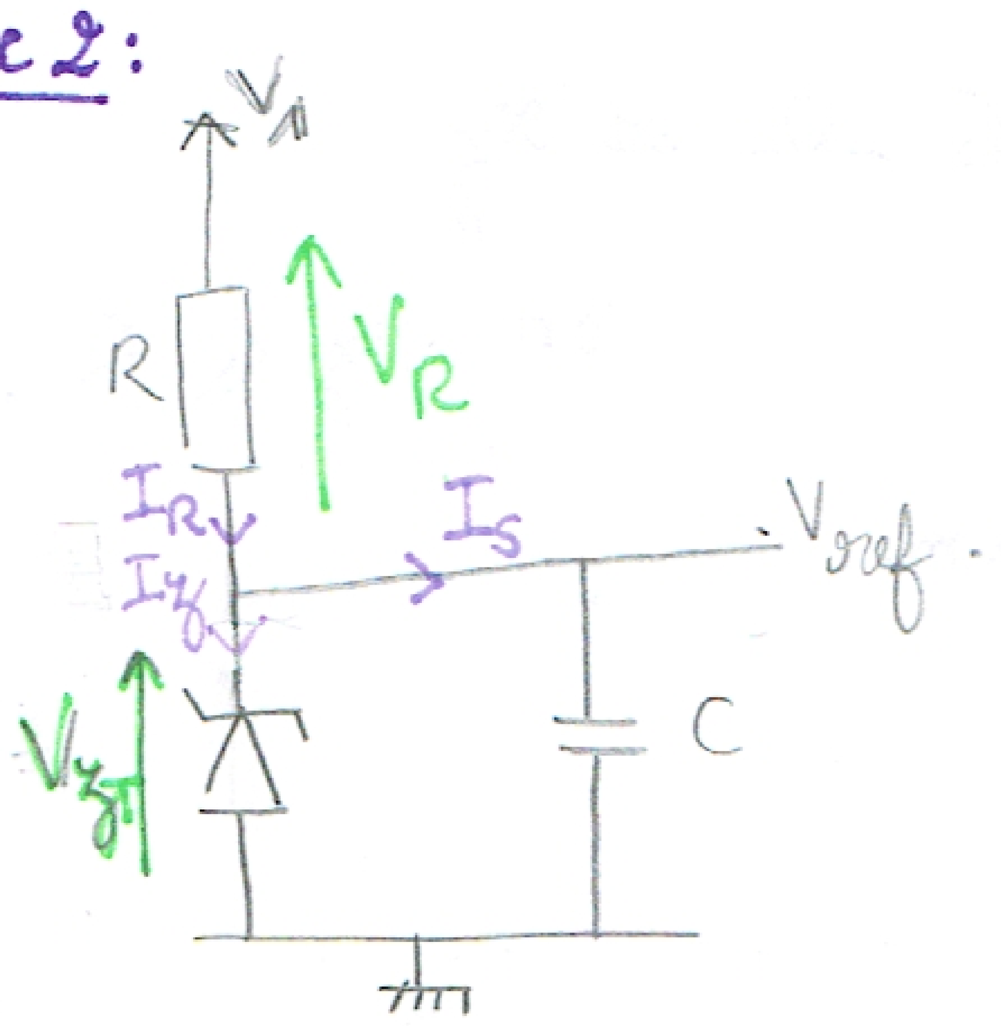
TP1 : Sources de courant et de tension

Partie 2 :



avec * $4,8 < V_{ZT} < 5,4\,V$ et $r_z < 35\,\Omega$.

* $V_1 = 12\,V$ DC $+ 200\,mV_{cc}$ à $f = 100\,Hz$.

* $V_{ref} = 5,1\,V$ avec précision $= 5\,\%$.
$+ 10\,mV_{pp}$ à $f = 100\,Hz$

* $I_Z = 5\,mA$.

1/ on a $V_{ref} = V_{Z_T} \in [4,8 ; 5,4\,V]$.

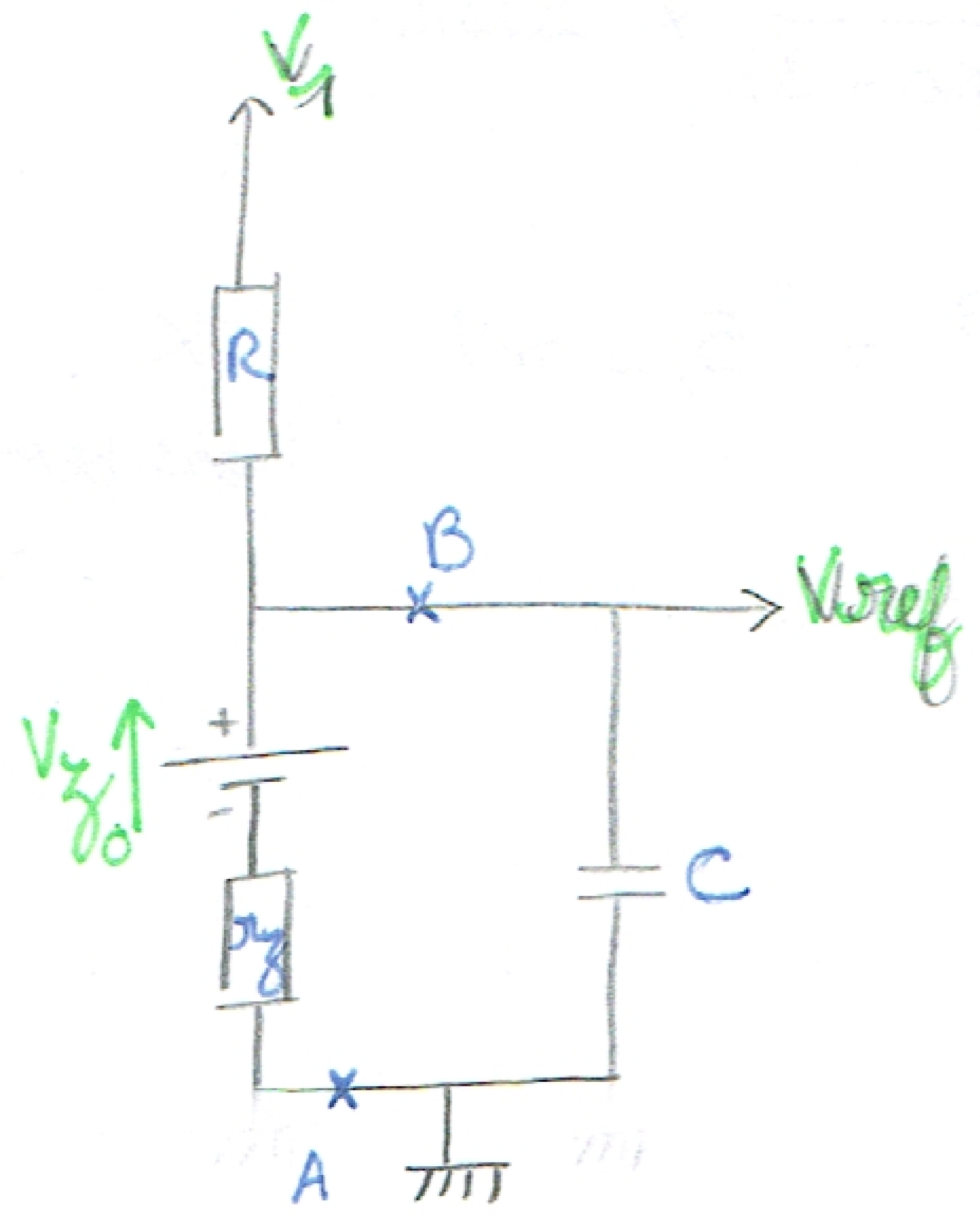
2/ $I_S = 1\,mA$. $I_Z = 5\,mA$. $I_S = I_R - I_Z \Rightarrow I_R = I_S + I_Z$
$= 6\,mA$.

$V_1 = V_R + V_{ZT} \Rightarrow V_R = V_1 - V_{ZT}$
$= 12 - 5,1$
$= 6,9\,V$

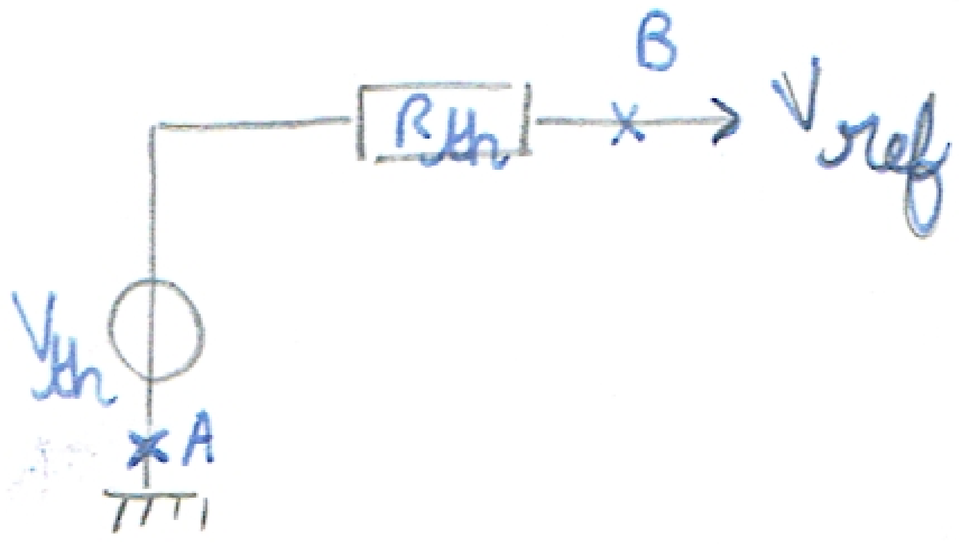
d'où $R = 1150\,\Omega$.

3/ $r_Z < 35\,\Omega$.

$V_{ZT} = V_{Z0} + r_Z I_Z \Rightarrow V_{Z0} = V_{ZT} - r_Z I_Z$
$= 5,1 - 35 \times 5.10^{-3}$
$= 4,925\,V$.

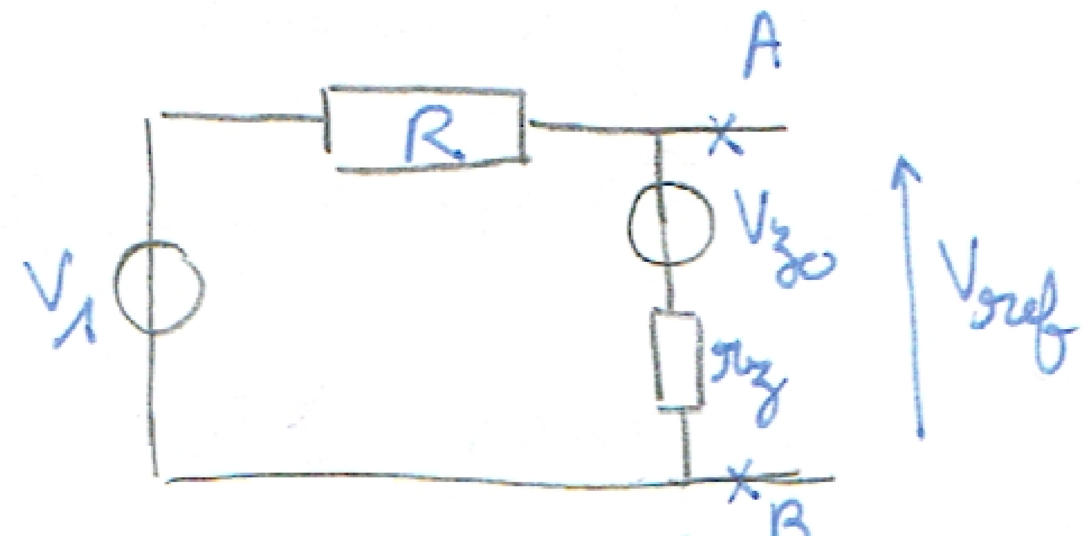


4/



$$R_{th} = r_z \,//\, R = \frac{r_z R}{r_z + R} = \frac{1150 \times 35}{1180 + 35} = 33,966\ \Omega \approx r_z$$

car $r_z \ll R$.



= théorème de superposition.

$$V_{th_1}(V_1) = \frac{r_z}{r_z + R} V_1 \qquad V_{th_2}(V_{z0}) = \frac{R}{r_z + R} V_{z0}$$

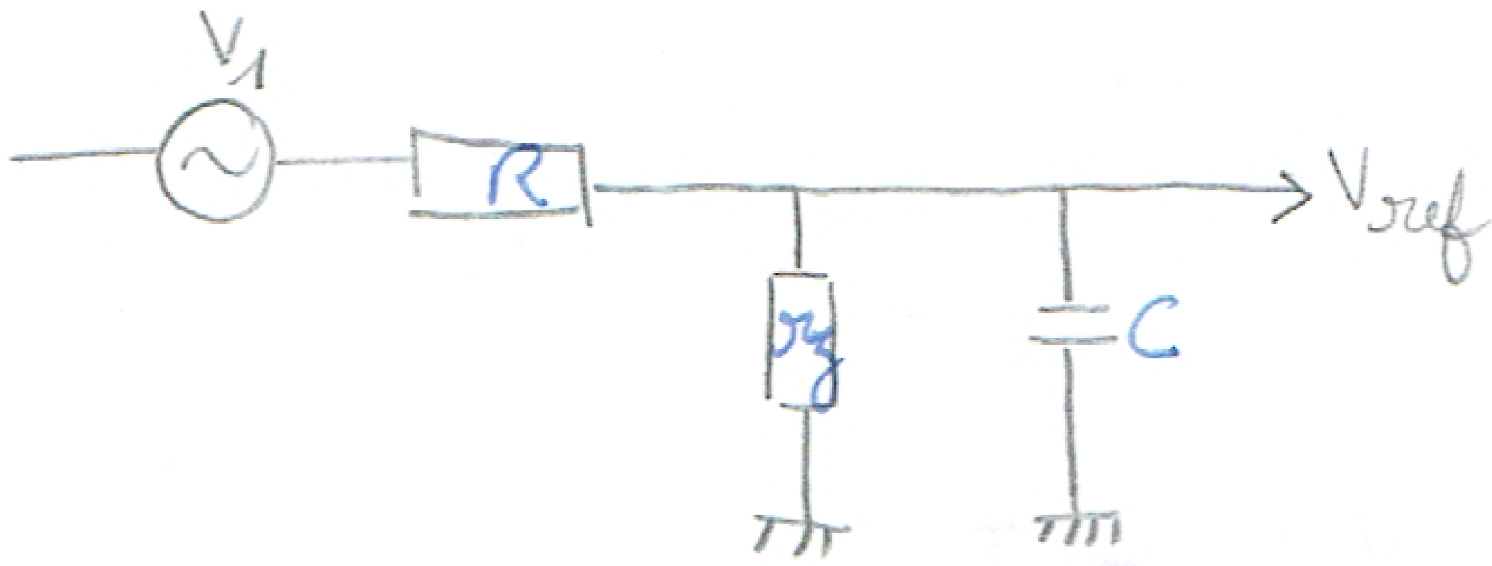
$$V_{th} = V_{th_1} + V_{th_2} = \frac{r_z V_1}{r_z + R} + \frac{R V_{z0}}{r_z + R}$$

$$= \frac{r_z V_1 + R V_{z0}}{r_z + R} = 4,925\ V.$$

5/ $\Delta V = R_{th}\, \Delta I_{th} = 35 \times 1.10^{-3} - 35 \times 0 = 35\ mV.$

donc $\frac{0,035}{5,1} = 0,068\ \%.$

6/



sans C, on a $V_{ref} = \frac{r_z}{R + r_z} V_1 = \frac{35}{1180 + 35} \times 200.10^{-3}$

$= \underbrace{0,03}_{3\% < 5\%} \times 200.10^{-3} = 5,9\ mV.$ OK.

