Analog Electronic Circuits

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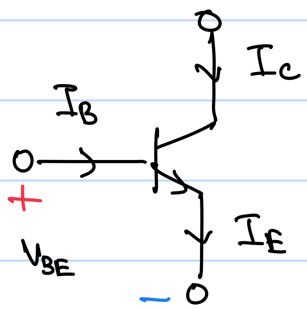
I)

1.1. Given:

npn BJT transistor, $I_B = 14.46\,\mu A$, $I_E = 1.46\,mA$,
$V_{BE} = 0.7V$. ⟶ Fwd Active Mode

To find: $\alpha = ?$, $\beta = ?$, $I_S = ?$

By KCL,



$$I_C + I_B = I_E$$

$$\Rightarrow \quad I_C = I_E - I_B$$

Since $I_E \gg I_B$

$$I_C \approx I_E = 1.46\,mA$$

$$\beta = \frac{I_C}{I_B} = \frac{1.46 \times 10^{-3}}{14.46 \times 10^{-6}} \approx 100.968 \approx \underline{\underline{101}}$$

$$\alpha = \frac{\beta}{\beta+1} = \frac{101}{102} = \underline{\underline{0.9901}}$$

$$I_C = I_S e^{V_{BE}/V_T} \Rightarrow I_S = I_C e^{-\frac{V_{BE}}{V_T}}$$

$$I_S = (1.46 \times 10^{-3})\, e^{-\frac{\cancel{700 \times 10^{-3}}}{\cancel{26 \times 10^{-3}}}} \approx \underline{\underline{2.96 \times 10^{-15}\,A}}$$

1.2 Given:

$I_S = 10^{-16}\,A$, $\beta = 100$, $I_C = 1\,mA$

To find:

$V_{BE} = ?$, $I_{SE} = ?$, $I_{SB} = ?$

W.k.t,

(Assuming room temp)

$$V_{BE} = V_T \ln \frac{I_C}{I_S} = (26 \times 10^{-3}) \ln\left(\frac{10^{-3}}{10^{-16}}\right) V$$

$$= (26 \times 10^{-3}) \ln 10^{13}$$

$$= (26 \times 10^{-3})(13 \times 2.303)$$

$$= \underline{\underline{0.778\ V}} \longrightarrow \text{Fwd Active Mode}$$

Also, since $I_C \approx I_E$ if $\beta >> 1$,

$$\Rightarrow I_{SE} \approx I_S$$

$$= I_{SE} \approx \underline{\underline{10^{-16}\,A}}$$

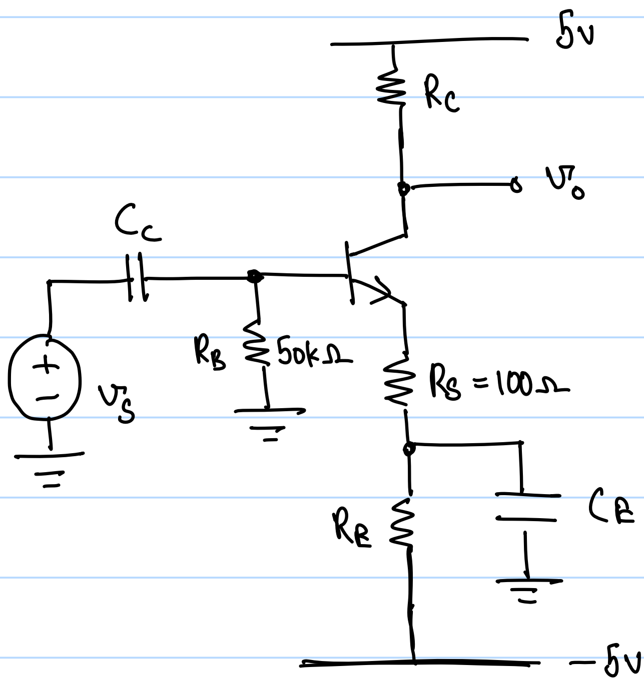
$$I_{SB} = \frac{I_S}{\beta} = \frac{10^{-16}}{10^2}$$

$$= \underline{\underline{10^{-18}\,A}}$$

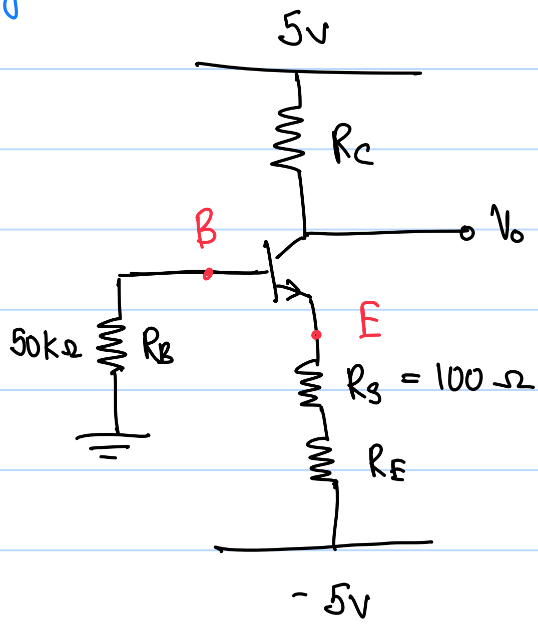
1.3. Given: $\beta = 100$, $V_a = \infty$, $I_{CQ} = 0.25\,mA$, $V_{CEQ} = 3V$

↳ Early Effect Negligible

To Find: small-sig. gain A_V, i/p resistance as seen from source V_S



For DC analysis,



$V_{CEQ} = 3V$, $I_{CEQ} = 0.25mA$ $\quad I_{BEQ} = \frac{0.25}{100} = 2.5\mu A$

$V_C = 5 - I_C R_C$ $\quad V_B = (2.5\times10^{-6})(5\times10^{4})$

$V_E = -5 + (I_C R_E) + (I_C R_S)$ $\quad = 10 \times 10^{-2} = 0.1V$

$V_{CE} = V_C - V_E$ $\quad V_{BE} = 0.7V$ (Assume)

