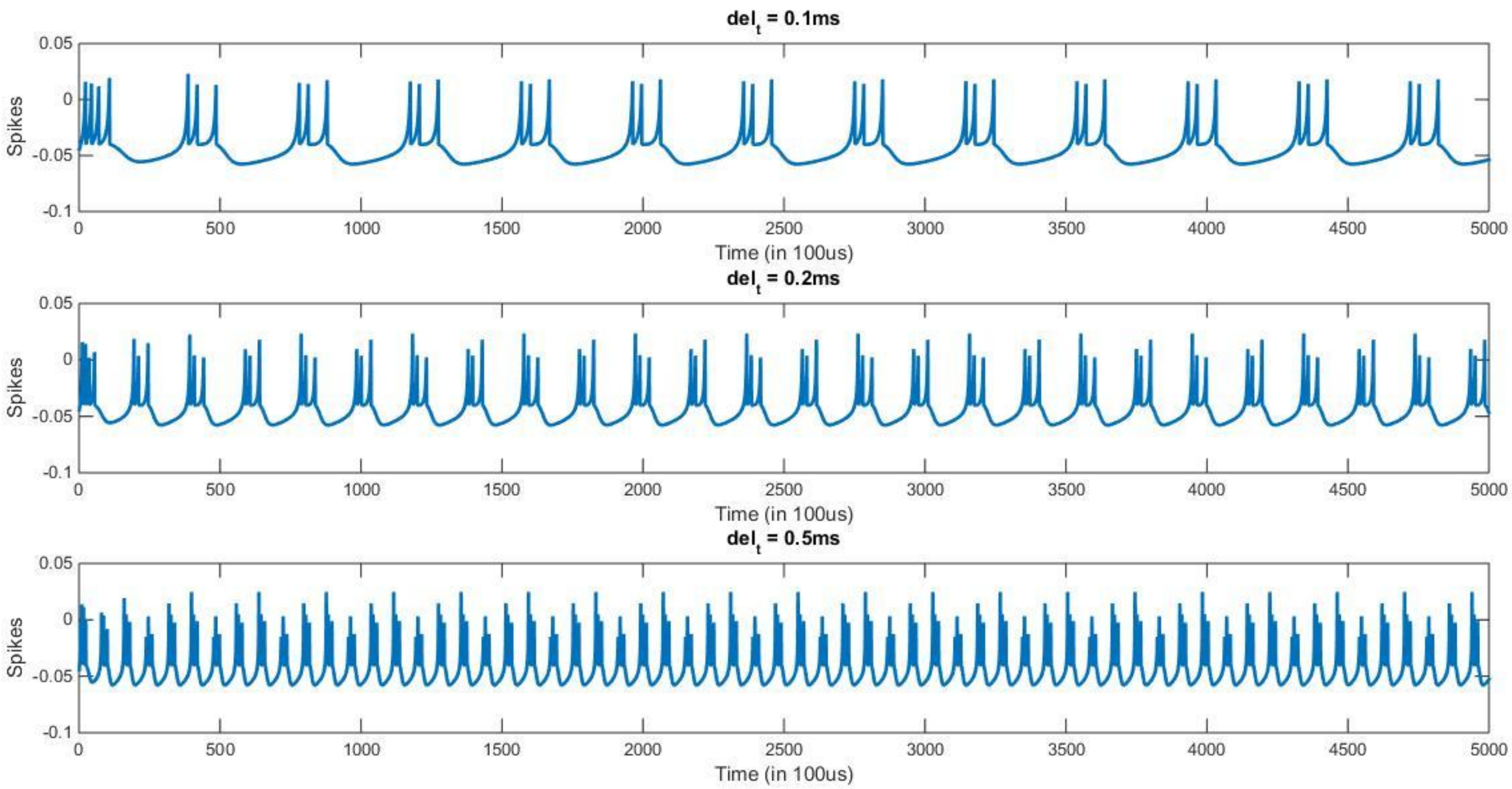


RS
Spikes
Time (in 100us)
IB
Spikes
Time (in 100us)
CH
Spikes
Time (in 100us)