(pas besoin de la capa).

donc $A_V = 20 \log \left(\left| \frac{r_z}{R + r_z} \right| \right)$

$= 20 \log (0,03)$

$= -30,46.$

TP1, suite.

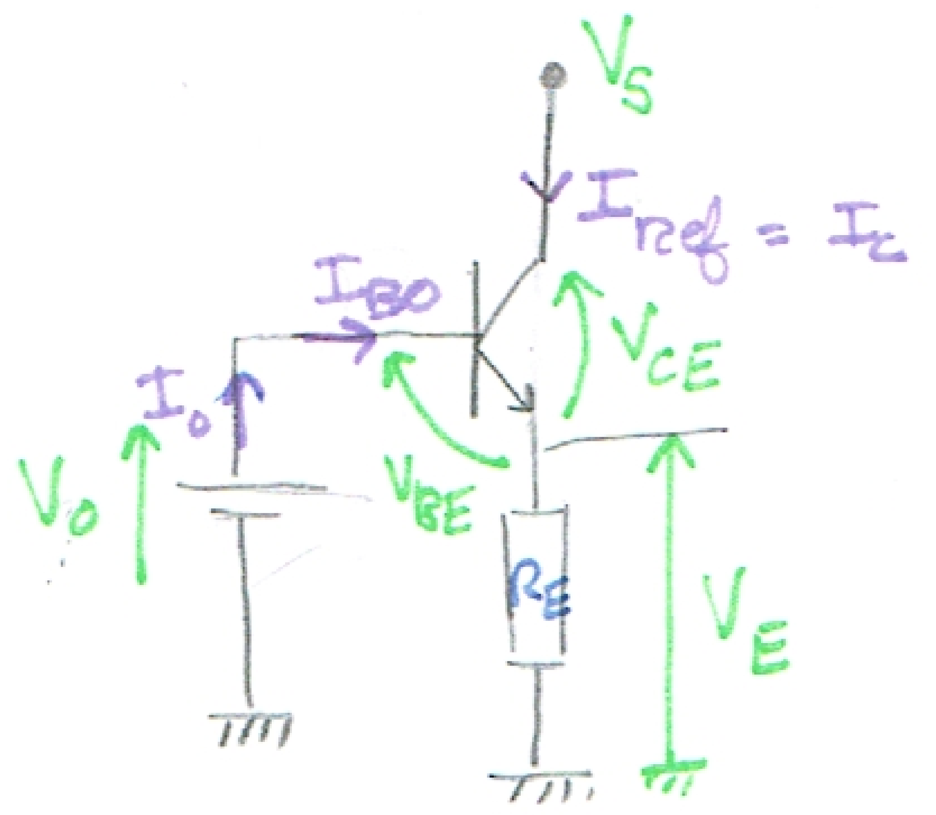
Partie 3 : Source de courant

3.3 Utilisation d'une référence de tension.

1/ $V_{CE_{max}} = 30\ V$

$V_{CE_{sat}} = 400\ mV$ donc on prend $V_{CE_{min}} = 0{,}5\ V$

2/ on cherche $V_{E_{max}}$ tel que $V_{S_{min}} = 4V$ et $V_{CE} = V_{CE_{min}} = 0{,}5\ V$



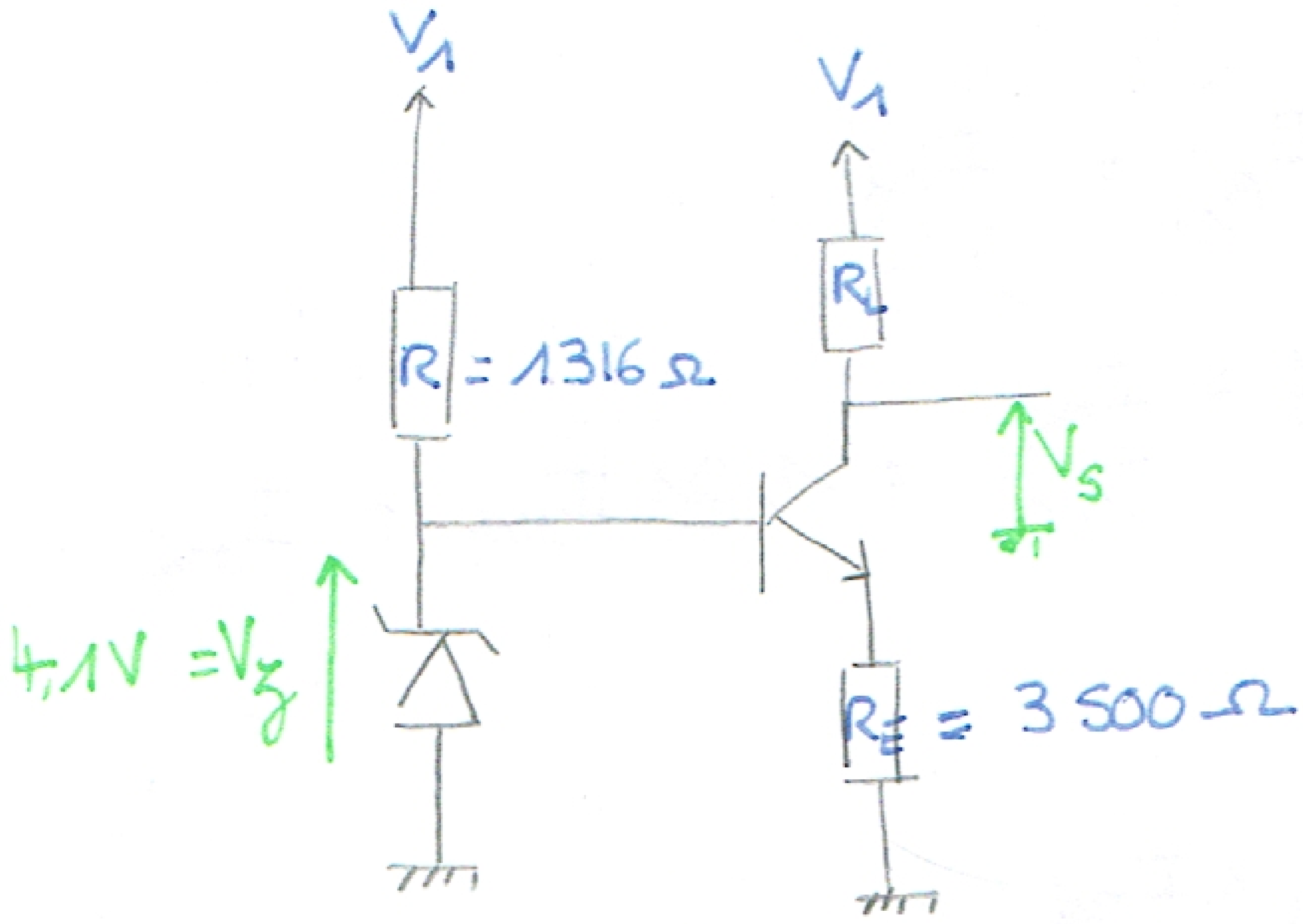
d'où * $V_{CE} + V_E = V_S \Rightarrow V_{E_{max}} = V_{S_{min}} - V_{CE_{min}}$

$= 4 - 0{,}5$

$= 3{,}5\ V \Rightarrow R_E = \frac{V_E}{I_E} = \frac{3{,}5}{1m} = 3500\ \Omega$

* $V_0 = V_{BE} + V_E = 4{,}1\ V$

3/ on veut $V_0 = 4{,}1\ V$; on reprend le circuit de la partie 2.



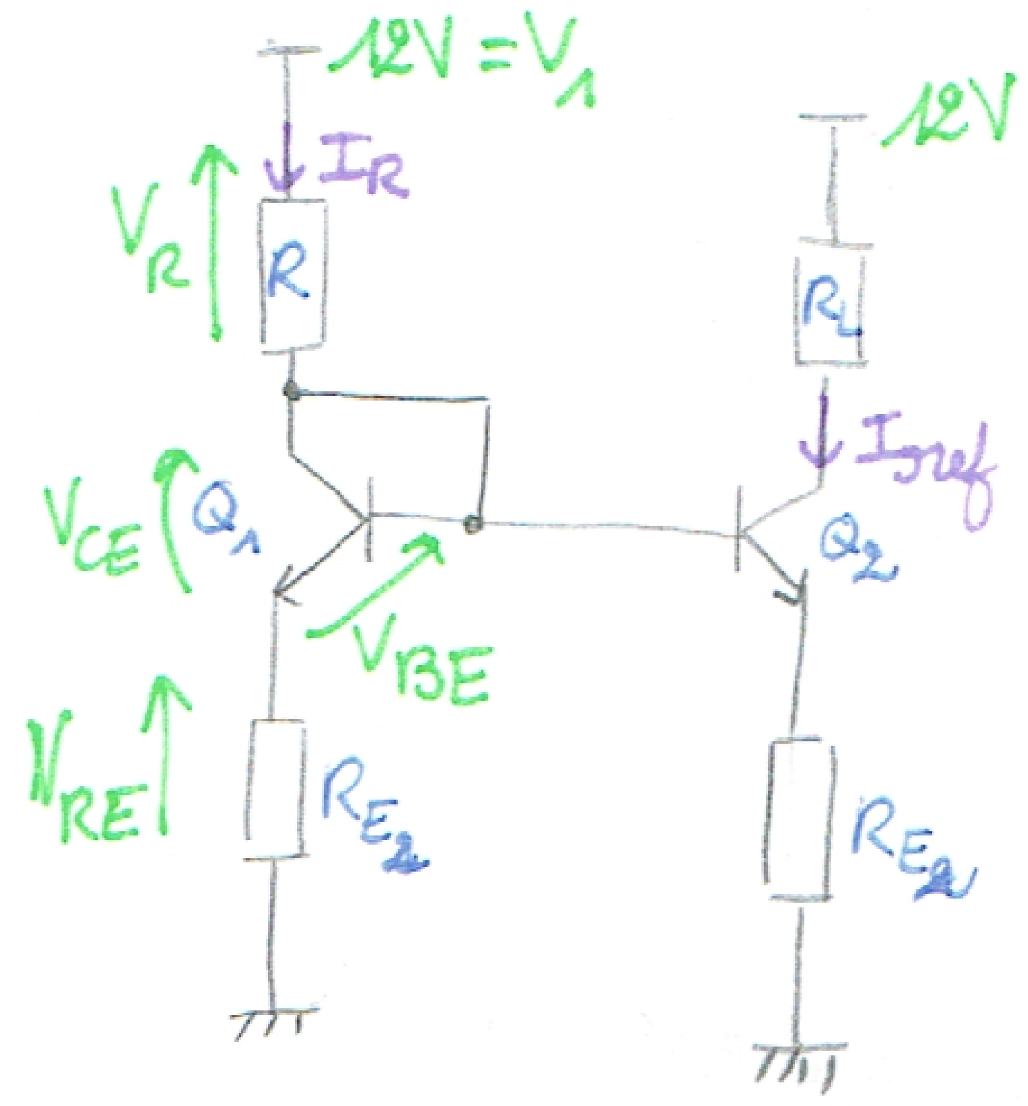
* calcul de R :

$V_R = V_1 - V_Z = 12 - 4{,}1 = 7{,}9\ V$.

$I_R = 6\ mA$.

$\Rightarrow R = \frac{7{,}9}{6m} = 1316\ \Omega$.

$\boxed{3.5}$ Le miroir de courant.



$R_{E_1} = R_{E_2} = R_E = 3500\ \Omega$.

$Q_1 = Q_2$

$I_{ref} = 1mA$.

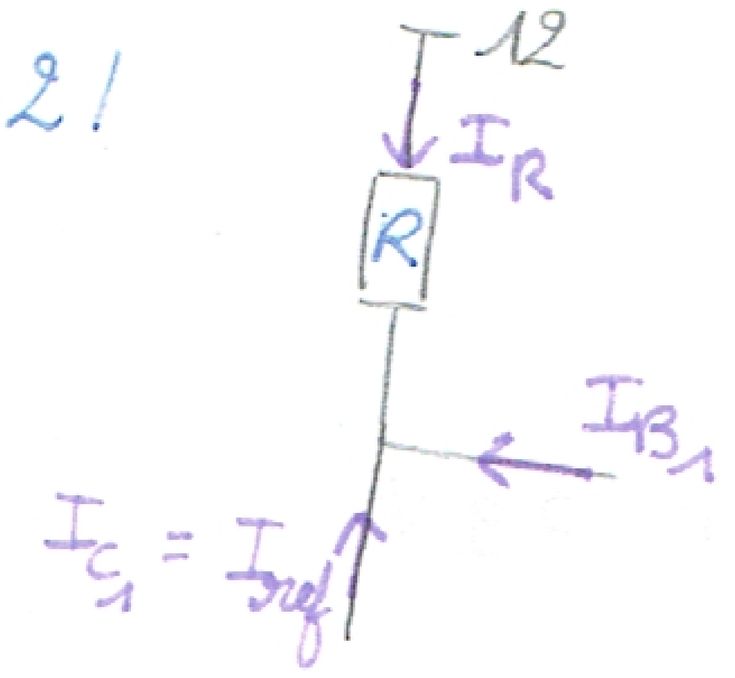
1/ V_{B_1} ? V_{B_2} ?

on sait que $Q_1 = Q_2$ et $R_{E_1} = R_{E_2}$ donc $V_{B_1} = V_{B_2}$.

donc $I_{B_1} = I_{B_2}$

donc $I_{C_1} = I_{C_2} = I_{ref}$.

2/



$I_R = I_{ref} + I_{B_1}$

Si $\beta = 100$ alors $I_{B_1} = \dfrac{I_{ref}}{100}$

$\Rightarrow I_R = I_{ref} + \dfrac{I_{ref}}{100} = 1{,}01\, I_{ref} \approx I_{ref}$.

3/ $I_R = I_{ref} = 1mA$.