$= 5 - I_C R_C - (-5 + I_C R_E + I_C R_S)$ $\Rightarrow V_E = 0.1 - 0.7 = -0.6V$

$= 10 - I_C R_C - I_C R_E - I_C R_S$

$$3 = 10 - I_c(R_c + R_E + R_S)$$

$$7 = (0.25\times10^{-3})(R_c + R_E + 100)$$

$$R_c + R_E + 100 = \frac{7\times1000}{0.25} = 28000$$

$$\Rightarrow \quad R_c + R_E = 27900\,\Omega$$

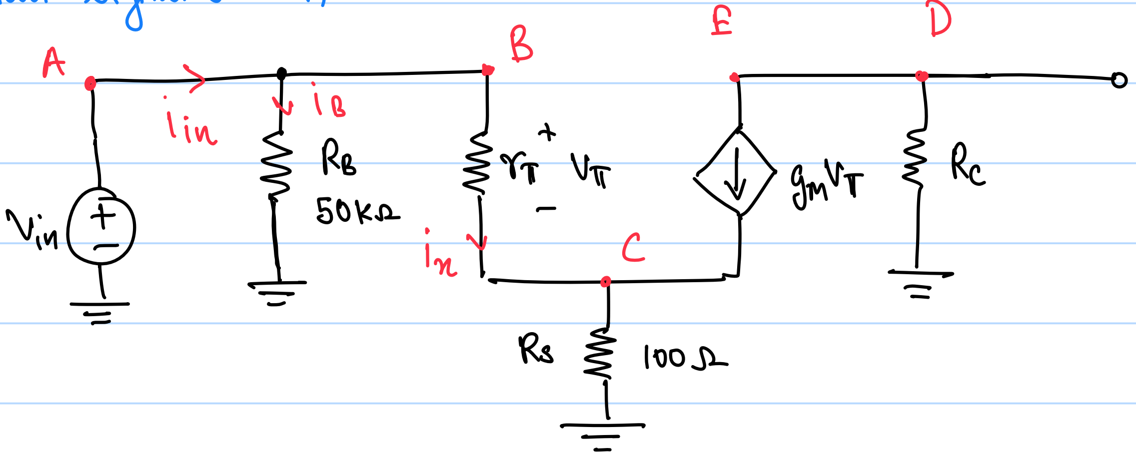
KVL from E to Gnd,

$$-0.6 - (R_E + R_S) I_c = -5$$

$$(R_E + R_S) I_c = 4.4$$

$$R_E = \frac{4.4}{I_c} - R_S = 17.5\,k\Omega \Rightarrow R_c = 10.4\,k\Omega$$

Small signal model,



Applying KCL at E,

$$i_y = g_m V_\pi$$

$$= -\frac{V_o}{R_c} = g_m V_\pi$$

$$= V_\pi = \frac{-V_o}{R_c g_m}$$

$$g_m = \frac{I_{CEQ}}{V_T} = \frac{0.25\times10^{-3}}{26\times10^{-3}}$$

$$= 9.615\times10^{-3}$$

Applying KVL in ABCA,

$$V_{in} = V_\pi + (i_x + g_m V_\pi) R_S \qquad r_\pi = \frac{\beta}{g_m} = \frac{100}{9.615 \times 10^{-3}}$$

$$= V_\pi + \left(\frac{V_\pi}{r_\pi} + g_m V_\pi\right) R_S \qquad \simeq 10.4\,k\Omega$$

$$= V_\pi \left(1 + \left(\frac{1}{r_\pi} + g_m\right) R_S\right)$$

$$= \frac{-V_o}{R_C g_m} \left(1 + \left(\frac{1}{r_\pi} + g_m\right) R_S\right)$$

$$\frac{V_o}{V_{in}} = \frac{-R_C g_m}{1 + \left(\frac{1}{r_\pi} + g_m\right) R_S}$$

$$= \frac{-(10.4 \times 10^3)(9.615 \times 10^{-3})}{1 + \left(\frac{1}{10.4 \times 10^3} + 9.615 \times 10^{-3}\right)(100)}$$

$$\boxed{A_v = -49.016}$$

To find input impedance r_{in},

$$r_{in} = \frac{V_{in}}{i_{in}} \qquad r_\pi = \frac{\beta}{g_m}$$

$$i_{in} = i_B + i_x \qquad g_m r_\pi = \beta$$

$$i_B = \frac{V_{in}}{R_B}, \quad i_x = \frac{V_\pi}{r_\pi} = \frac{-V_o}{R_C g_m r_\pi} = \frac{-A_v V_{in}}{\beta R_C}$$

$$i_{in} = \frac{V_{in}}{R_B} - \frac{A_v V_{in}}{R_C \beta}$$

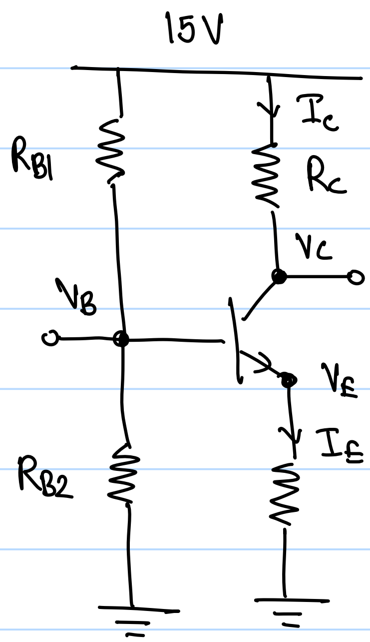
$$\Rightarrow r_{in} = \frac{V_{in}}{V_{in}\left(\frac{1}{R_B} - \frac{A_v}{R_C \beta}\right)} = \frac{1}{\frac{1}{R_B} - \frac{A_v}{R_C \beta}} = \frac{1}{\frac{1}{50 \times 10^3} + \frac{49.016}{(10.4 \times 10^3)(10^2)}}$$

$$\Rightarrow \boxed{r_{in} = 14.896\ k\Omega}$$

II)

2.1. Given: $\beta = 100$, $R_{B1} = 100\,k\Omega$, $R_{B2} = 50\,k\Omega$, $R_C = 5\,k\Omega$, $R_E = 3\,k\Omega$

To find: V_B, V_C, V_E, I_C, I_E



$$V_B = V_{CC} \frac{R_{B2}}{R_{B1} + R_{B2}}$$

$$= 15 \frac{50}{100 + 50}$$

$$= \underline{\underline{5\ V}}$$

Assume $V_{BE} = 0.7V$

$$V_E = V_B - V_{BE} = 5 - 0.7 = \underline{\underline{4.3V}}$$

$$I_E = \frac{V_E}{R_E} = \frac{4.3}{3 \times 10^3} = 1.43\,mA$$

$I_E = I_C + I_B$ (By KCL within the BJT)