At 600pA

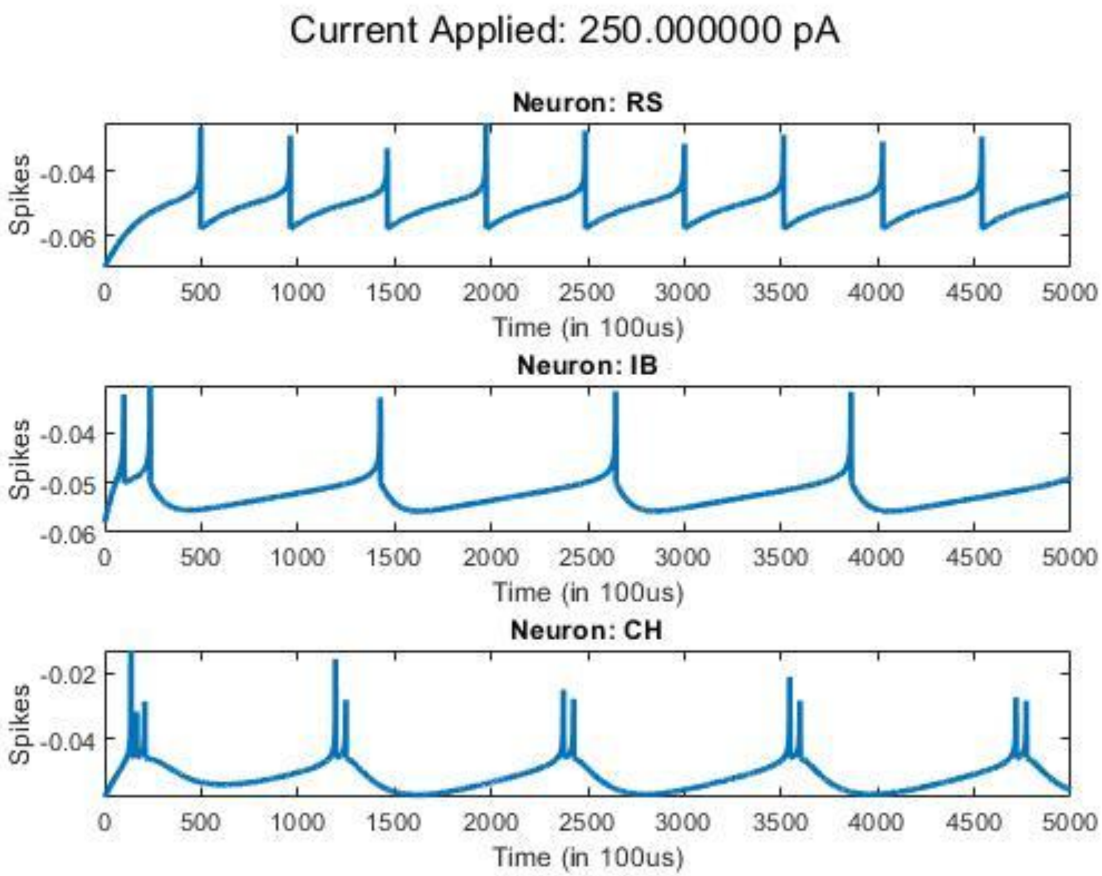

RS
Spikes
0.02
0
-0.02
-0.04
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Time (in 100us)
IB
Spikes
0.04
0.02
0
-0.02
-0.04
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Time (in 100us)
CH
Spikes
0.05
0
-0.05
-0.1
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Time (in 100us)

After changing step time for CH neuron:

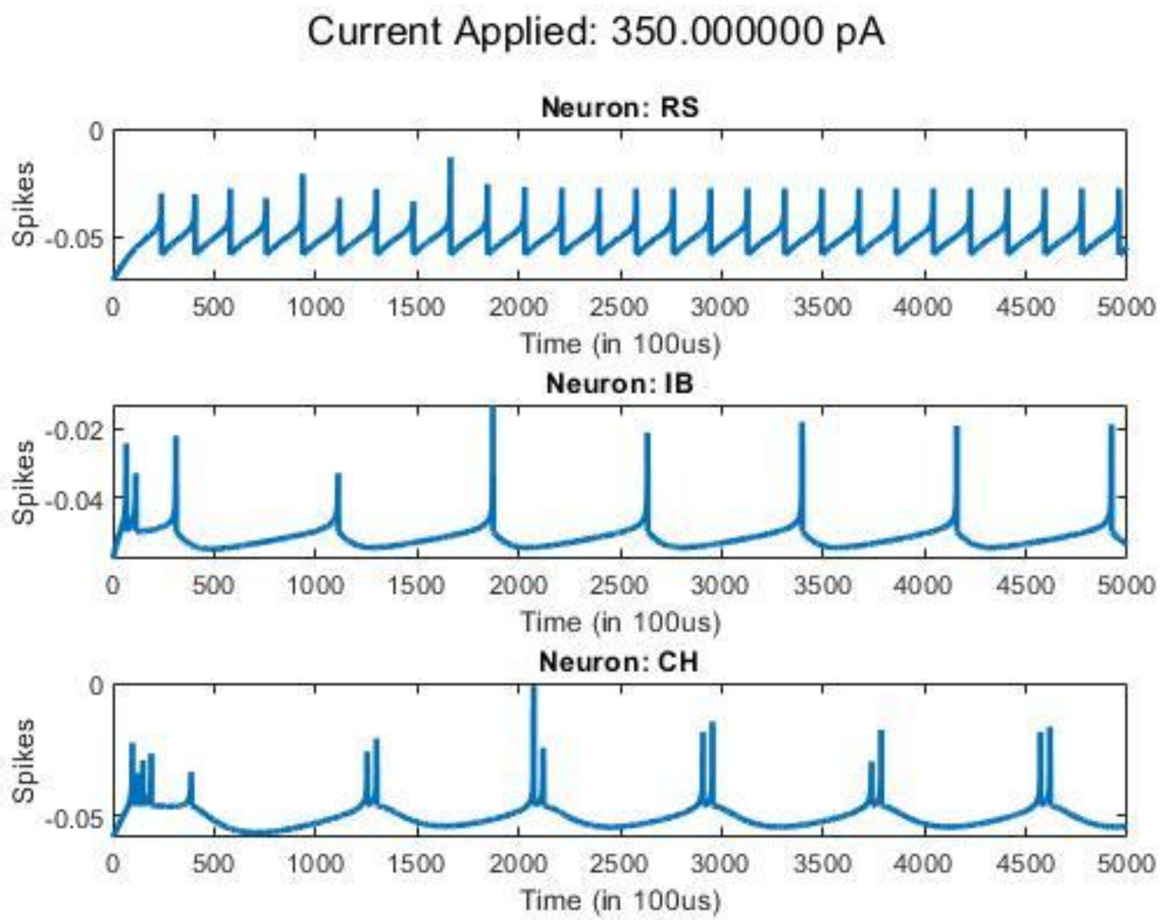


<u>Q-3-</u>

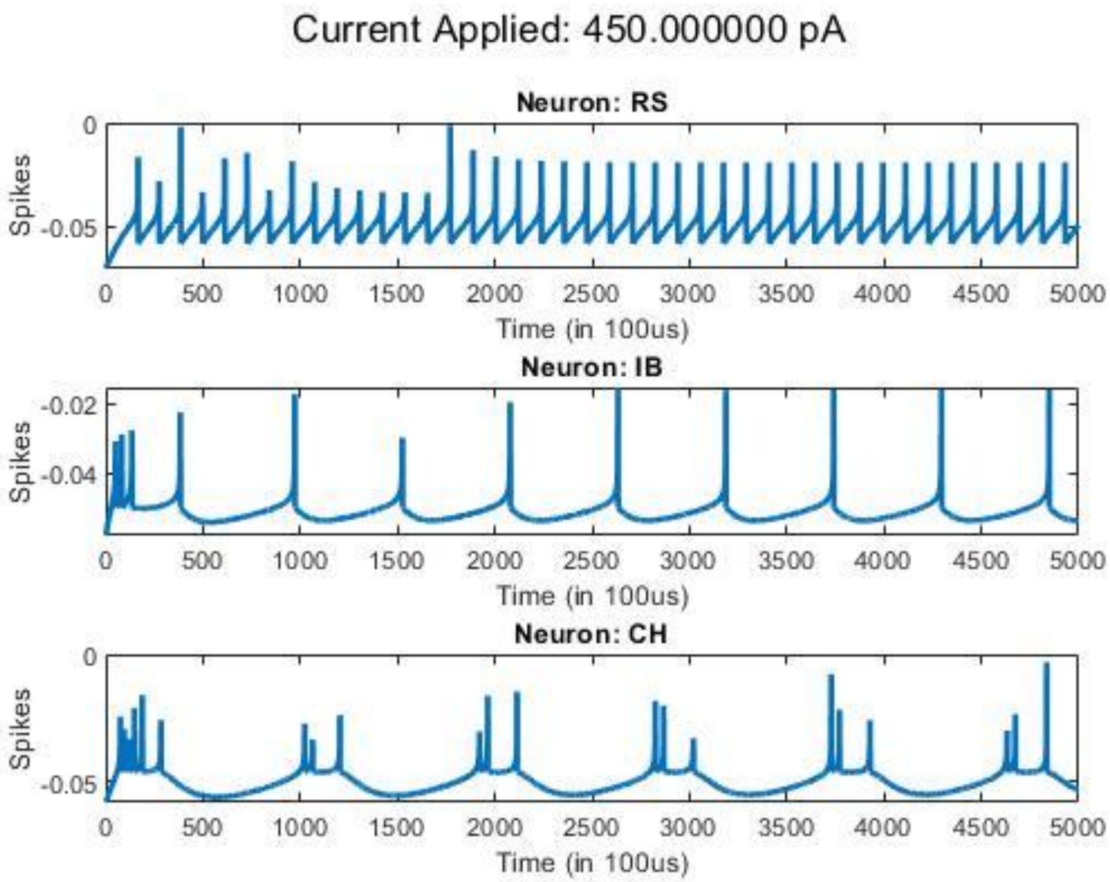
(c)At 250pA



At 350pA

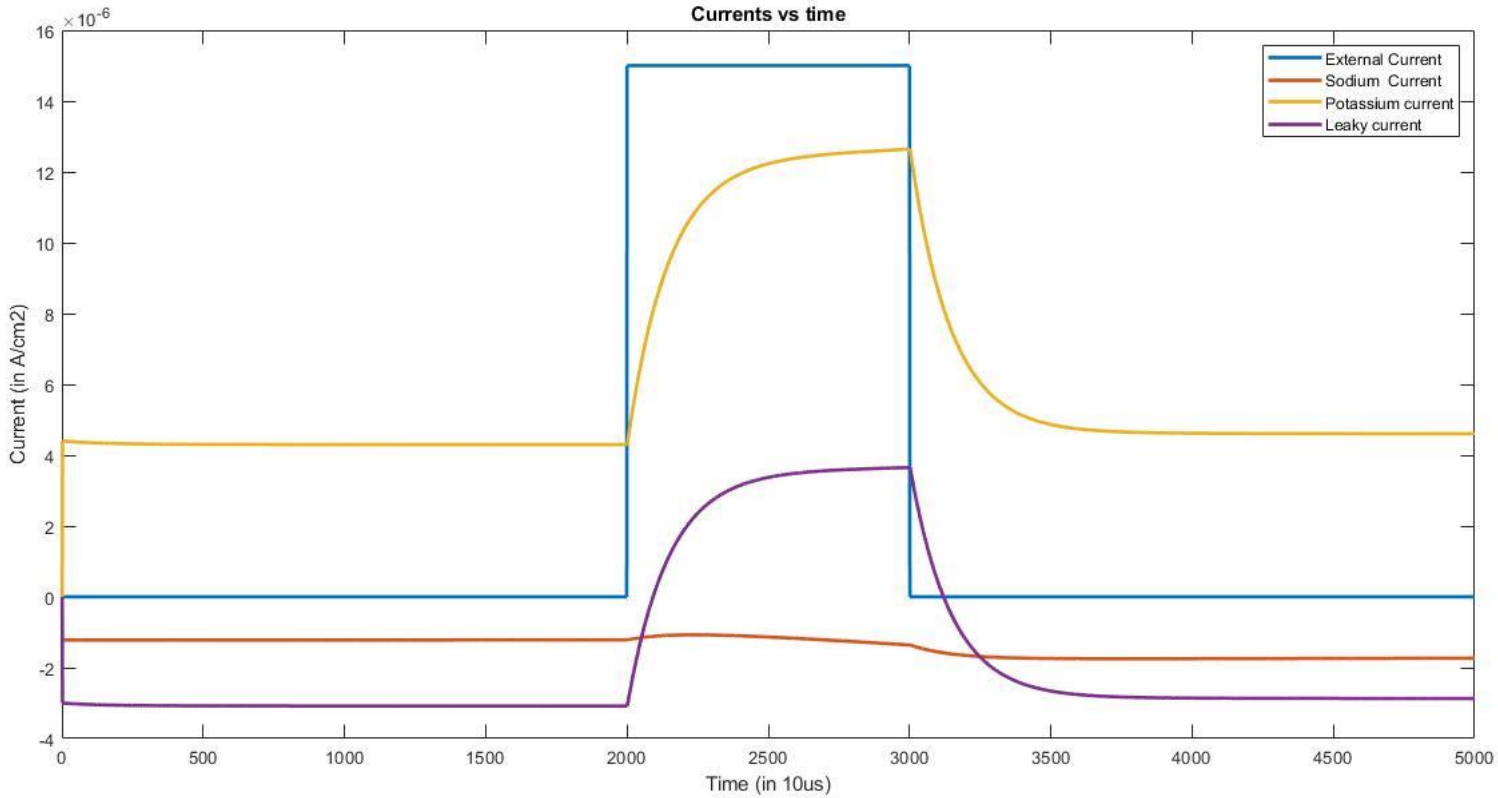

Current Applied: 350.000000 pA
Neuron: RS
Spikes
Time (in 100us)
Neuron: IB
Spikes
Time (in 100us)
Neuron: CH
Spikes
Time (in 100us)