$V_R = V_1 - V_{BE} - V_{RE} = 12 - 0{,}6 - R_{E_1} \times I_{ref}$

$= 7{,}9\ V$

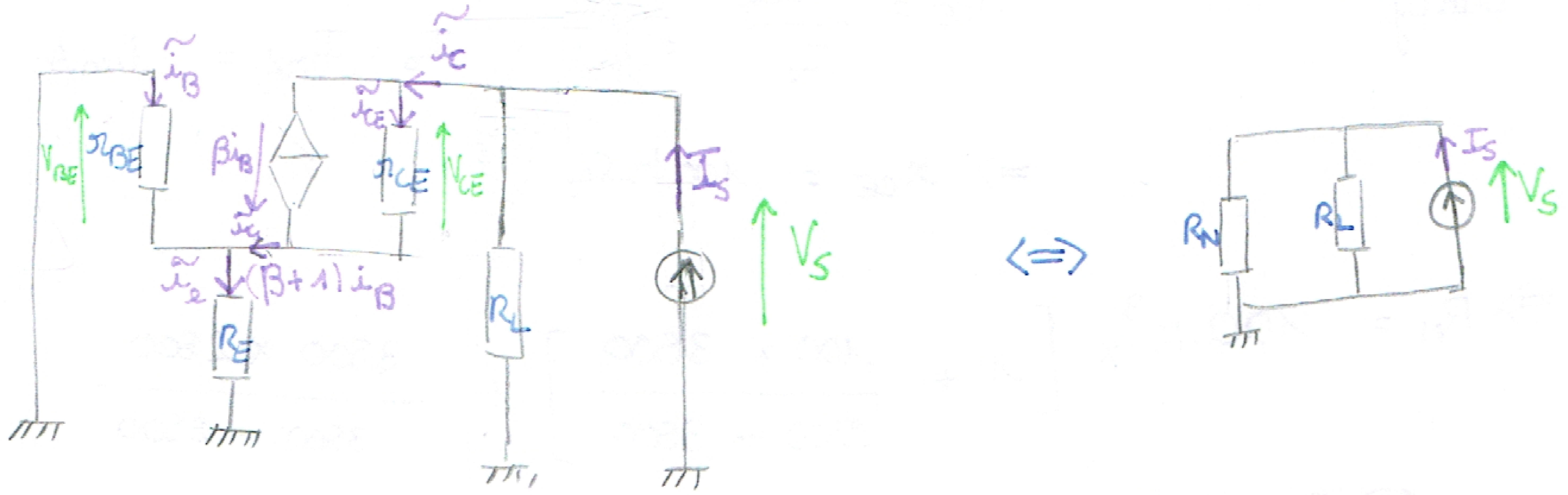
$R = \dfrac{V_R}{I_R} = 7900\ \Omega$.

TP1, suite

Partie 3, suite

3.7 Étude dynamique de la source de courant.

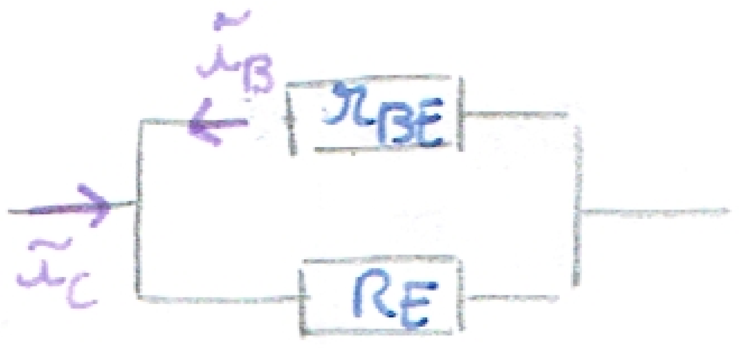
1/

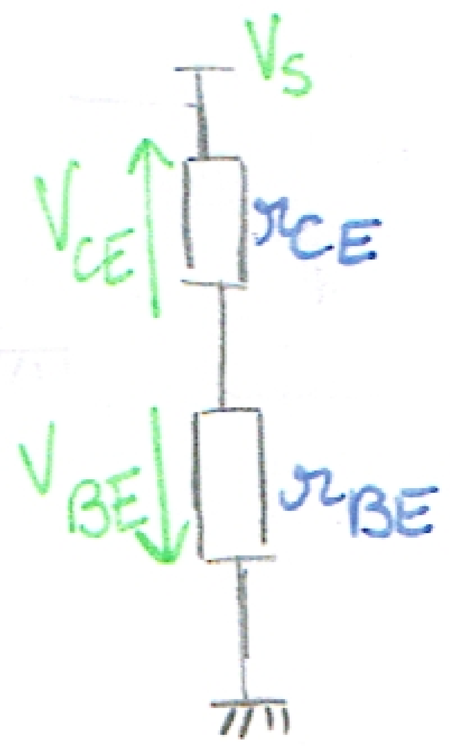


2/ $R_N = \dfrac{V_S}{I_S}$

$\Rightarrow$ pont diviseur de courant entre R_E et r_{BE}

$$-i_B = \frac{R_E}{r_{BE} + R_E}\, i_C$$





$$V_S = V_{CE} - V_{BE} = \tilde{i}_{CE}\, r_{CE} - \tilde{i}_B\, r_{BE}$$

avec $\tilde{i}_{CE} = \tilde{i}_C - \beta \tilde{i}_B$

$$V_S = (\tilde{i}_C - \beta \tilde{i}_B)\, r_{CE} - \tilde{i}_B\, r_{BE}$$

$$= \tilde{i}_C\, r_{CE} + \beta \frac{r_{CE} R_E}{r_{BE}+R_E}\, \tilde{i}_C + \frac{R_E}{r_{BE}+R_E}\, r_{BE}\, \tilde{i}_C$$

$$R_N = \frac{V_S}{\tilde{I}_C} = r_{CE}\left[1 + \frac{\beta R_E}{r_{BE}+R_E}\right] + \frac{R_E\, r_{BE}}{r_{BE}+R_E}$$

3/ * $u_T = 25\ mV$ $\quad r_{BE} = \frac{u_T}{I_{B0}}$ avec $I_{B0} = \frac{I_{C0}}{\beta} = \frac{I_{ref}}{\beta} = \frac{1m}{100}$

$\Rightarrow r_{BE} = 2\,500\ \Omega$. $\qquad = 10\ \mu A$.

* $V_{Early} = 100\ V$ $\quad r_{CE} = \frac{V_{Early}}{I_0}$ avec $I_0 = I_{ref} = 1\ mA$

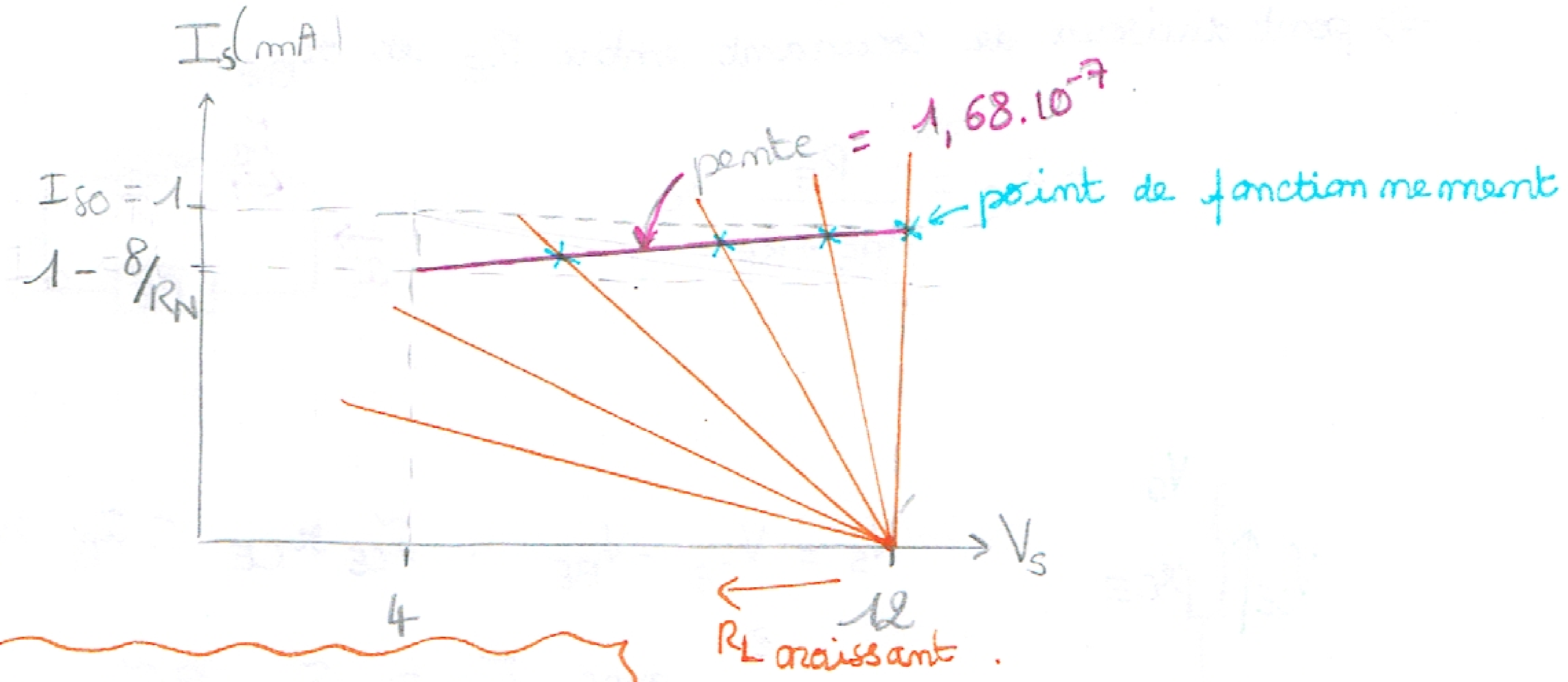
$\Rightarrow r_{CE} = 100k\Omega$.

$$\Rightarrow R_N = 100.10^3 \times \left[1 + \frac{100 \times 3500}{2500 + 3500}\right] + \frac{3500 \times 2500}{3500 + 2500}$$

4/ pente $= \frac{1}{R_N} = 1,68.10^{-7}$. $\Rightarrow$ $R_N = 5,935.10^6\ \Omega$

$= 5,9\ M\Omega$

$(I_{S0}, V_{S0}) = (1mA, 12V)$

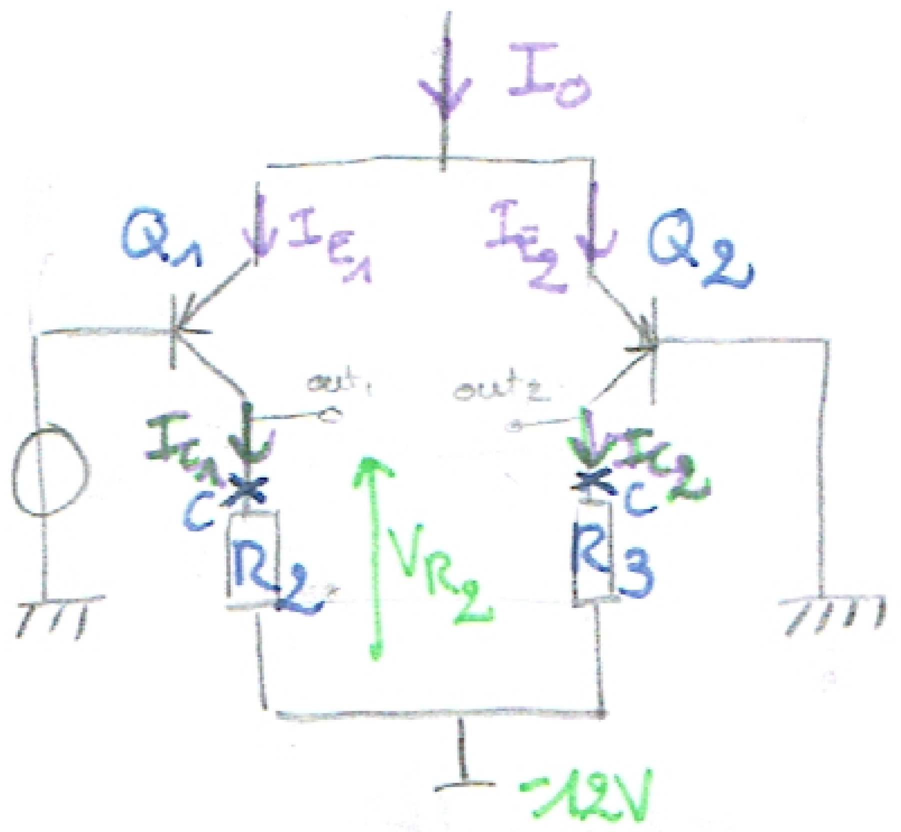


$$I_S = \frac{V_1 - V_S}{R_L} = \frac{-V_S}{R_L} + \frac{V_1}{R_L}$$

TP2 : Étage différentiel.

Partie 1 : Analyse et dimensionnement

1/

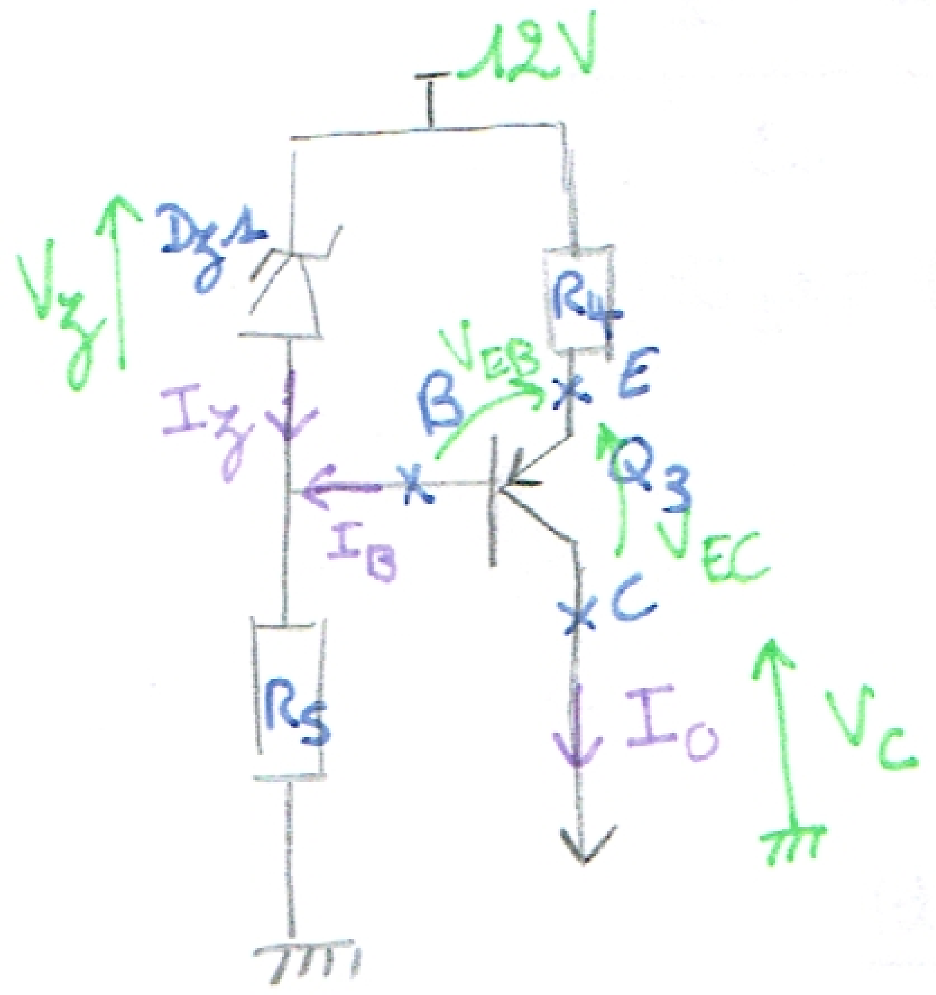


$Q_1 = Q_2 = 2N2907$.