& $I_B = \frac{I_C}{\beta}$

$$\Rightarrow I_E = I_C\left(1 + \frac{1}{\beta}\right) \Rightarrow I_C = I_E\left(\frac{\beta}{\beta+1}\right)$$

$$I_C = 1.43\left(\frac{100}{101}\right) mA \simeq \underline{\underline{1.419\ mA}}$$

$$I_B = \frac{1.419}{100} \simeq \underline{0.014\ mA}$$

$$V_C = V_{CC} - I_C R_C = 15 - (1.419\times10^{-3})(5\times10^{3})$$

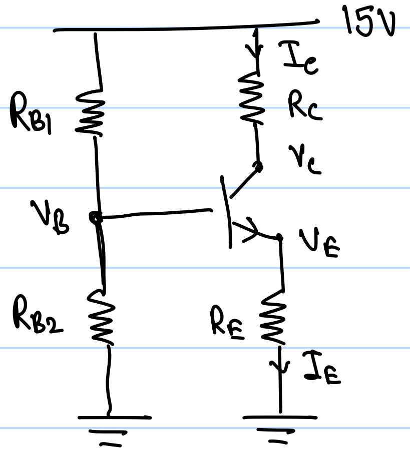
$$= \underline{\underline{7.905\ V}}$$

∴

I_C	I_B	V_C	V_B	V_E	I_E
1.419 mA	0.014 mA	7.905 V	5V	4.3V	1.43 mA

2.2. Given : Same as 2.1 . $\beta \rightarrow 50$

To Find : ΔI_C %, ΔI_B %, ΔI_E %, ΔV_B %, ΔV_C %, ΔV_E %



$$V_B = V_{CC}\frac{R_{B2}}{R_{B2}+R_{B1}}$$

$$= 15\ \frac{50}{50+100}$$

$$= 5V$$ (Same as before, since V_B does not depend on β)

Assuming $V_{BE} = 0.7V$,

$$V_E = V_B - V_{BE} = 5 - 0.7 = 4.3V$$

$$I_E = \frac{V_E}{R_E} = 1.43 mA$$

Also does not depend on β.

$$I_C = \left(\frac{\beta}{\beta+1}\right) I_E = \frac{50}{51} 1.43 \text{ mA} \approx \underline{1.402 \text{ mA}}$$

$$I_B = \frac{I_C}{\beta} \approx \underline{0.028 \text{ mA}}$$

$$V_C = V_{CC} - I_C R_C$$
$$= 15 - (1.402 \times 10^{-3})(5 \times 10^{3}) = \underline{7.99 \text{ V}}$$

	I_C	I_B	I_C	V_C	V_B	V_E
$\beta = 100$	1.419 mA	0.014 mA	1.43 mA	7.905 V	5 V	4.3 V
$\beta = 50$	1.402 mA	0.028 mA	1.43 mA	7.99 V	5 V	4.3 V
$\Delta\%$	1.198 %	100 %	0	1.063 %	0	0

2.3. We know that if $V_{CE} > 0.8V$, then the BJT is in forward active mode. If $V_{CE} < 0.7V$, then it is in Saturation mode and if $V_{CE} \in (0.7V, 0.8V)$, then it is at the Edge of Saturation.

V_{CE} is given by,

$$V_{CE} = V_C - V_E$$

In question 2.1,

$$V_{CE} = V_C - V_E = 7.905 - 4.3 = \underline{3.605} > 0.8V$$

$\therefore$ In Q.2.1, the BJT is in Forward Active mode of operation.

In question 2.2,

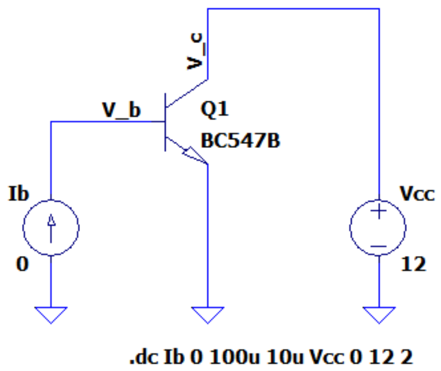
$$V_{CE} = V_C - V_E = 7.99 - 4.3 = \underline{3.69\ V} > 0.8V$$

$\therefore$ In Q.2.2, the BJT is in Forward Active mode of operation.