At 450pA

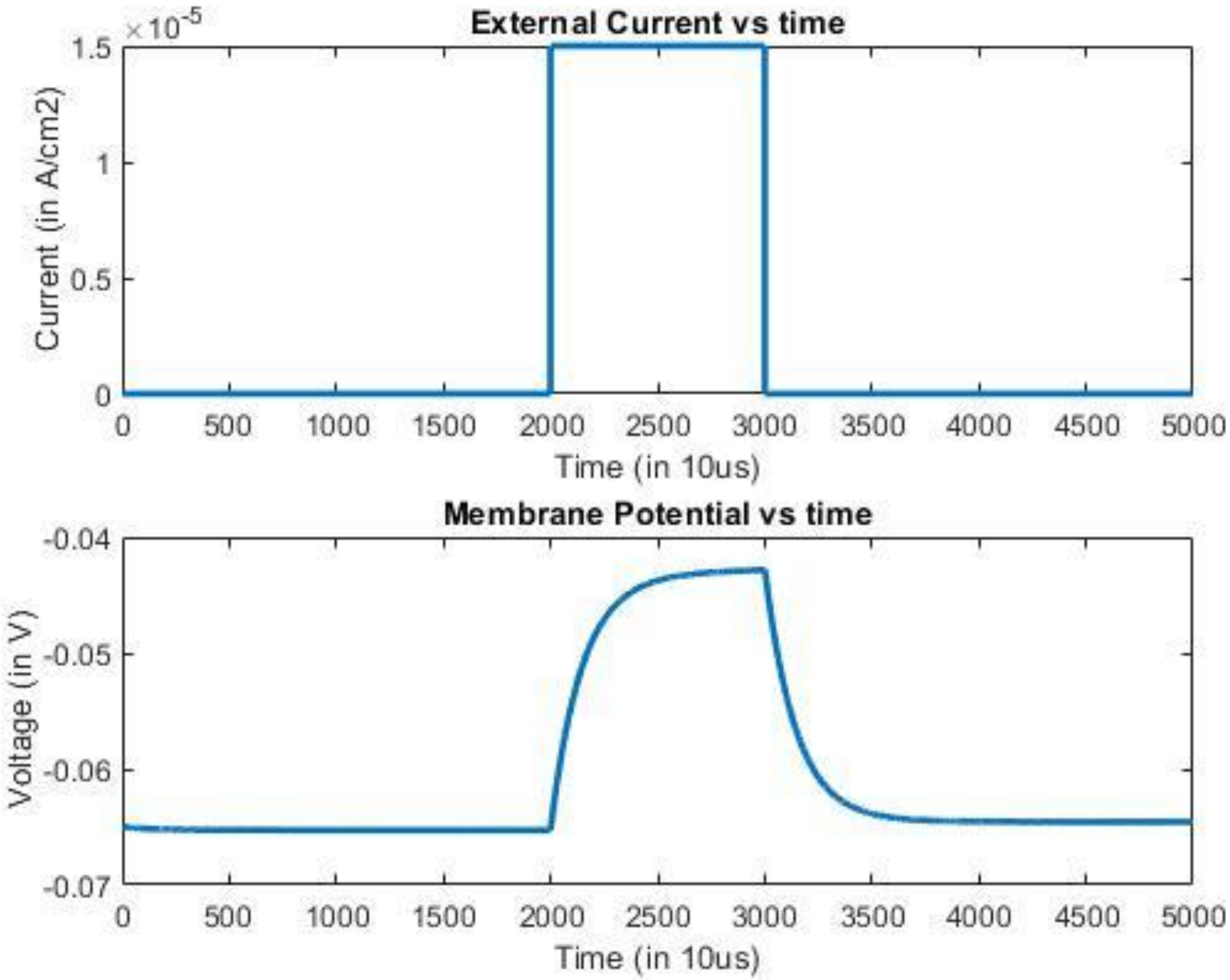

Current Applied: 450.000000 pA
Neuron: RS
Spikes
0
-0.05
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Time (in 100us)
Neuron: IB
Spikes
-0.02
-0.04
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Time (in 100us)
Neuron: CH
Spikes
0
-0.05
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Time (in 100us)