$I_{C_1} = I_{C_2} \Rightarrow R_2 = R_3$.

$V_{R_2} = V_{R_3} = 1,8\,V$.

2/



= polarisation par diode zener

⇒ générateur de courant au collecteur constant.

3/ $I_0 = I_C = 250\,\mu A$ $\quad Q_3 = 2N2907$

$V_Z = 5,1\,V$ $\quad V_{EB} = 0,6\,V$ $\quad V_{EC_{sat}} = 0,2\,V$. $\quad \beta = 100$

$I_Z = 5\,mA$. $\quad \Rightarrow V_{EC_{min}} = 0,5\,V$

* $I_{R_5} = I_B + I_Z = \underbrace{\frac{I_C}{\beta}}_{\text{négligeable}} + I_Z = 5\,mA$.

* $V_{R_5} = 12 - V_Z = 6,9\,V$.

$$\Rightarrow \boxed{R_5 = \frac{V_{R_5}}{I_{R_5}} = 1380\,\Omega}$$

* $I_{R_4} = I_E \approx I_0 = 250\,\mu A$.

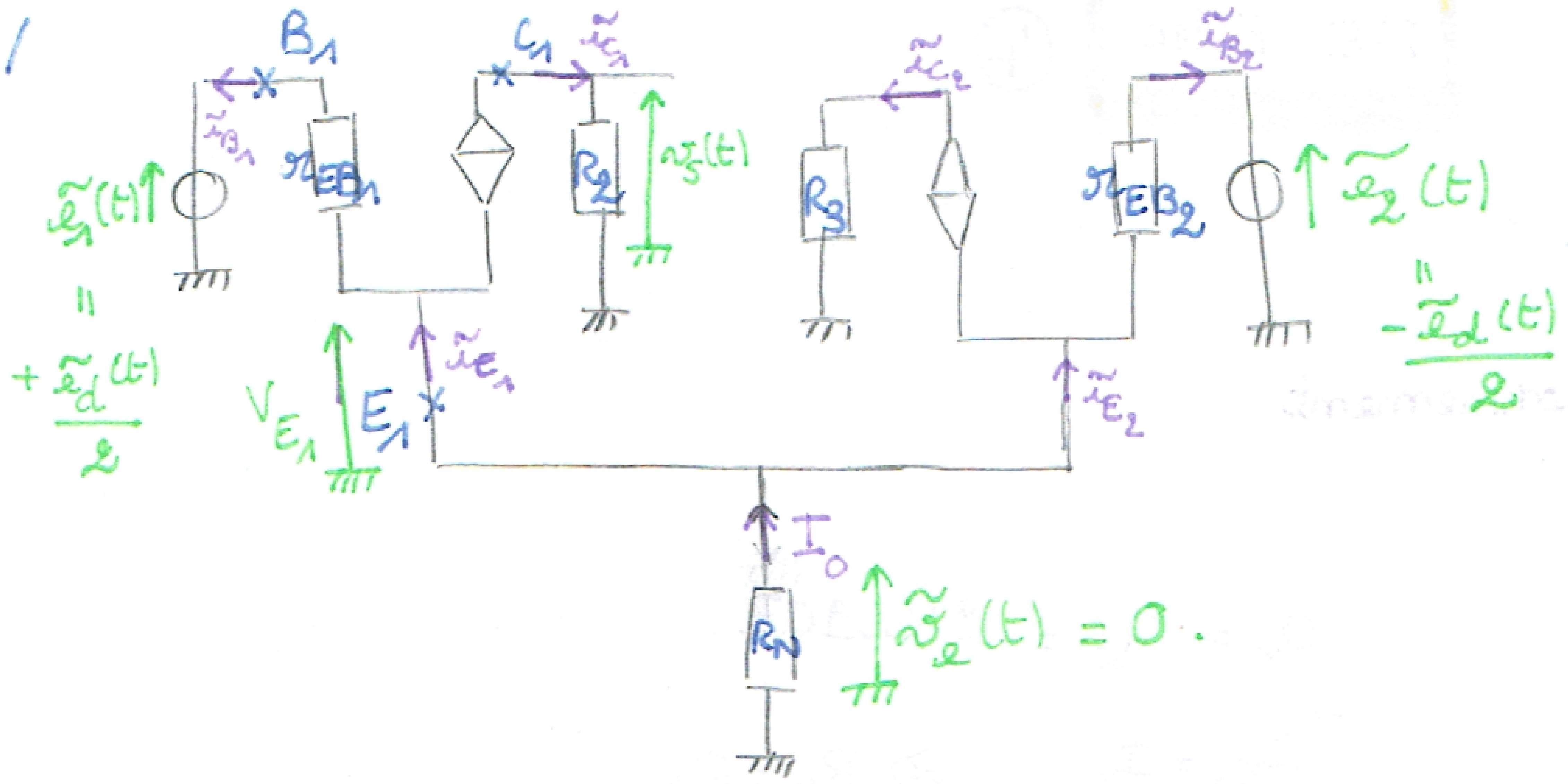
* $V_{R_4} = 12 - V_{R_5} - V_{EB} = 4,5\,V$

$$\Rightarrow \boxed{R_4 = \frac{V_{R_4}}{I_{R_4}} = 18\,k\Omega}.$$

4/ $V_{C_{max}} = 12 - V_{EC_{min}} - V_{R_4} = 7\,V$.

5/ * $V_{R_2} = 1,8\,V$ $\quad$ * $I_{R_2} = I_{C_1} = I_0/2 = 125\,\mu A$ $\quad \Rightarrow \boxed{R_2 = R_3 = 14,4\,k\Omega}$

6/



7/ → mode différentiel pur $\Rightarrow e_{MC} = 0$

$$\begin{cases} e_1(t) = e_{MC}(t) + \frac{e_d(t)}{2} \\ e_2(t) = e_{MC}(t) - \frac{e_d(t)}{2} \end{cases} \Leftrightarrow \begin{cases} e_{MC}(t) = \frac{e_1(t) + e_2(t)}{2} \\ e_d(t) = e_1(t) - e_2(t) \end{cases}$$

d'où $e_1(t) = \frac{e_d(t)}{2}$ $\quad e_2(t) = \frac{-e_d(t)}{2}$

→ impédance d'entrée différentielle : $R_{e_{diff}} = \frac{\tilde{e}_d(t)}{\tilde{i}_{B_1}(t)}$

avec $\frac{\tilde{e}_d(t)}{2} + \tilde{i}_{B_1} r_{EB_1} - \tilde{i}_{B_2} r_{EB_2} + \frac{\tilde{e}_d(t)}{2} = 0$

$$\Rightarrow \tilde{e}_d(t) = + r_{BE}\,(\tilde{i}_{B_2}(t) - i_{B_1}(t)) = -2 r_{BE}\,\tilde{i}_{B_1}(t)$$

d'où $R_{e_{diff}} = 2 r_{BE}$ $\qquad \tilde{i}_{B_1} = -\tilde{i}_{B_2}$ (à prouver).

Calcul du gain différentiel :

* $\tilde{i}_{E_1} + \tilde{i}_{E_2} = 0 \Rightarrow \tilde{i}_{E_1} = -\tilde{i}_{E_2} \Rightarrow \tilde{i}_{B_1} = -\tilde{i}_{B_2}$.

* $v_S(t) = R_2 \beta\, \tilde{i}_{B_1}(t) = -R_2 \beta \frac{\tilde{e}_d(t)}{2 r_{BE}}$ avec $r_{BE} = \frac{U_T}{I_{B0}}$

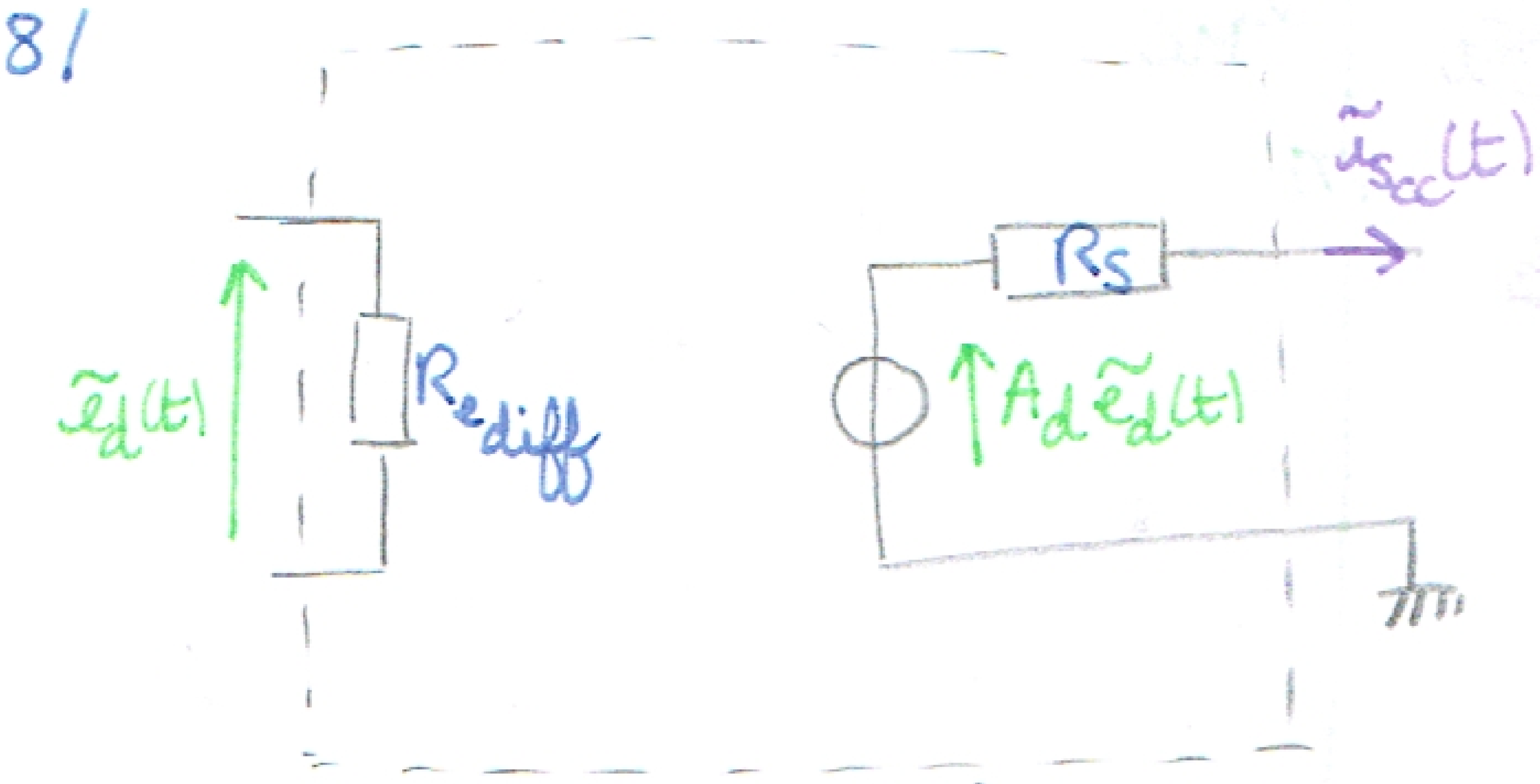
* $A_d = \frac{\tilde{v}_S(t)}{\tilde{e}_d(t)} = -R_2 \beta \times \frac{1}{2 r_{BE}} = -R_2 \beta \frac{I_{B0}}{2U_T} = -R_2 \frac{I_{C0}}{2U_T}$ $\quad I_{C0} = 125\,\mu A$ avec $U_T = 25\,mV$

$Ad = -36$ $\Rightarrow$ $\boxed{G = 20 \log (1/36) = -31,12}$

TP2, suite

Partie 1, suite

8/



↑ schéma équivalent (= quadripole).