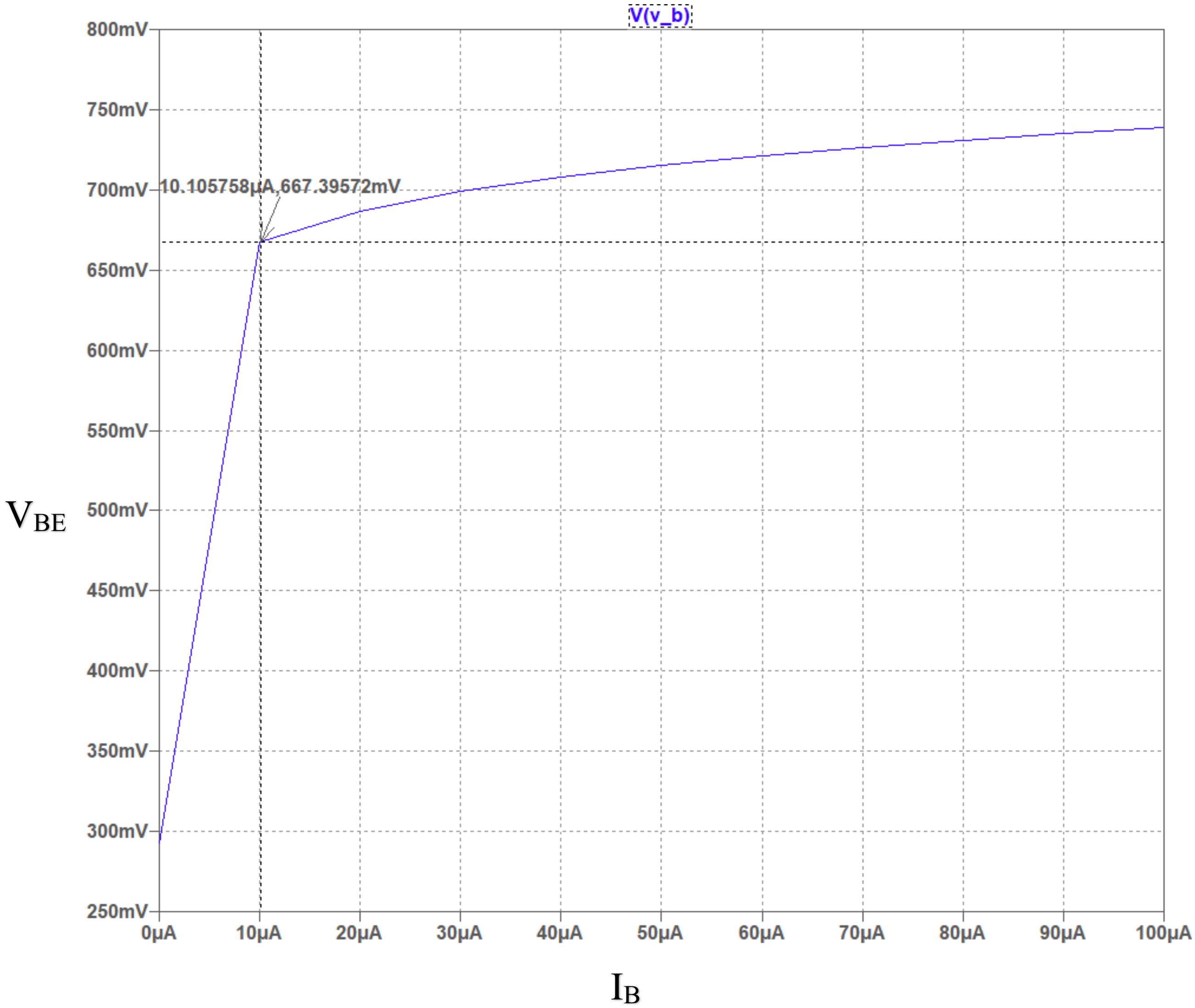
III)

Q.3.1

Circuit Diagram:



V_{BE} vs I_B:

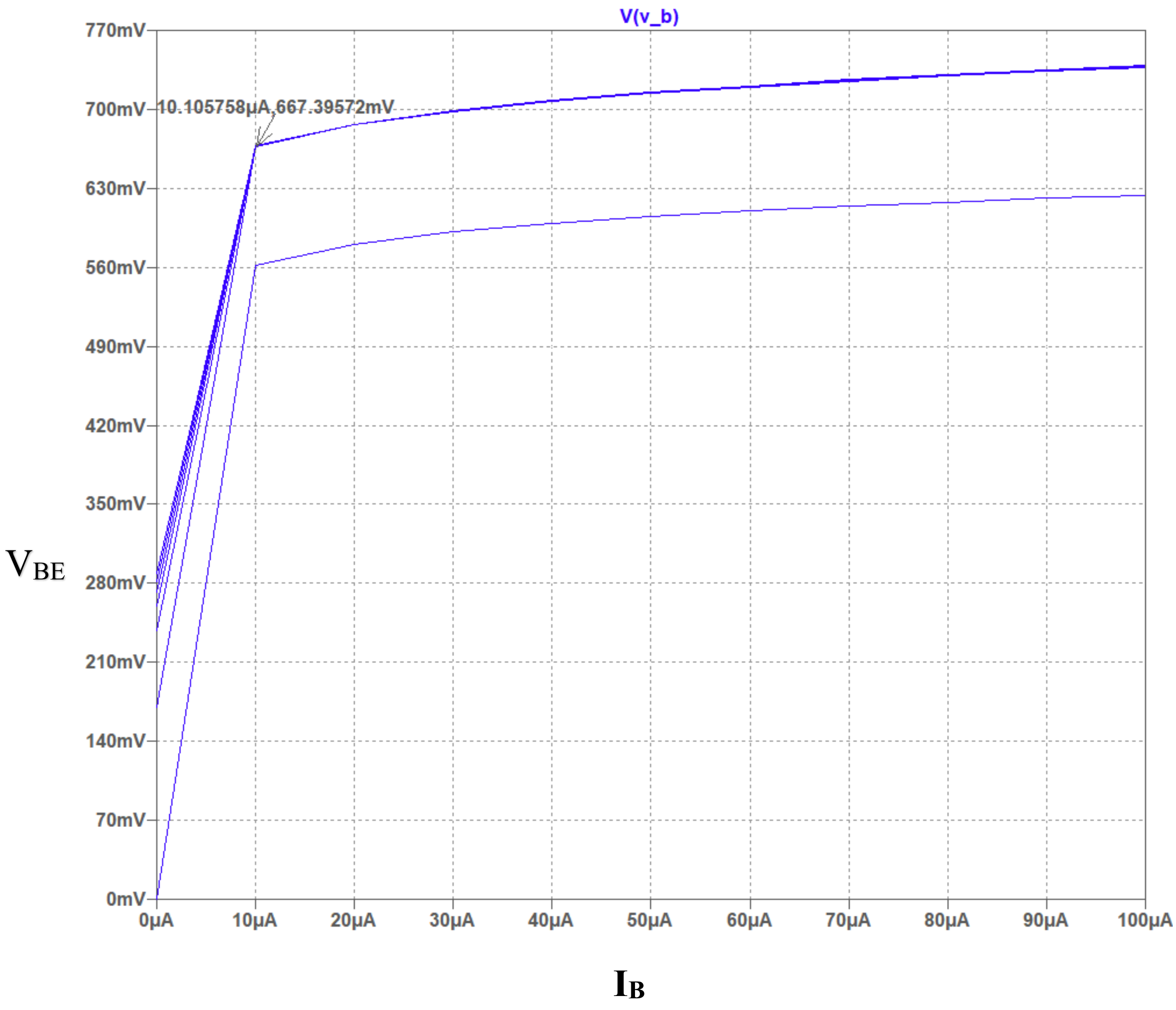


X Axis: I_B (ranging from 0 to 100µA in steps of 10µA)