<u>Q-4-</u>

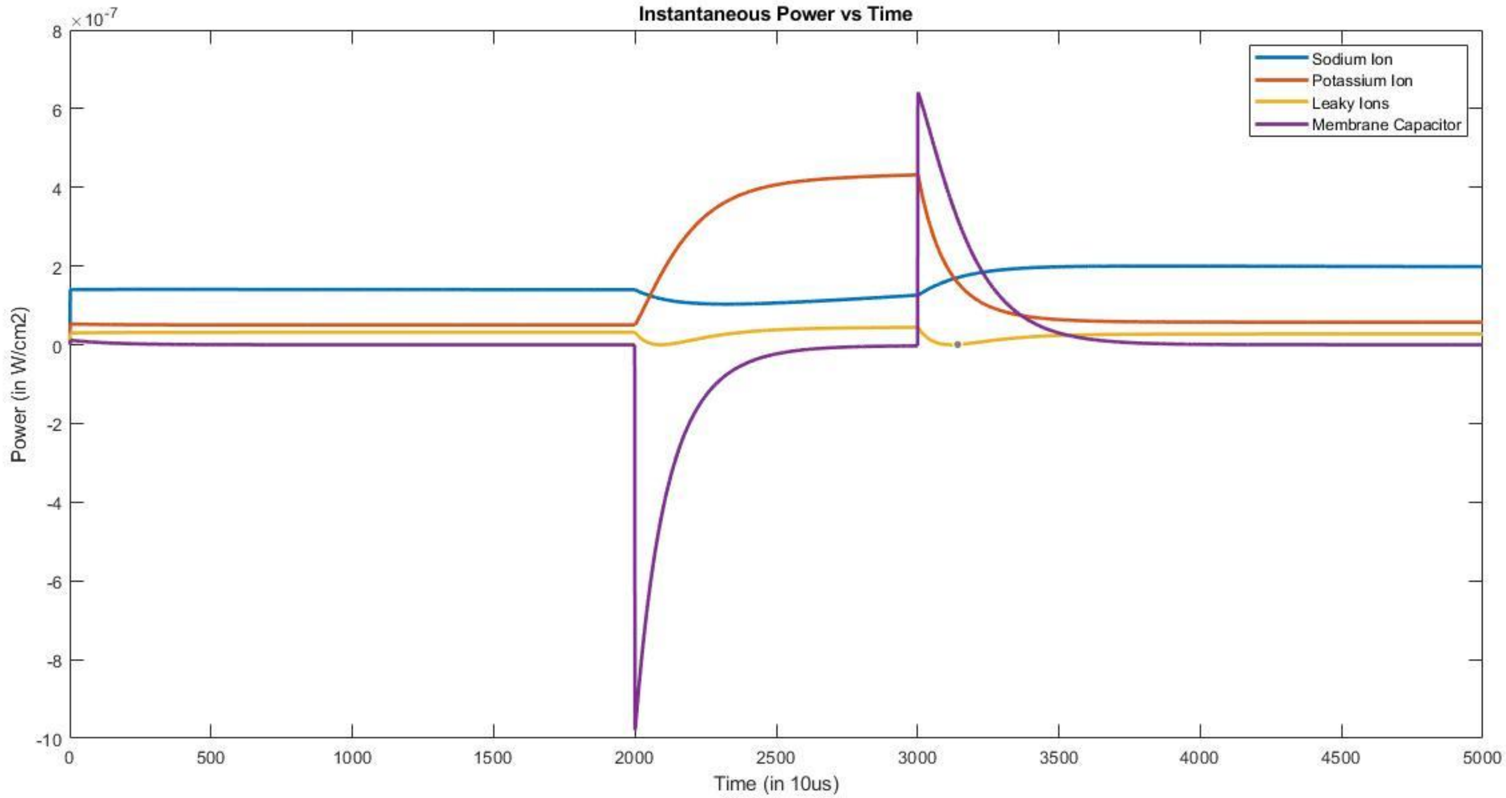
(a)Ion Currents



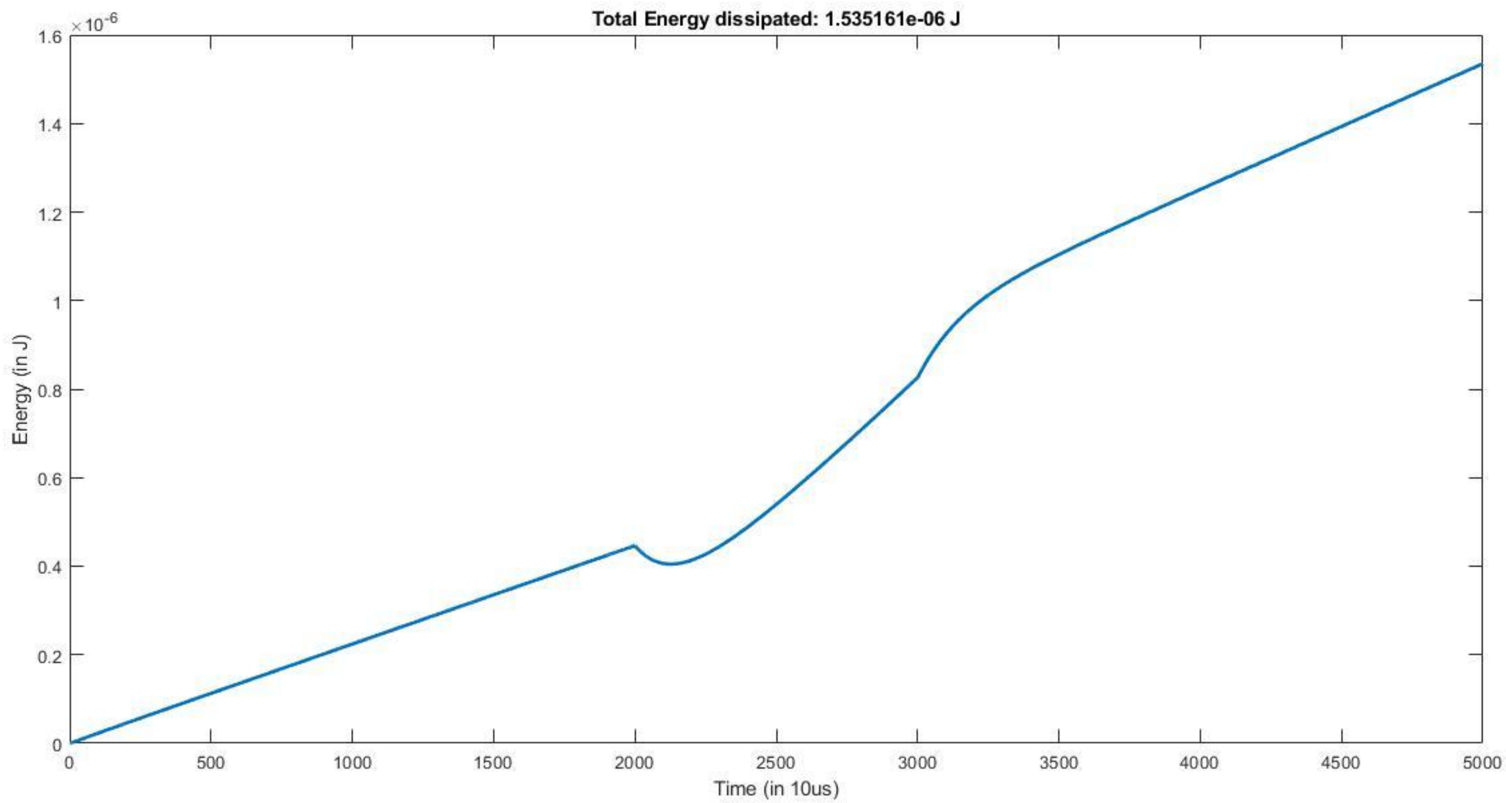
Membrane Potential



(b)


Instantaneous Power vs Time
$\times 10^{-7}$
8
6
4
2
0
-2
-4
-6
-8
-10
Power (in W/cm2)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Time (in 10us)
Sodium Ion
Potassium Ion
Leaky Ions
Membrane Capacitor

(c)



Total Energy dissipated: 1.535161e-06 J
×10^-6
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Energy (in J)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Time (in 10us)

Assignment 1

Problem 1 :

(a) $$C \frac{dV(t)}{dt} = -g_L (V(t) - E_L) + I_{app}(t)$$

$$\therefore \frac{dV(t)}{dt} + \frac{g_L}{C} V(t) = \frac{g_L E_L}{C} + \frac{I_{app}(t)}{C}$$

Here $I_{app}(t) = I_0$.

Multiplying both sides by $e^{\frac{g_L}{C}t}$