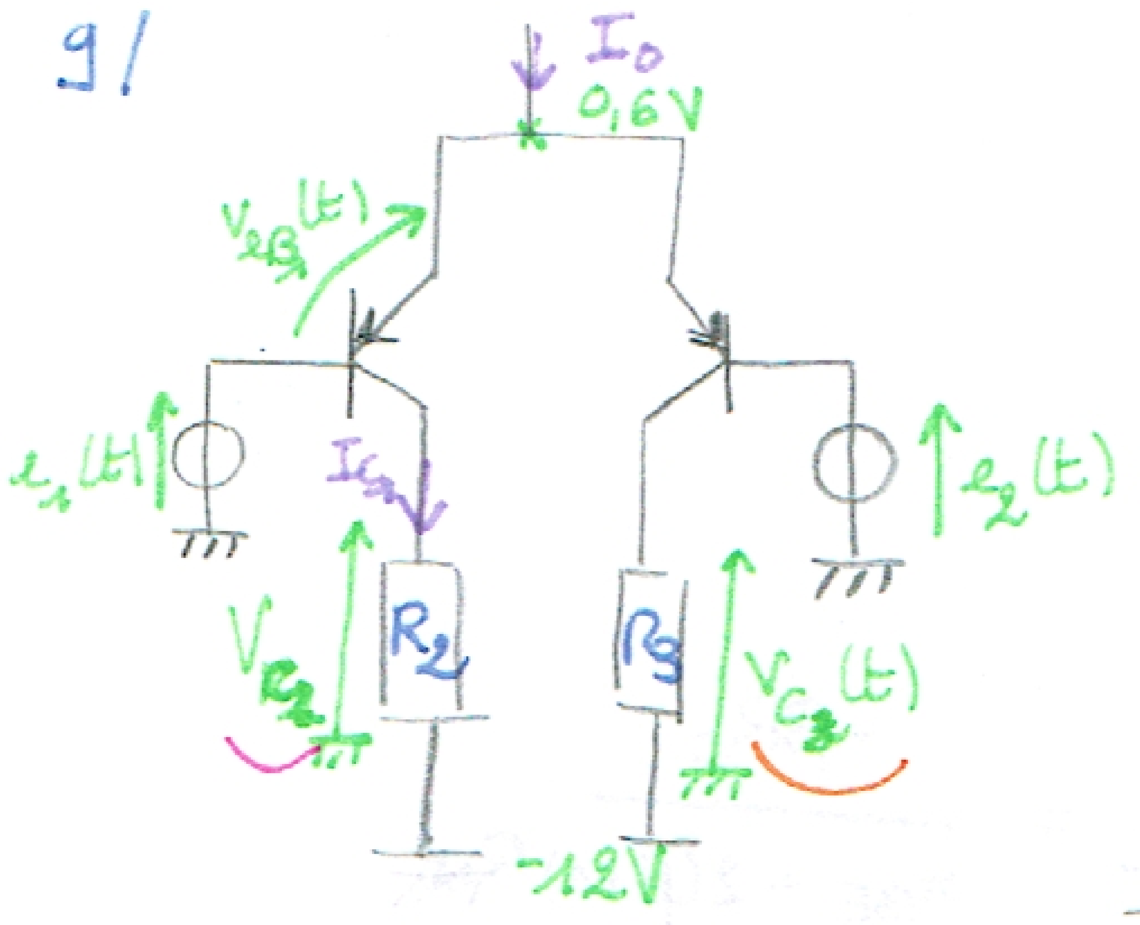
$$\tilde{i}_{S_{cc}}(t) = \frac{A_d\,\tilde{e}_d(t)}{R_S} \Rightarrow R_S = \frac{A_d\,\tilde{e}_d(t)}{\tilde{i}_{S_{cc}}(t)}$$

↳ on exprime $\tilde{e}_d(t)$ en fonction $\tilde{i}_{S_{cc}}(t)$:

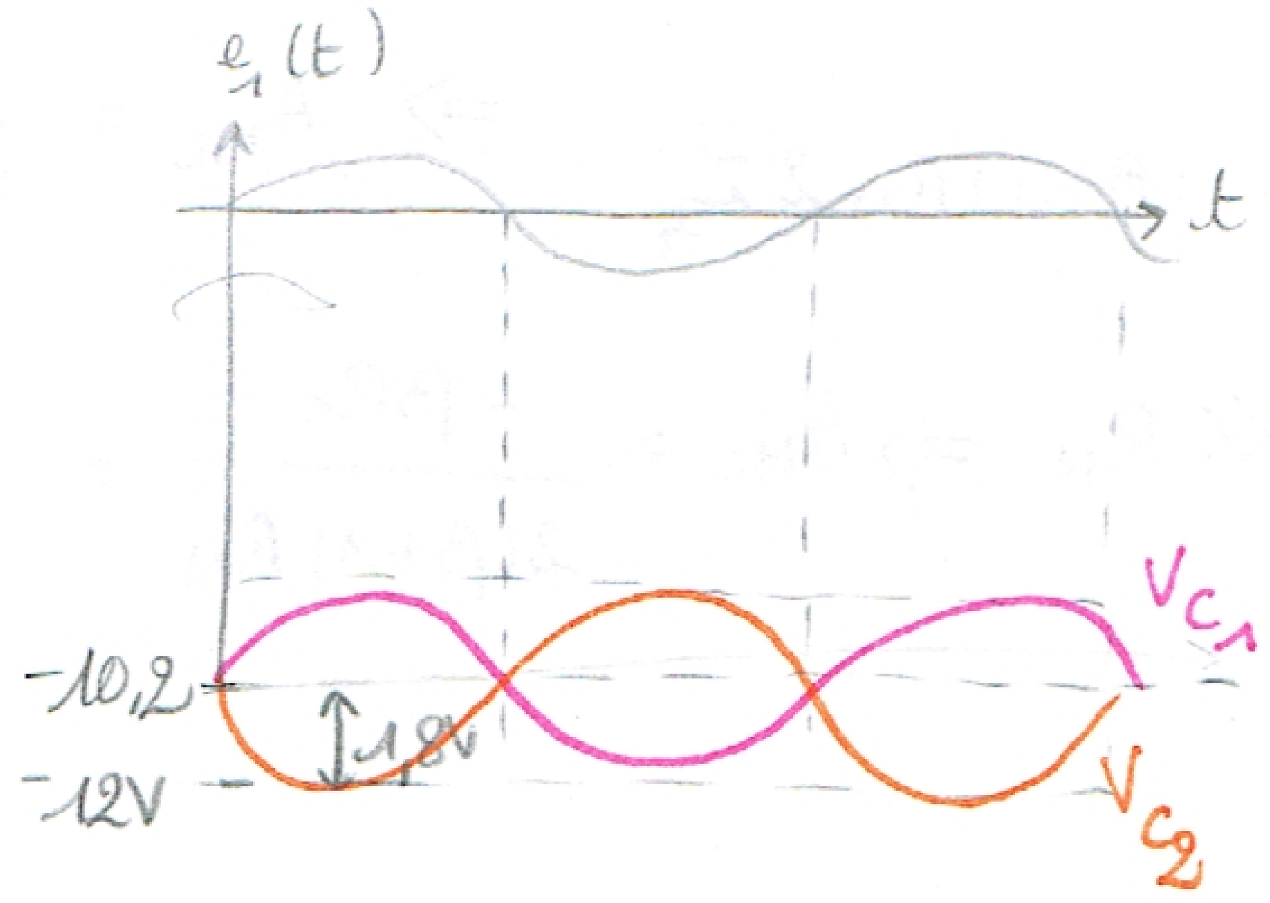
$$\begin{cases} \tilde{i}_{S_{cc}}(t) = \beta\,\tilde{i}_{B_1}(t) \\ \dfrac{\tilde{e}_d(t)}{2} = -r_{BE}\,\tilde{i}_{B_1}(t) \end{cases} \Rightarrow \begin{cases} \tilde{i}_{Scc}(t) = \dfrac{-\beta\,\tilde{e}_d(t)}{2r_{BE}} \\ \tilde{i}_{B_1}(t) = \dfrac{-\tilde{e}_d(t)}{2r_{BE}} \end{cases}$$

d'où $R_S = \dfrac{-A_d\,2r_{BE}}{\beta}$ avec $A_d = \dfrac{-R_2\beta}{2r_{BE}} \Rightarrow R_S = R_2$.

9/

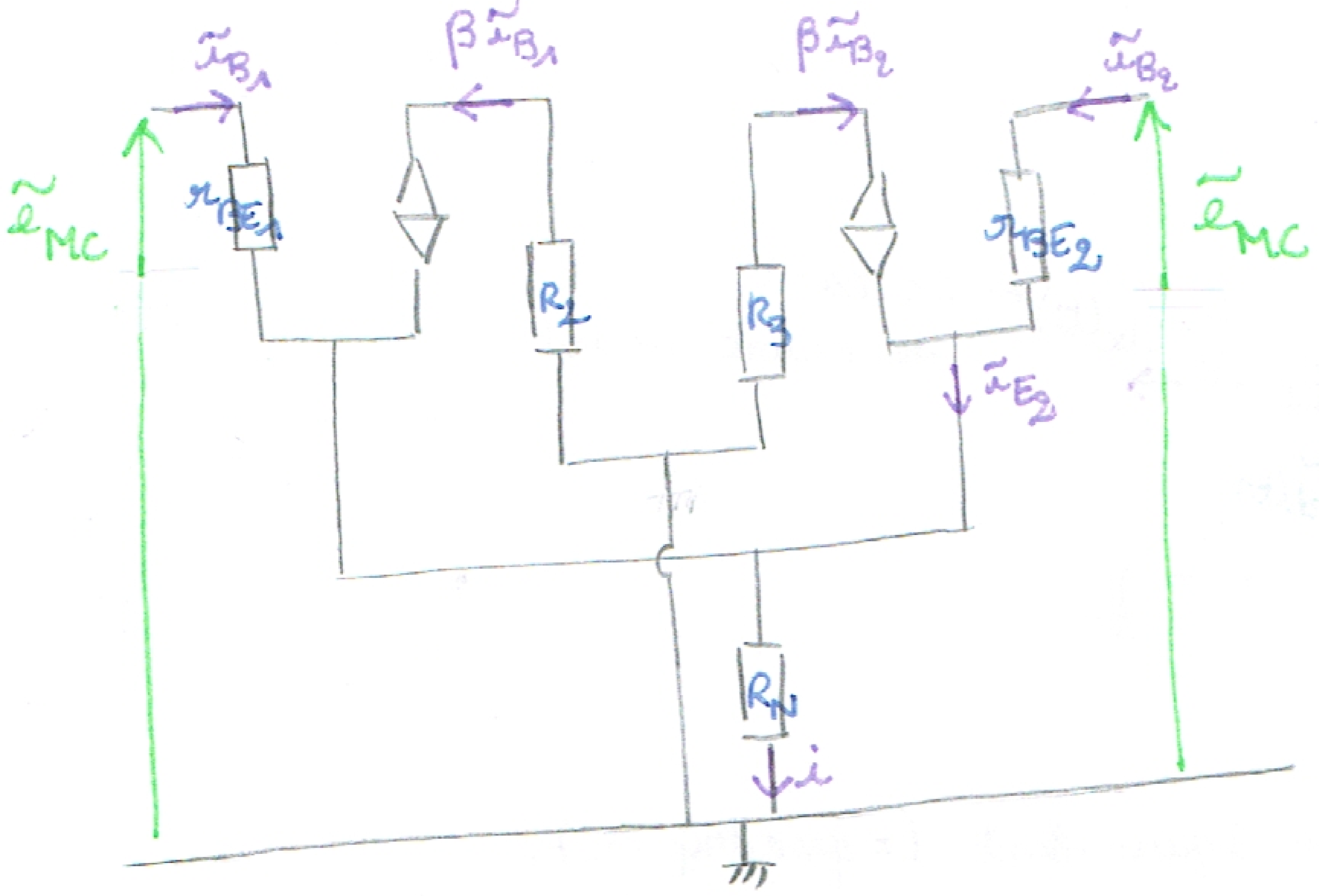


si $e_1(t)$ ↗ alors v_{EB_1} ↘ donc T_1 est ⊖ passant.
d'où I_{C_1} ↘ d'où V_{R_2} diminue.
et on sait que $I_{C_1} + I_{C_2} = 0 \Rightarrow V_{C_1}$ et V_{C_2} sont en opposition de phase.



Partie 4 : Étude du mode commun

* mode commun : $\tilde{e}_d = 0$



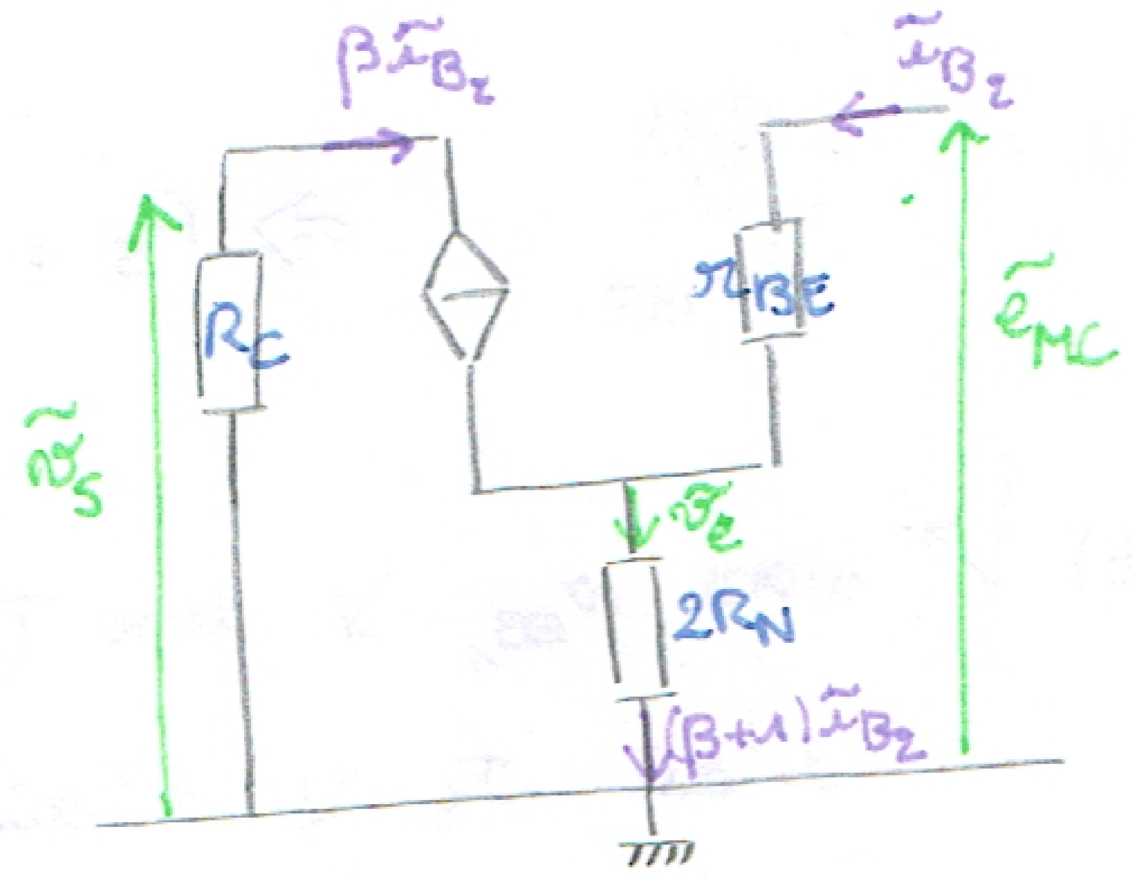
* $i = (\beta+1)\tilde{i}_{B_1} + (\beta+1)\tilde{i}_{B_2}$

$= (\beta+1)(\tilde{i}_{B_1} + \tilde{i}_{B_2})$ or $\tilde{i}_{B_1} = \tilde{i}_{B_2}$

$= 2(\beta+1)\tilde{i}_{B_2} \Rightarrow \tilde{v}_2 = 2R_N(\beta+1)\tilde{i}_{B_2}$

* $\tilde{v}_S = -R_3\,\beta\,\tilde{i}_{B_2}$

$\Rightarrow$ demi-schéma



- $\tilde{v}_S = -\beta R_C\,\tilde{i}_{B_2}$

- $\tilde{e}_{MC} = r_{BE}\,\tilde{i}_{B_2} + (\beta+1)R_N\,2\,\tilde{i}_{B_2}$ $\Rightarrow A_{MC} = \dfrac{-\beta R_C}{r_{BE} + 2(\beta+1)R_N}$

or $r_{BE} \ll R_N \Rightarrow A_{MC} = \dfrac{-\beta R_C}{2(\beta+1)R_N} = \dfrac{-R_C}{2R_N}$.