Y Axis: V_{BE}

Obtained Emitter Base Junction Voltage = 667.39572mV

$\underline{V_{BE}\text{ vs }I_B\text{ and }V_{CC}}$:



X Axis: I_B (ranging from 0 to 100µA in steps of 10µA)

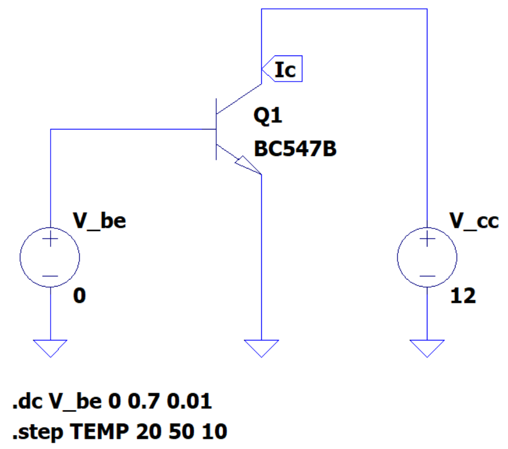
Y Axis: V_{BE}

V_{CC} ranging from 0 to 12V in steps of 2V

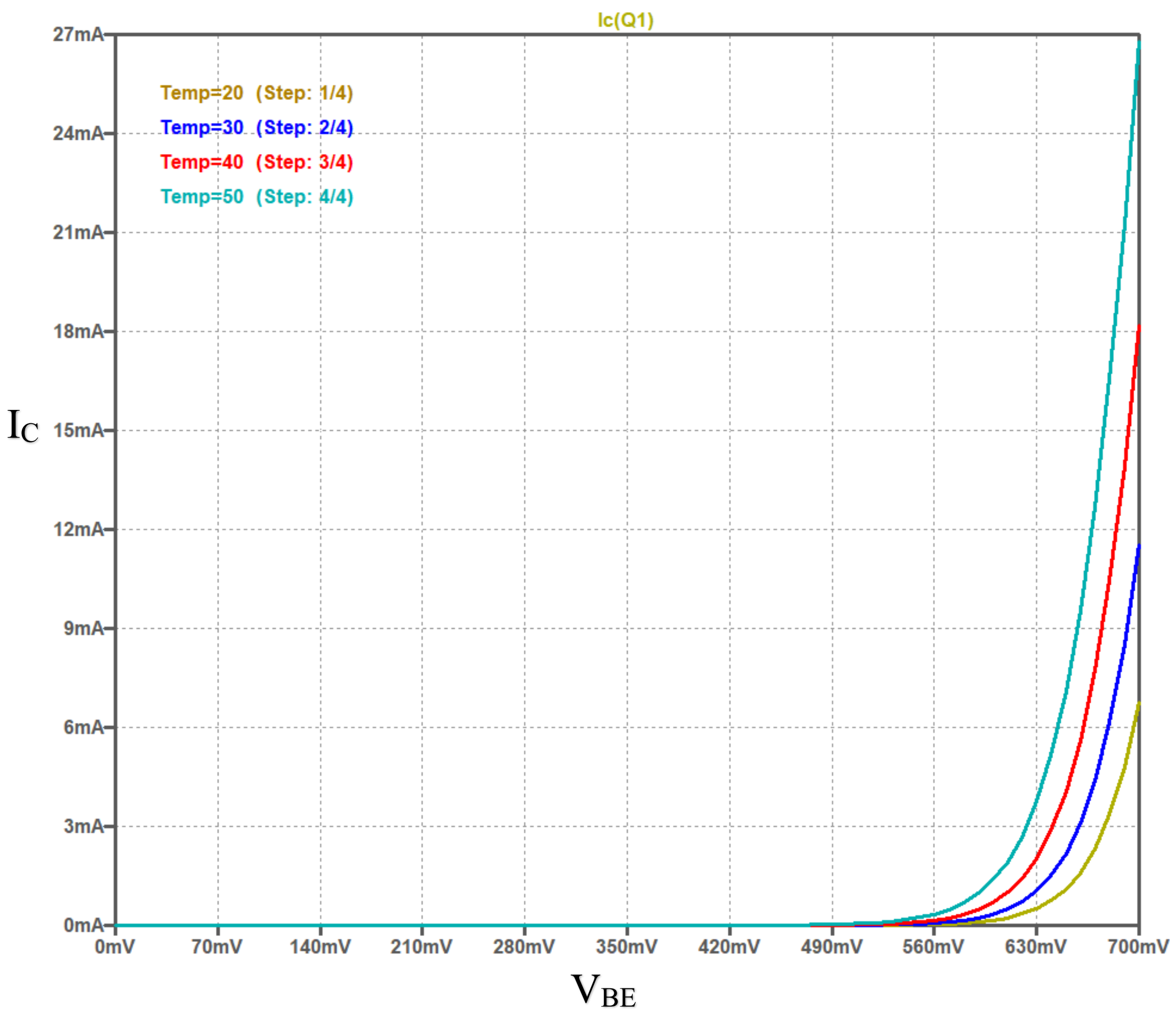
The different plot lines converging together after I_B shows that V_{BE} does not depend on V_{CC} while in Forward Active mode. The single separate plot line is for $V_{CC} = 0$, as it represents Saturation mode.

Q.3.2

Circuit Diagram:



I_C vs V_{BE} and Temperature:



X Axis: V_{BE} ranging from 0 to 700mV in steps of 10mV

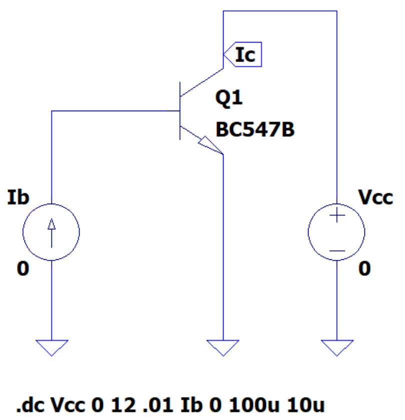
Y Axis: I_C

Calculated for temperatures 20ºC, 30ºC, 40ºC and 50ºC

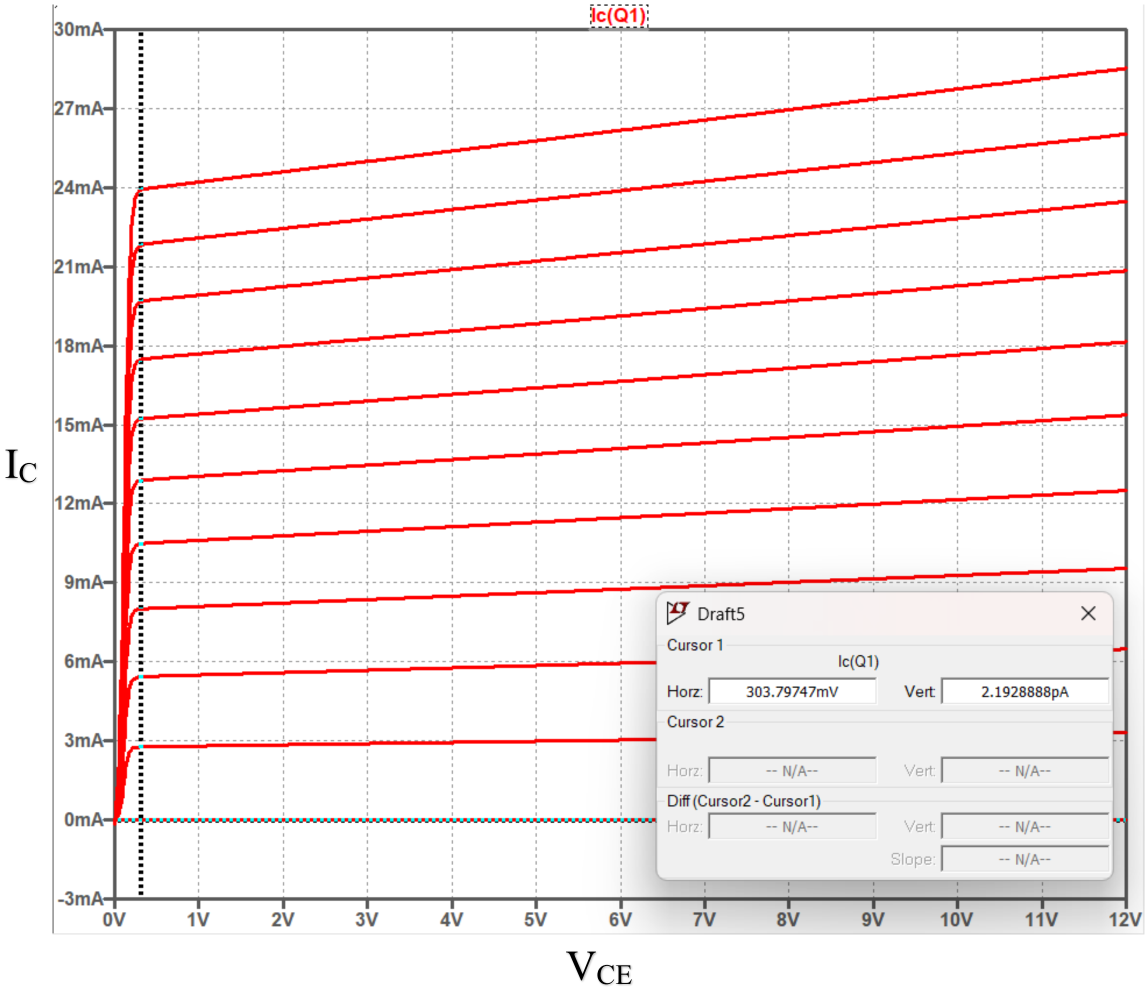
This calculation shows that collector current increases with temperature during Forward Active Mode of operation

Q.3.3

Circuit Diagram:



Ic vs V_{CE} and I_B:



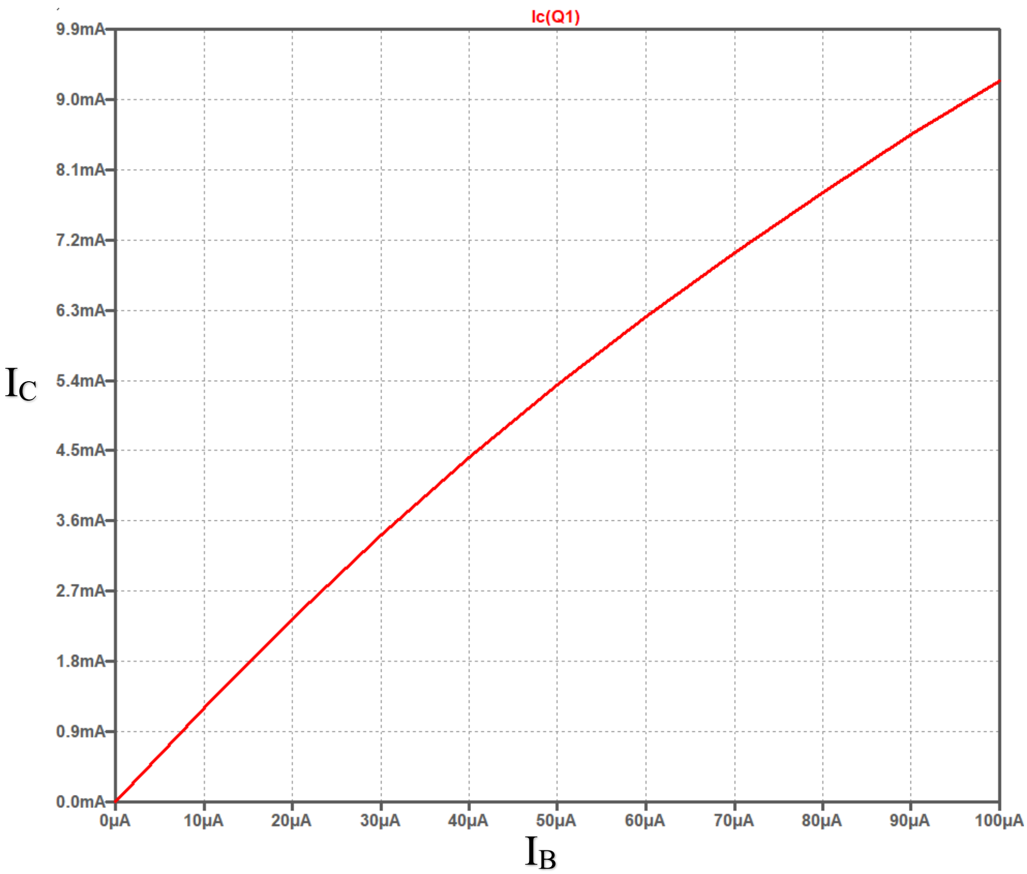
X Axis: V_{CE} (ranging from 0 to 12V in steps of 0.01V)

Y Axis: I_C

I_B ranging from 0 to 100µA in steps of 10µA

The boundary between the Saturation region and Forward Active region is roughly at V_{CE} = 303.79747mV, as shown by the cursor in the plot.