$$\therefore e^{g_L/C\, t} \frac{dV(t)}{dt} + \frac{g_L}{C} e^{g_L/C\, t} V(t) = e^{g_L/C\, t} \left(\frac{g_L E_L + I_0}{C} \right)$$

$$\therefore \frac{d\left(e^{g_L/C\, t} V(t)\right)}{dt} = e^{g_L/C\, t} \left(\frac{g_L E_L + I_0}{C} \right)$$

Integrating both sides.

$$e^{g_L/C\, t} V(t) - V(0) = \frac{g_L E_L + I_0}{g_L} \left(e^{g_L/C\, t} - 1 \right)$$

$$\therefore V(t) = V(0) e^{-\frac{g_L}{C}t} + \left(E_L + \frac{I_0}{g_L} \right) \left(1 - e^{-g_L/C\, t} \right)$$

At steady state i.e. as $t \to \infty$,

$$V_{ss} = E_L + \frac{I_0}{g_L}$$

$\therefore$ To initiate a spike, $V_{ss} \geq V_T$

$$\therefore E_L + \frac{I_c}{g_L} \geq V_T$$

or $$I_c \geq g_L (V_T - E_L) = 30 \times 10^{-9} \times 90 \times 10^{-3}$$
$$= 2.7\ nA.$$

$\therefore$ Steady-state current of 2.7nA is required to initiate a spike.