TP2, suite

Partie 4, suite

on reprend la formule de R_N du TP1. 3.7. (p°3)

* $r_{CE} = \frac{V_{early}}{I_0} = \frac{50}{250\mu} = 200\,k\Omega$.
* $\beta = 100$
* $R_E = R_4 = 18\,k\Omega$.
* $r_{BE} = \frac{u_T}{I_{B0}} = \frac{\beta u_T}{I_{C0}} = \frac{100 \times 25m}{250\mu} = 10\,k\Omega$.

$$\Rightarrow \boxed{R_N = 13\,M\Omega}.$$

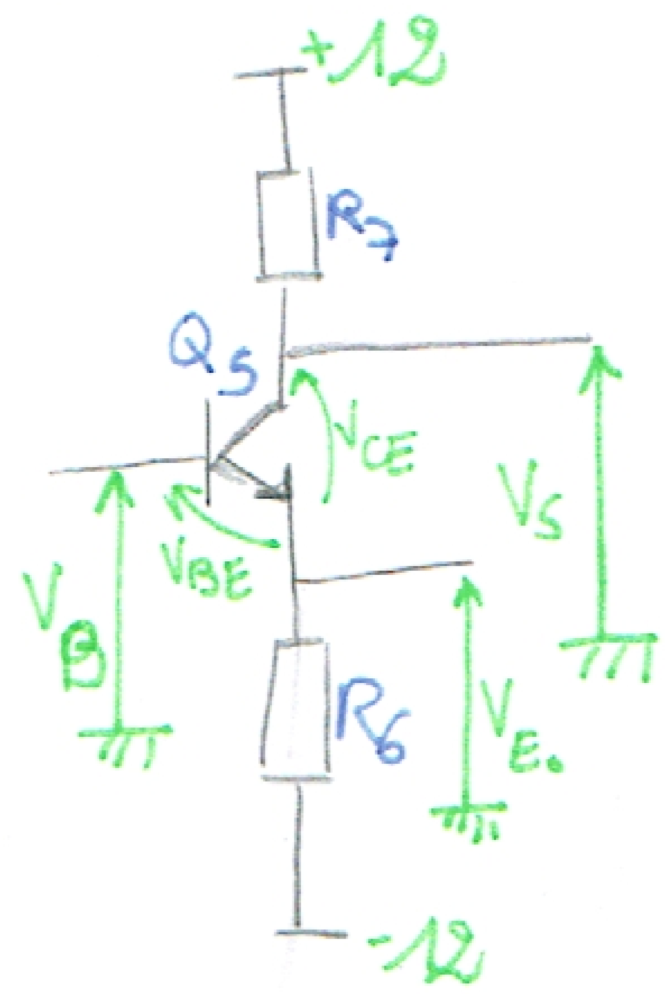
d'où $A_{MC} = -\frac{R_C}{2R_N} = -\frac{R_2}{2R_N} = -\frac{14,4k}{2 \times 13M} = -5,5.10^{-4}$

$TRMC = \frac{|A_d|}{|A_{MC}|} = \frac{36}{5,5.10^{-4}} \Rightarrow TRMC = 65\,454. \Rightarrow$ en dB $96,32$ dB.

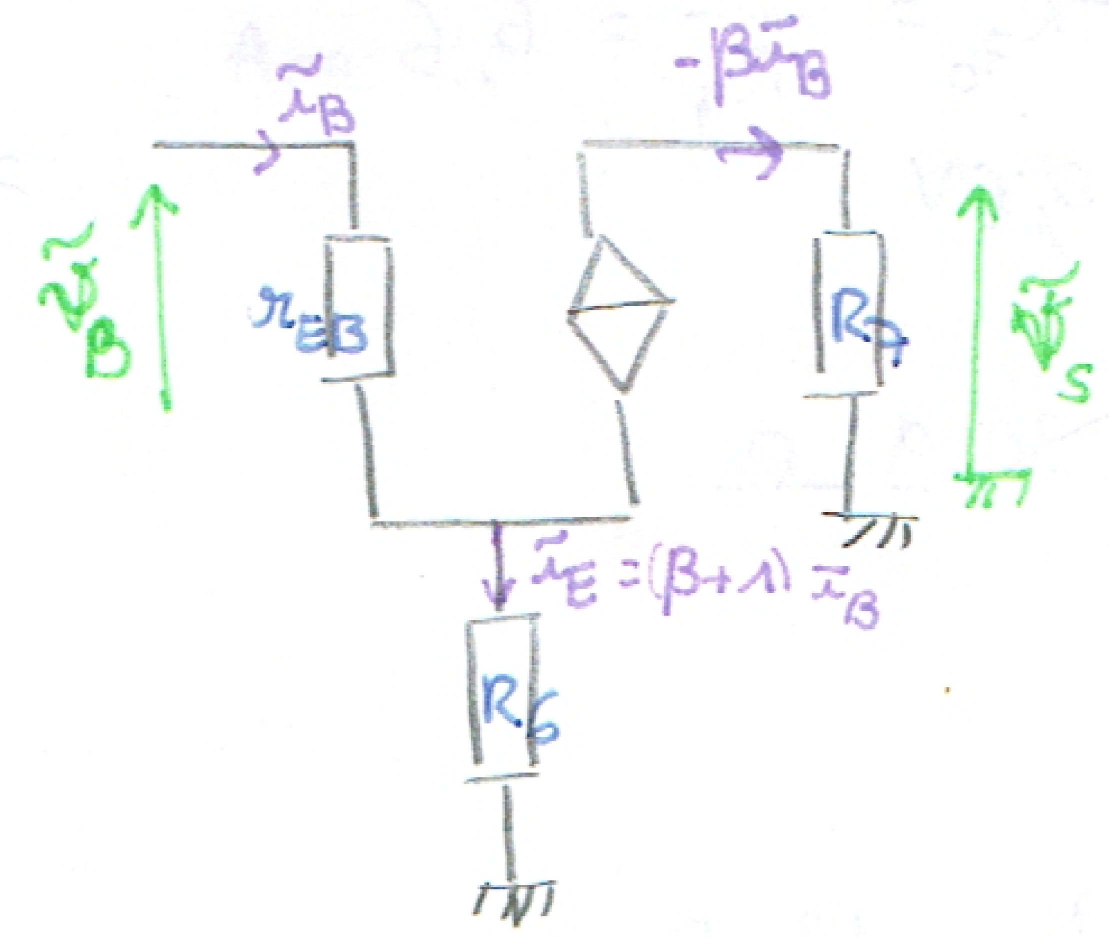
TP3 : étage émetteur commun

Partie 1 : étage simplifié

1/



$\Rightarrow$

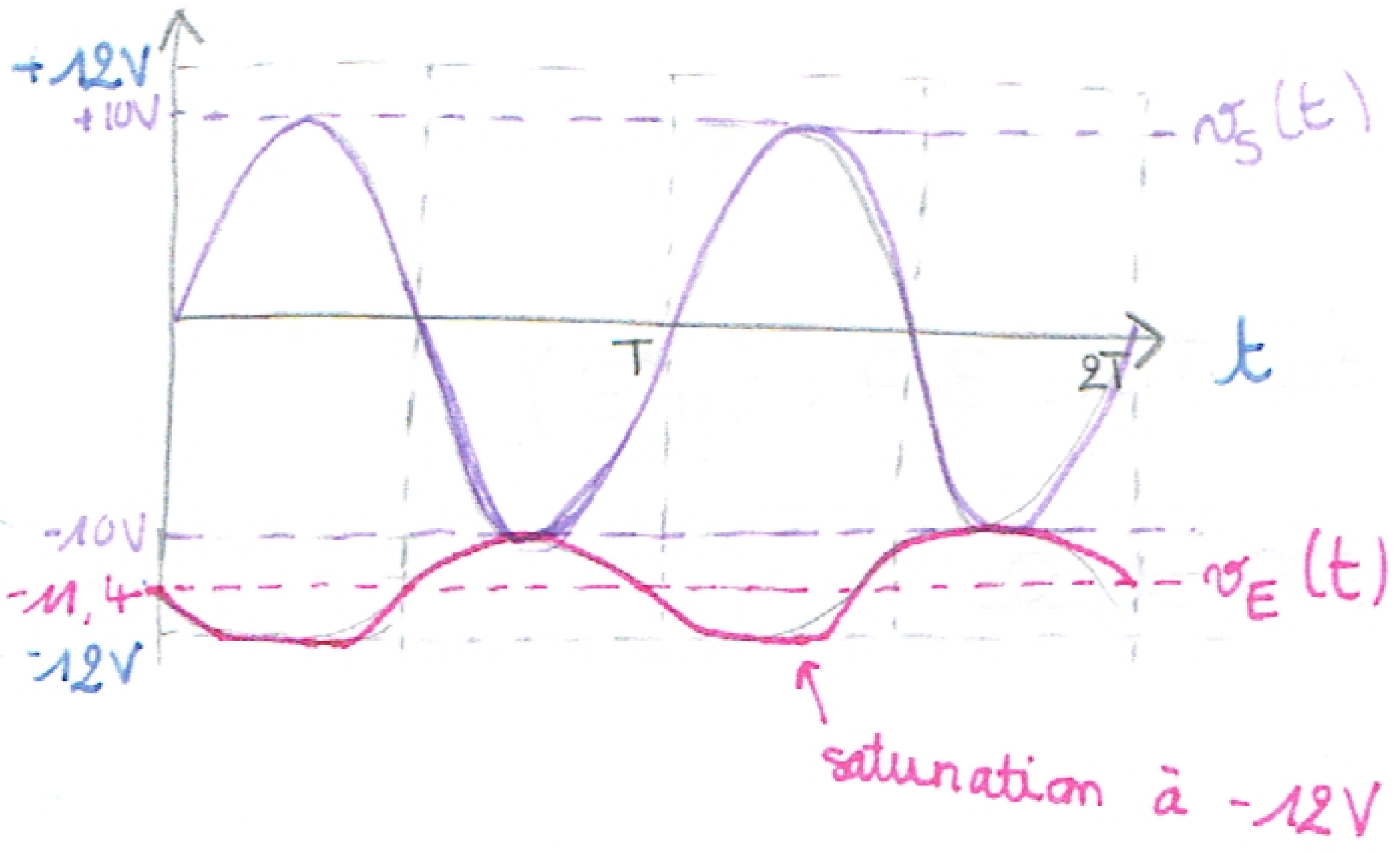


* $\tilde{v}_S(t) = -\beta \tilde{i}_B R_7$
* $\tilde{v}_B(t) = r_{EB}\,\tilde{i}_B + R_6\,\tilde{i}_B(\beta+1)$

$$\Rightarrow A = \frac{\tilde{v}_S}{\tilde{v}_B} = \frac{-\beta R_7}{r_{EB} + (\beta+1)R_6}$$ avec $r_{EB} \ll R_6$

$$\boxed{A \approx -\frac{\beta R_7}{\beta R_6} \approx -10}.$$

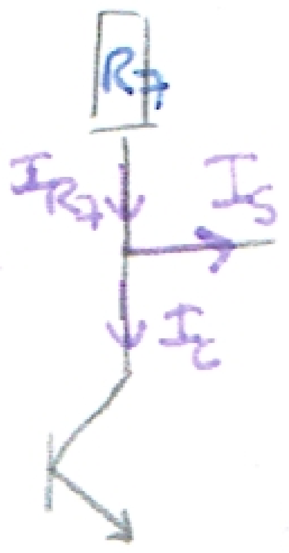
2/ $V_{E_0} = V_{B_0} - V_{BE} = -10,8 - 0,6 = -11,4\,V$.



3/ $V_{CE_{sat}} = 0,3\,V$

4/ $v_{S_{max}} = 10\,V$ $\quad R_L = 10\,k\Omega$ d'où $I_{S_{max}} = \frac{10}{10k} = 1\,mA$

5/



$I_C = I_{R_7} - I_S$ donc quand v_S est max, i_S est max donc I_C est min
$\Rightarrow$ risque de blocage.

6/ * $I_{C_{min}} = 100\,\mu A$ $\quad I_{S_{max}} = 1\,mA$ $\quad \Rightarrow I_{R_7} = I_C + I_S = 1,1\,mA$.

* $V_{R_7} = V_{cc} - V_S = 12 - 10 = 2V$

$\Rightarrow \boxed{R_7 = 1,8\,k\Omega}$

* au repos, $I_{R_6} = I_{C_0} = I_{R_{7_0}} = \frac{V_{cc}}{R_7} = 6,6\,mA$
* $V_{R_6} = V_{CC} - V_{E_0} = 0,6V$

$\Rightarrow \boxed{R_6 = 90,9\,\Omega}$

$\Rightarrow A = \frac{R_7}{R_6} = 19,8$

TP3, suite :

Partie 2 : Adapter les impédances, améliorer le gain

2.2.1 L'adaptation d'impédance statique.

1/ * $I_{C_1} = I_{C_2} = \frac{I_0}{2} = 125\,\mu A$.

* $I_{B_0} = \frac{I_{C_0}}{\beta} = \frac{6{,}6m}{100} = 66\,\mu A$.

2/ $I_{C_1} > I_{B_0}$ donc on a un courant trop grand en entrée de l'émetteur commun.

2.2.2 L'adaptation d'impédance dynamique.

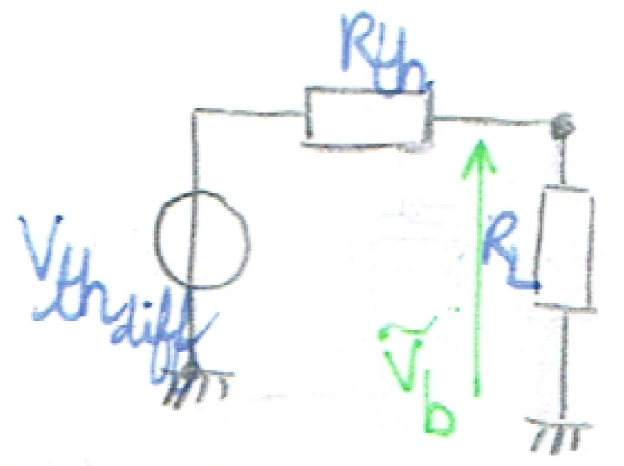
3/ $R_S = R_2 = 14{,}4\,k\Omega$.

4/ $R_e = \frac{\tilde{v}_B}{\tilde{i}_B} = r_{BE} + R_6(\beta+1)$

avec $r_{BE} = \frac{u_T}{I_{B_0}} = \frac{25m}{66\mu} = 378{,}8\,\Omega$.

$R_e = 9468\,\Omega$.