<u>Ic vs I_B at V_{CE} = 100mV (Saturation):</u>

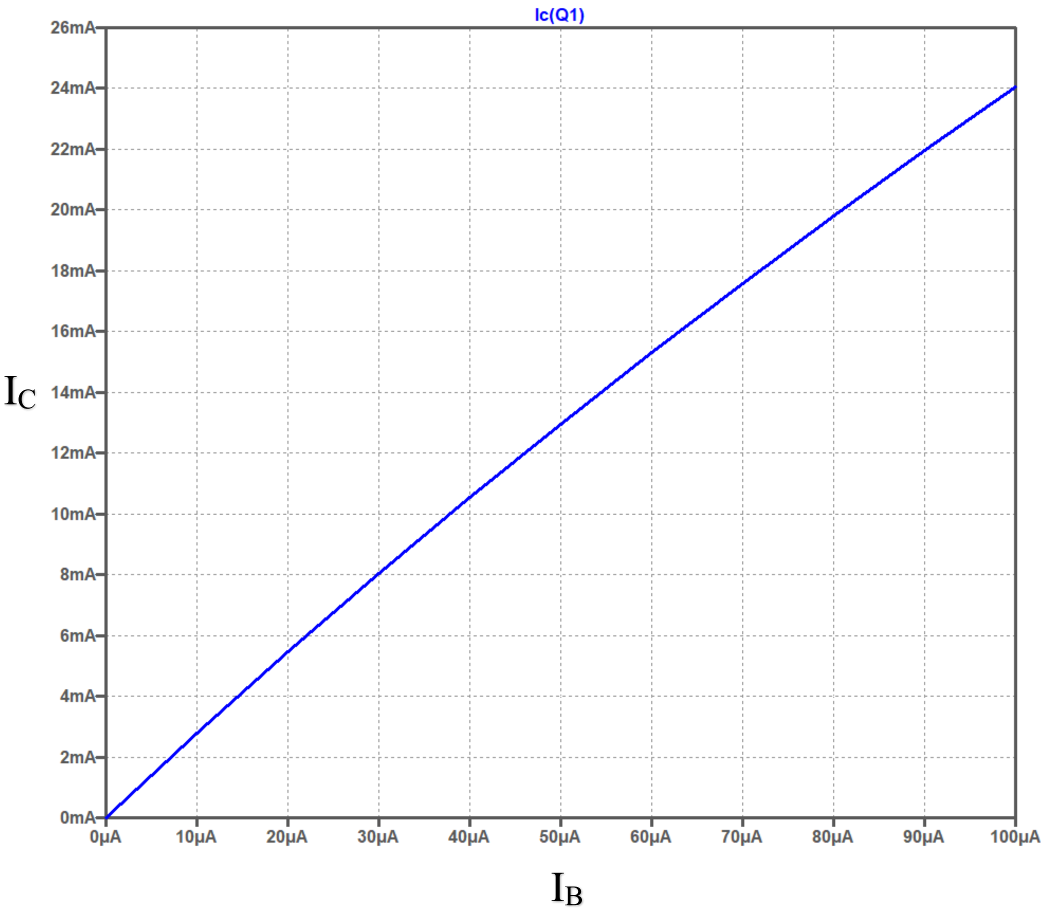


I_C at I_B = 50µA: 5.34046 mA

I_C at I_B = 60µA: 6.21322 mA

$$\beta = \frac{\Delta I_C}{\Delta I_B} = 87.276$$

Ic vs I_B at V_{CE} = 600mV (Forward Active):