Problem 3

(a) $Eq^n\ 5 \rightarrow$

$$C\frac{dV(t)}{dt} = -g_L(V(t)-E_L) + g_L\Delta_T \exp\left(\frac{V(t)-V_T}{\Delta_T}\right) - u(t) + I_{app}(t)$$

$Eq^n\ 6 \rightarrow$

$$\tau_m\frac{dU(t)}{dt} = a\left[V(t)-E_L\right] - u(t)$$

Equivalent difference equation:

$Eqn\ 5 \rightarrow$

$$V_{n+1} = V_n + h\left[-\frac{g_L}{C}(V_n-E_L) + \frac{g_L}{C}\Delta_T \exp\left(\frac{V_n-V_T}{\Delta_T}\right) - \frac{U_n}{C} + \frac{I_{app,n}}{C}\right]$$

$Eqn\ 6 \rightarrow$

$$U_{n+1} = U_n + h\left[\frac{a}{\tau_m}\left[V_n - E_L\right] - \frac{U_n}{\tau_m}\right]$$

(b) At steady state $V_{n+1} \approx V_n = V$ & $U_{n+1} \approx U_n = U$

$\therefore\ Eq^n\ 5 \rightarrow$

$$V = V + h\left[\frac{-g_L}{C}(V-E_L) + \frac{g_L\Delta_T}{C}\exp\left(\frac{V-V_T}{\Delta_T}\right) - \frac{U}{C} + 0\right]$$

$Eq^n\ 6 \rightarrow$

$$U = U + h\left[\frac{a}{\tau_m}\left[V - E_L\right] - \frac{U}{\tau_m}\right]$$

$\therefore\ u = a[V - E_L]$

Substituting in eqn 5,

$$-g_L(V-E_L) + g_L \Delta_T \exp\left(\frac{V-V_T}{\Delta_T}\right) - a(V-E_L) = 0$$

$$\therefore\ g_L \Delta_T \exp\left(\frac{V-V_T}{\Delta_T}\right) = (a+g_L)(V-E_L)$$

$\Rightarrow$ RS :

$$2\times10^{-11}\exp\left(\frac{V+50}{2}\right) = 12\times10^{-9}(V+70)\times10^{-3}$$

$$\exp\left(\frac{V+50}{2}\right) = 0.6(V+70) = 0.6V + 42$$

On solving, $V = -70\,mV,\ -44.548\,mV$

correspondingly, $u = -280\,pA,\ -229.096\,pA$

$\Rightarrow$ IB :

$$36\times10^{-12}\exp\left(\frac{V+50}{2}\right) = 22\times10^{-9}(V+58)\times10^{-3}$$

$$\exp\left(\frac{V+50}{2}\right) = 0.611V + 35.44$$

On solving, $V = -58.003\,mV,\ -46.018\,mV$

correspondingly $u = -464.012\,pA,\ 416.072\,pA$

$\Rightarrow$ CH : $\exp\left(\frac{V+50}{2}\right) = 0.6V + 34.8$

On solving, $V = -58\,mV,\ -46.062\,mV$

correspondingly, $u = -232\,pA,\ -208.124\,pA$

(2) (a) $0 = k_2 (V - E_r)(V - E_t) - U + 0$ — (1)

$0 = a[b(V - E_r) - U]$ — (2)

$\Rightarrow U = b(V - E_r)$ — (3)

$k_2(V - E_r)(V - E_t) = b(V - E_r)$

$V - E_t = \frac{b}{k_2}$

$\Rightarrow V = E_t + \frac{b}{k_2} , E_r$ — (4)

$U = b\left\{ E_t + \frac{b}{k_2} - E_r \right\} , 0$

RS: $V_{steady} = -42.8 \text{ mV}, -60 \text{ mV}$

$U_{steady} = -34.4 \text{ pA}, 0 \text{ A}$

IB: $V_{steady} = -40.83 \text{ mV}, -75 \text{ mV}$

$U_{steady} = 170.05 \text{ pA}, 0 \text{ A}$

CH: $V_{steady} = \overset{-44.33}{\cancel{-59.33}} \text{ mV}, -60 \text{ mV}$

$U_{steady} = 15.66 \text{ pA}, 0 \text{ A}$

(b) $C\left[\frac{V_{n+1} - V_n}{h}\right] = k_2[V_n - E_r][V_n - E_t] - U_n + I_n$ — (1)

$\frac{U_{n+1} - U_n}{h} = a[b(V_n - E_r) - U_n]$ — (2)

$$\Rightarrow V_{n+1} = V_n + \frac{h}{C}\left[k_2(V_n - E_r)(V_n - E_t) - U_n + I_n\right]$$

$$U_{n+1} = U_n + ah\left[b(V_n - E_r) - U_n\right]$$

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