5/

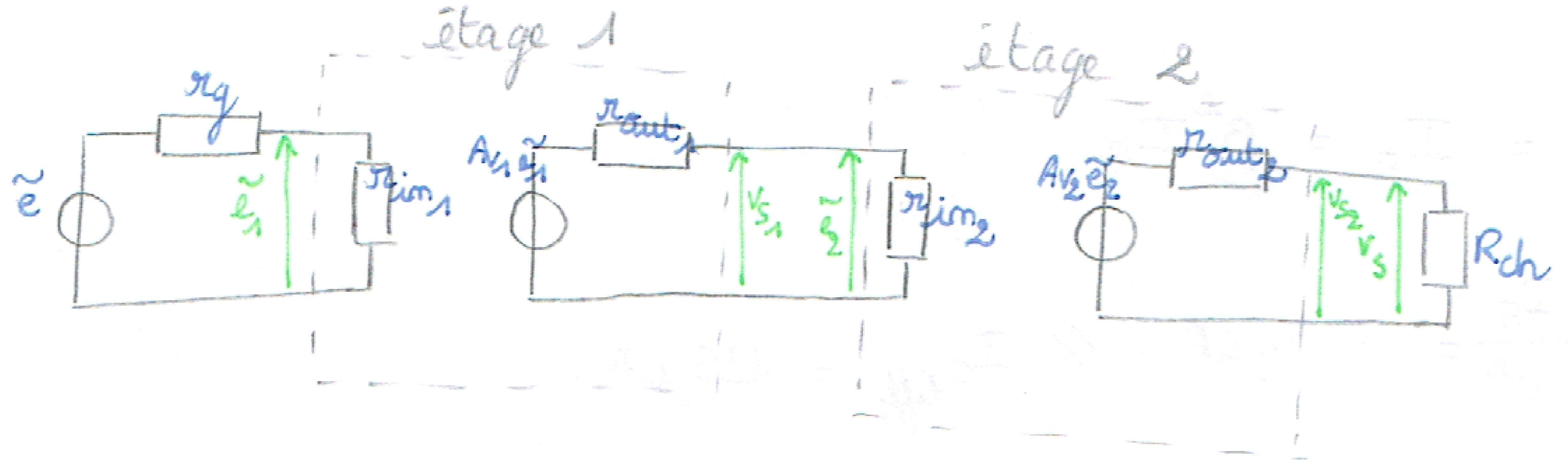


$R_{th} = R_S = 14{,}4\,k\Omega$

$V_{th_{diff}} = R_{th}\, I_{B_0} = 0{,}95\,V$.

$R_L = R_e = 9\,468\,\Omega$.

Bilan adaptation impédance :



↳ en charge, il faut tenir compte du pont diviseur de tension en entrée des étages ⇒ on veut $r_g \ll r_{in_1}$ et $r_{out_1} \ll r_{in_2}$.

↳ OK (pour $r_g \ll r_{in_1}$)

↳ pas OK ⇒ Darlington (pour $r_{out_1} \ll r_{in_2}$)

$$\tilde{v}_S = \frac{R_{ch}}{R_{ch}+R_{S_2}} \times Av_2 \times \frac{r_{in_2}}{r_{in_2}+r_{out_1}} \times Av_1 \times \frac{r_{in_1}}{r_{in_1}+r_g} \times \tilde{e}$$

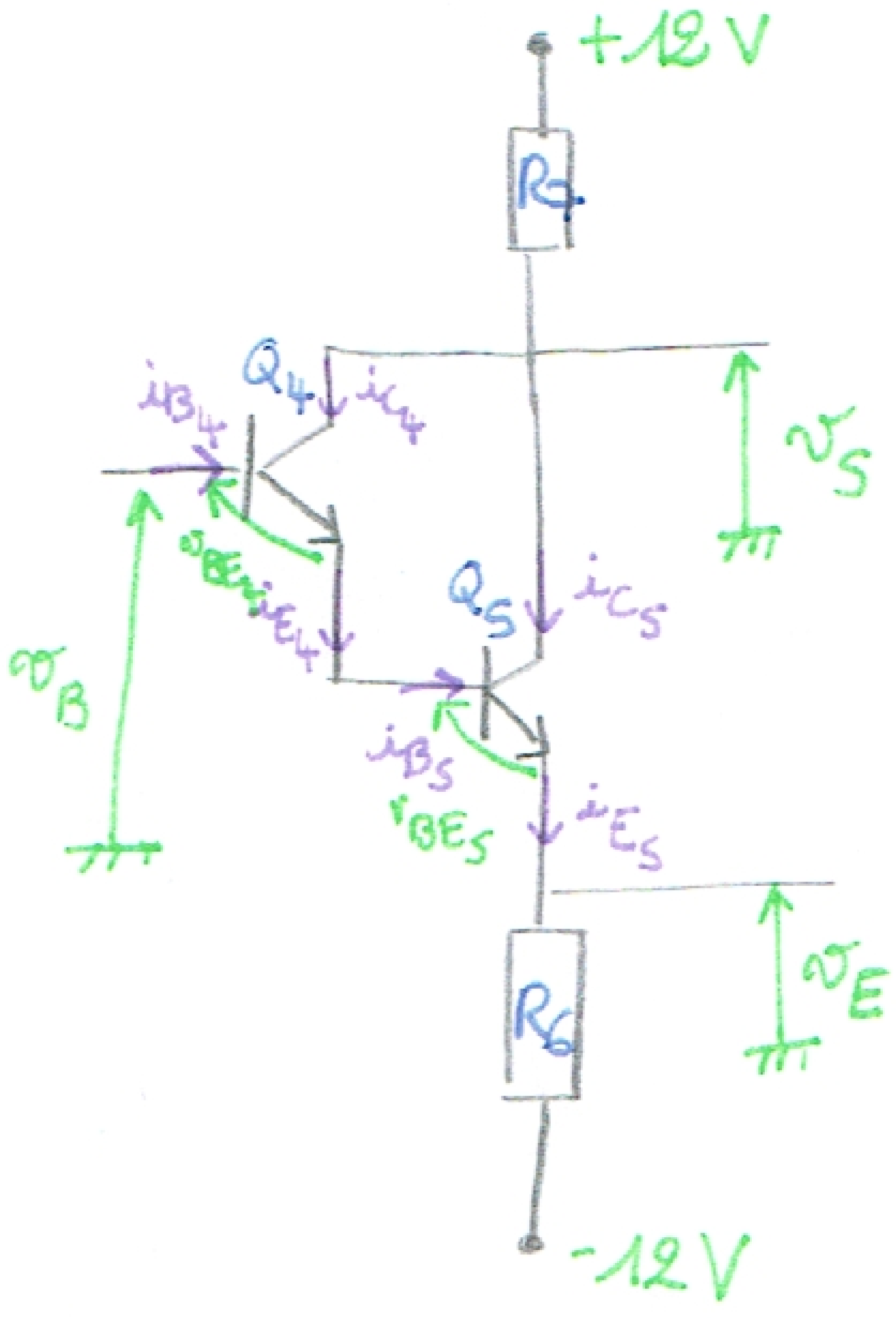
6/ pont diviseur de tension schéma q°5 Thévenin :

$$\frac{\tilde{v}_b}{\tilde{v}_{th\,diff}} = \frac{R_L}{R_L + R_{th}} = 0,3967 \ll 1.$$

7/ R_{th} trop grande par rapport R_L $\Rightarrow$ gain trop faible.

$\boxed{2.4.}$ Mise en oeuvre d'un étage de Darlington.

1/



2/ on veut $v_E = v_B - 2 \times v_{BE} = -11,4\,V$ $\Rightarrow$ $v_B = v_{B_0} + v_{BE} = -10,2\,V$

$= v_{B_0} - v_{BE}$

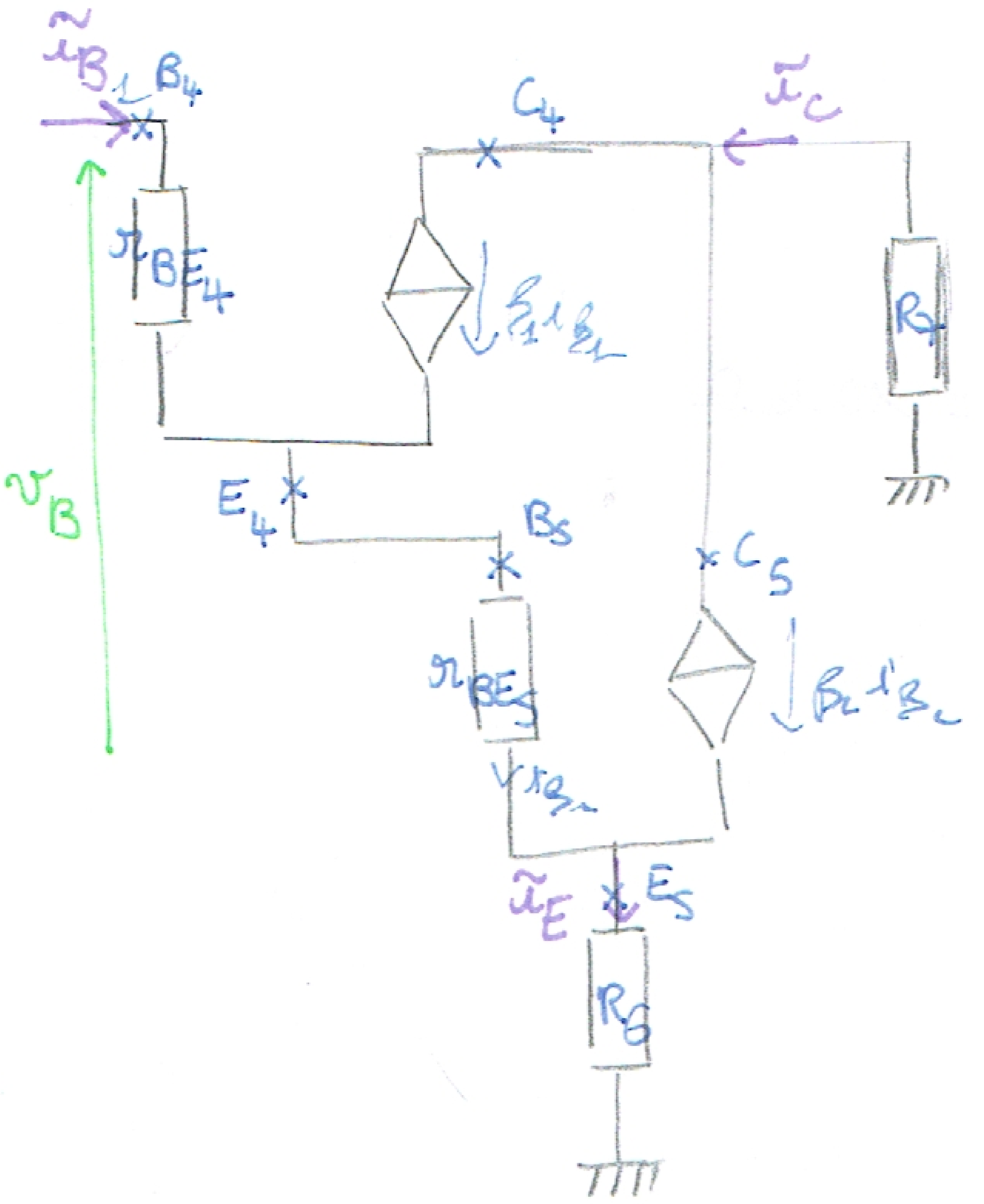
3/ $I_{R_6} = 6,6\,mA = I_E = \beta^2 I_B$

$\Rightarrow I_B = \frac{I_E}{\beta^2} = 0,66\,\mu A \ll I_{C_{diff}} = 125\,\mu A.$

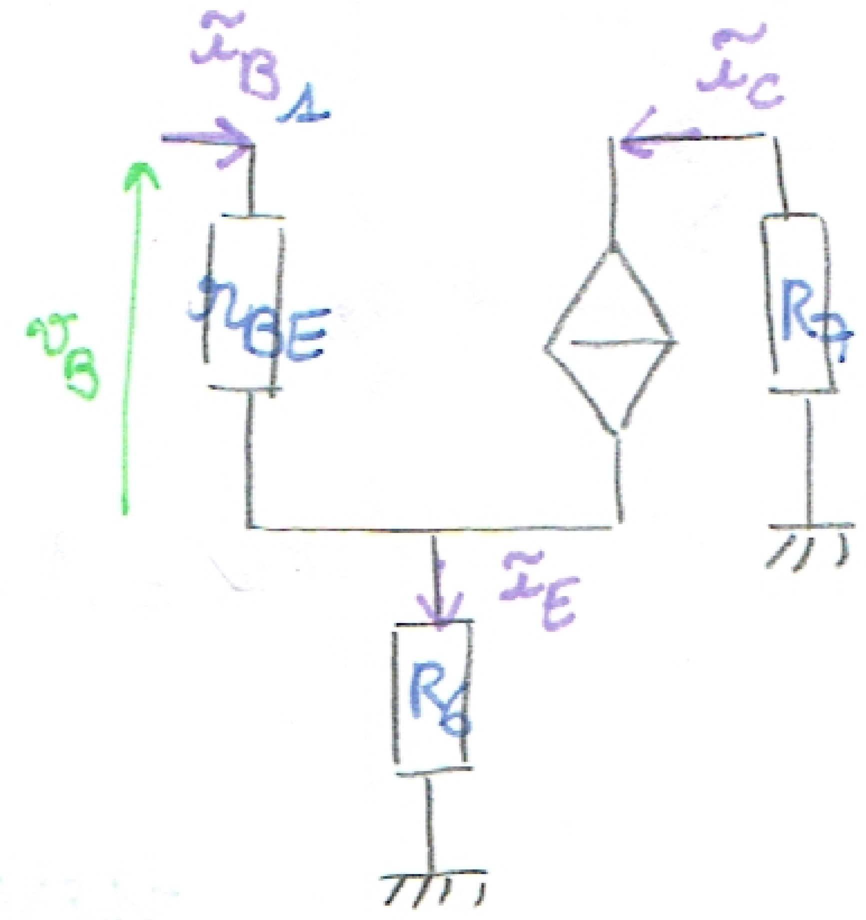
TP 3, suite

Partie 2, suite

4/



$\Rightarrow$



$* \; v_B = r_{BE_1} \tilde{i}_{B_1} + r_{BE_2} (\beta_1+1) \tilde{i}_{B_1} = r_{BE} \tilde{i}_{B_1}$