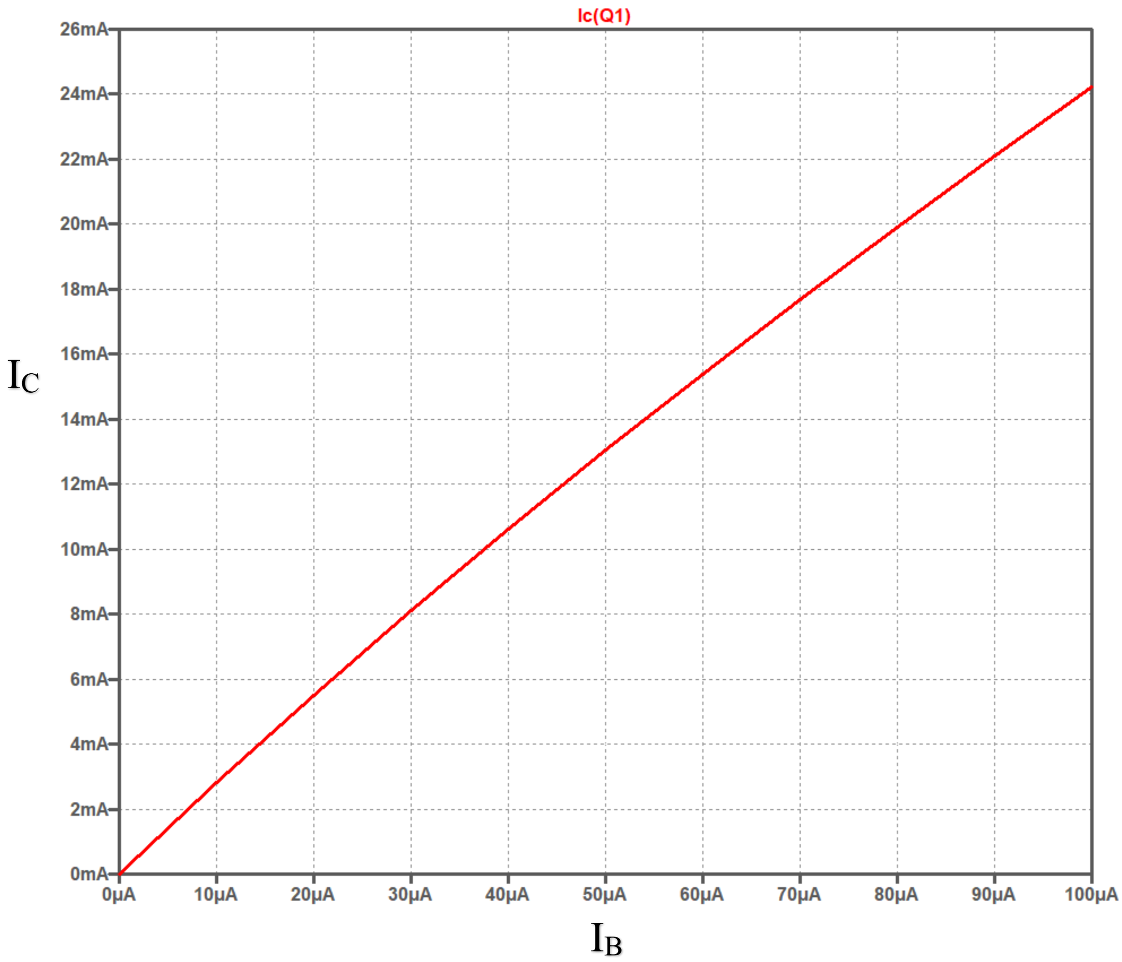
I_C at I_B = 50µA: 12.9573 mA

I_C at I_B = 60µA: 15.2992 mA

$$\beta = \frac{\Delta I_C}{\Delta I_B} = 234.19$$

Clearly, β during Forward Active is much higher than during Saturation. This is because the collector current decreases a lot in Saturation mode, due to the Collector Base Junction being in forward bias conducting in the opposite direction.

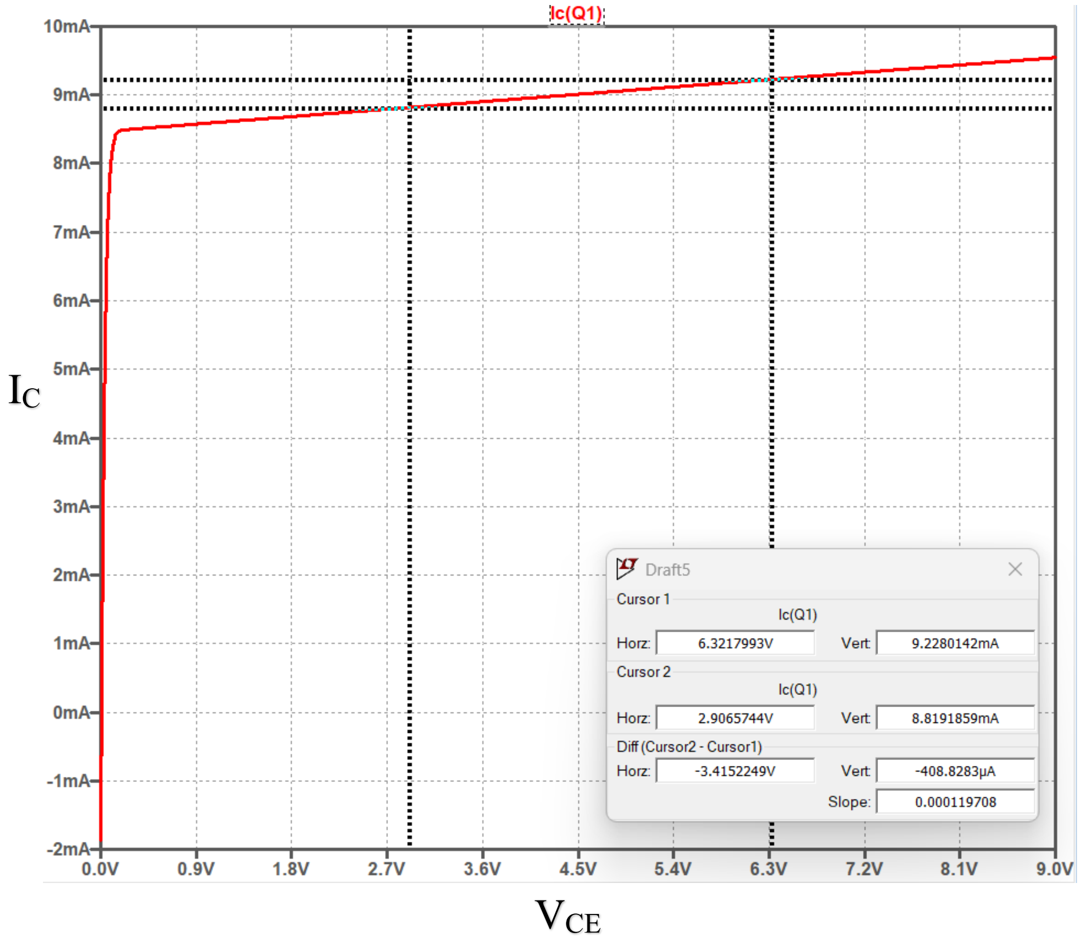
Ic vs I_B at $V_{CE} = 1V$:



I_B (uA)	I_C(mA)	β
10	2.80528	280.528
20	5.5026	275.13
30	8.10143	270.0477
40	10.6117	265.2925
50	13.0418	260.836
60	15.3989	256.6483
70	17.6893	252.7043
80	19.9181	248.9763
90	22.0902	245.4467
100	24.2097	242.097

We see a gradual decrease in the value of β, with increasing I_C. This shows the presence of Early effect, since an increase in I_B will cause the base width to decrease, (due to increase in V_B), which leads to an increase in I_C, with respect to the expected value, i.e., Early effect.

To find Early voltage, we need the plot of I_C vs V_{CE} at constant V_{BE},



Slope of the Graph = 0.000119708 A/V,

Take V_{CE} as the average of the 2 points measured, i.e., 4.6141867 V.

I_C at the edge of Forward Active Mode = 8.442923mA

We know that,

$$Slope = \frac{I_C}{V_A + V_{CE}}$$

$$\Rightarrow V_A = \frac{I_C}{Slope} - V_{CE}$$

$$\Rightarrow V_A = 65.91512\ V$$

Therefore, the Early voltage is estimated to be 65.91512 V.