$$\Rightarrow r_{BE} = r_{BE_1} + (\beta_1+1) r_{BE_2} .$$

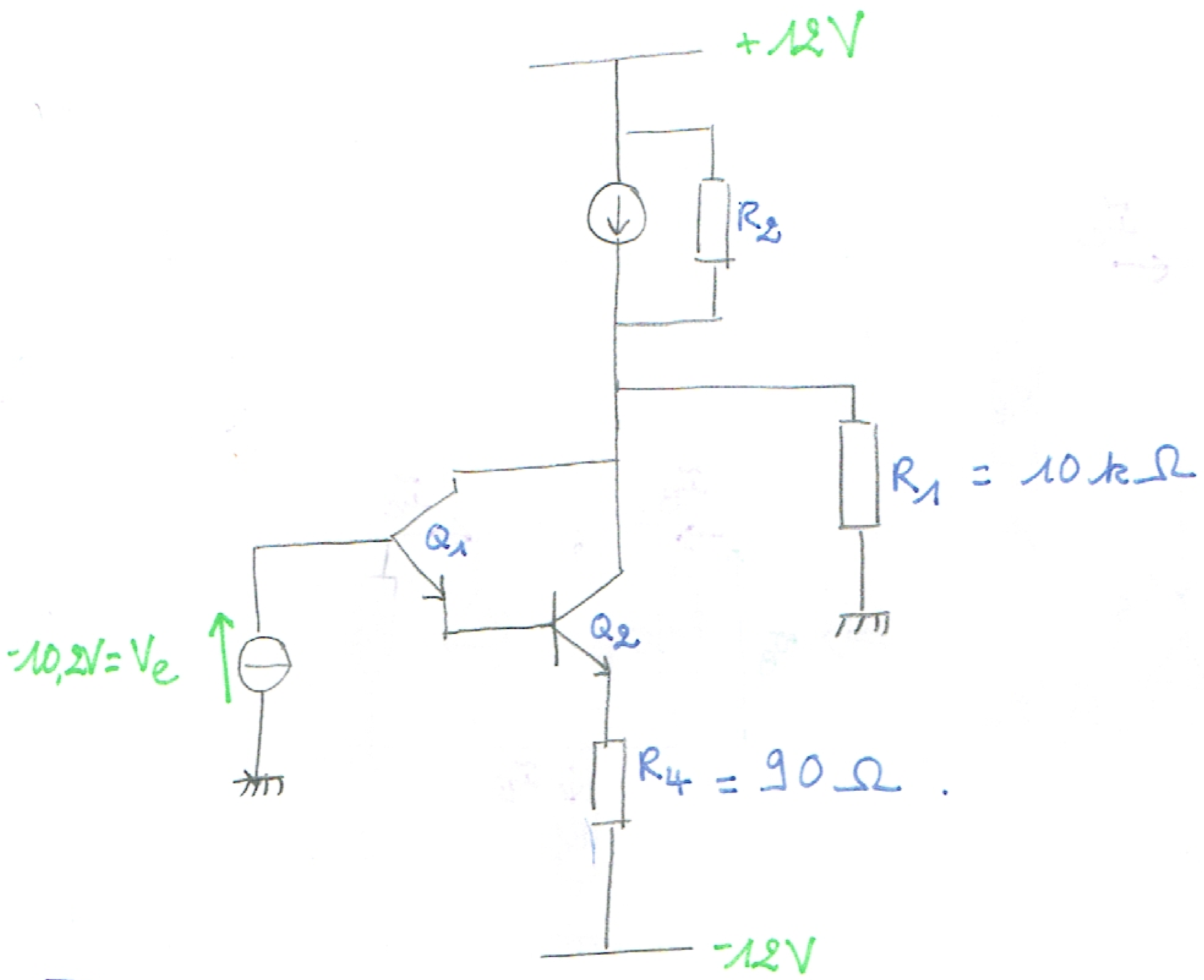
$* \quad i_C = \beta_1 \tilde{i}_{B_1} + \beta_2 \tilde{i}_{B_2} = \beta_1 \tilde{i}_{B_1} + \beta_2 \beta_1 \tilde{i}_{B_1} = \beta \tilde{i}_{B_1}$

$$\Rightarrow \beta = \beta_1 + \beta_1 \beta_2 .$$
$$\approx \beta_1 \beta_2$$

5/ $R_{in} = \dfrac{v_B}{i_B} = r_{BE} + (\beta+1) R_6$

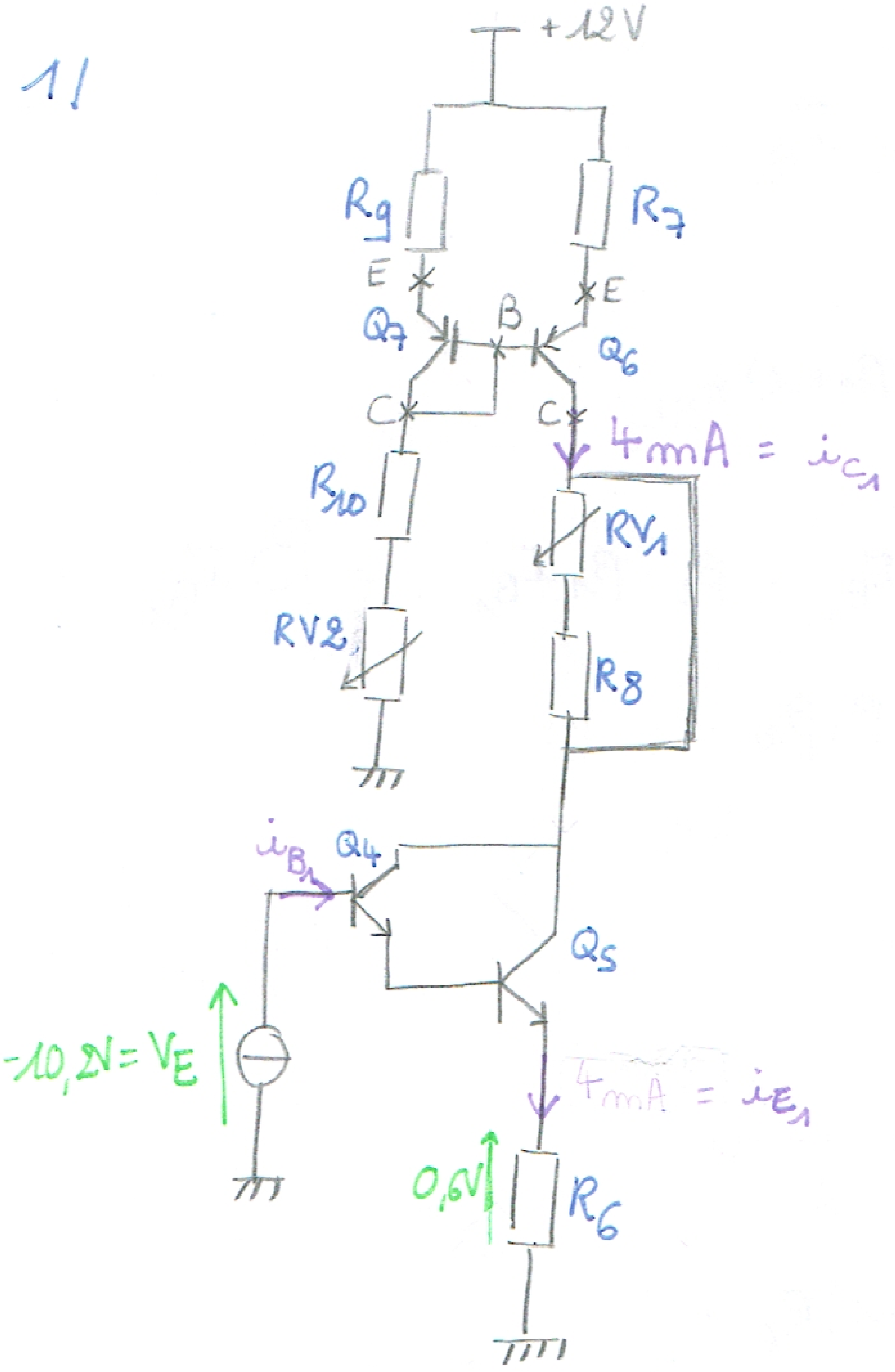
$= r_{BE_1} + r_{BE_2}(\beta_1+1) + (\beta_1\beta_2+1) R_6 .$

Partie 3 = Booster l'amplification par une charge active.



3.1. Analyse du schéma réel.

1/



TP3, suite :

Partie 3, suite :

2/ * on cherche R6 : on en déduit R7 et R9

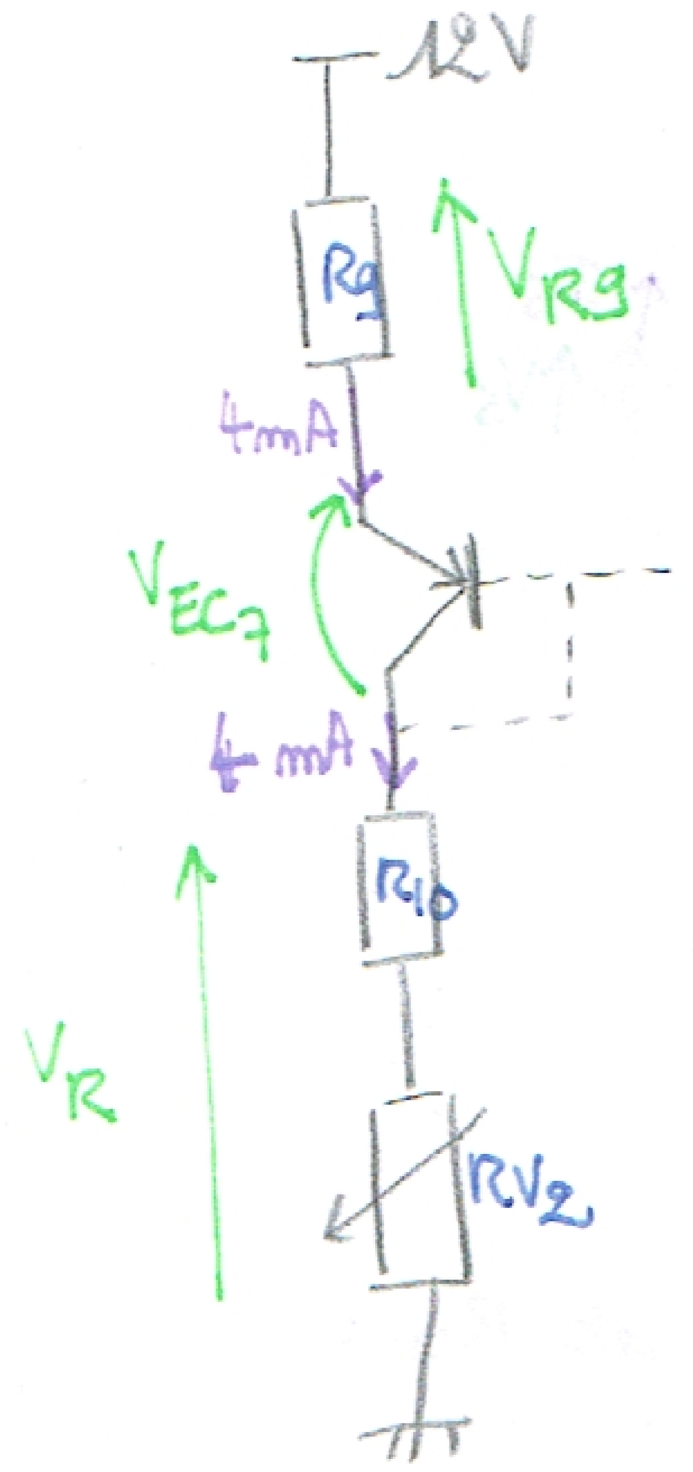
→ on considère que les 2 transistors de Darlington se comporte comme un grand transistor

d'où $I_{C_1} = I_{E_1} = 4\,mA$.

→ on a $V_{R_6} = 0{,}6\,V$

$\Rightarrow$ $\boxed{R_6 = R_7 = 150\,\Omega = R_9}$

* on cherche R10 et RV2 :



→ $V_{R9} = R_9 \times 4\,mA = 0{,}6\,V$.

→ $V_{EC_{sat}} = 0{,}6\,V$ (cf. data sheet).

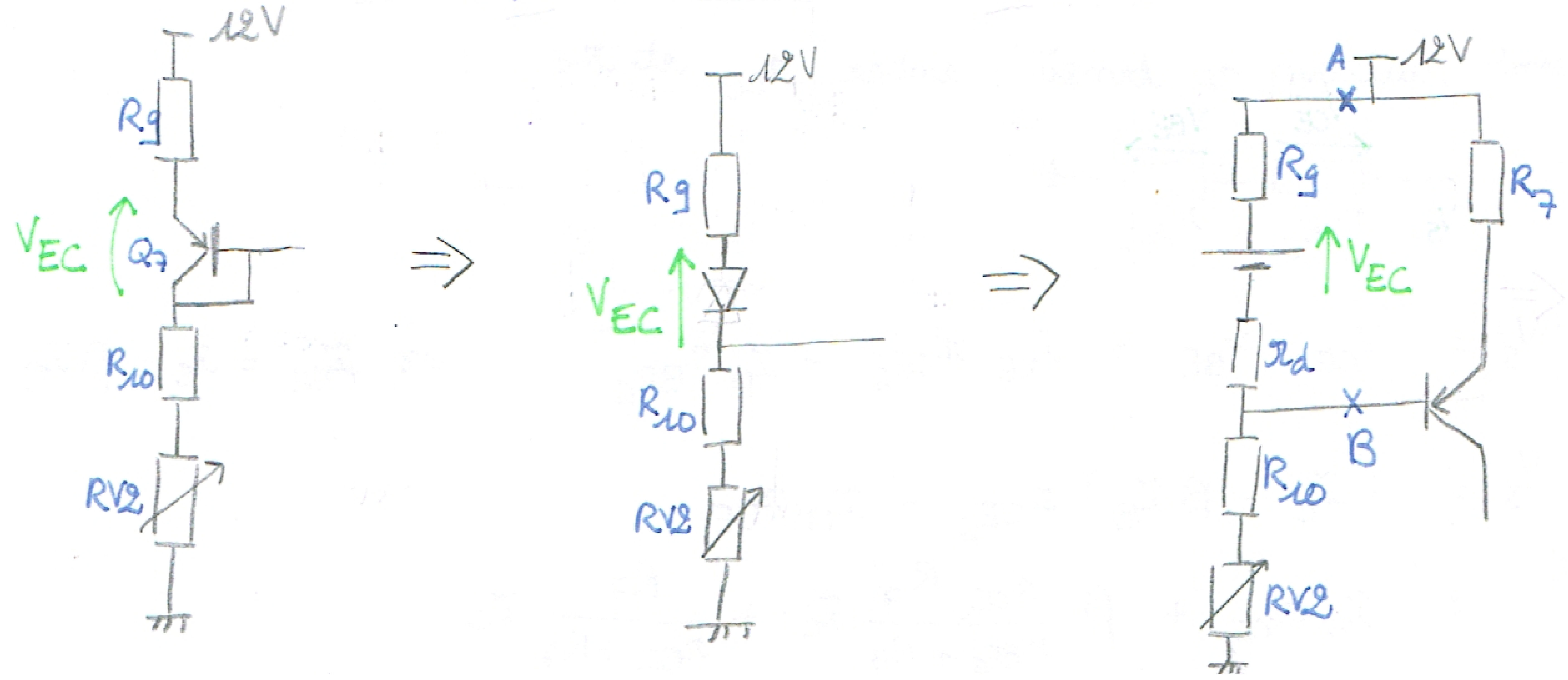
→ $V_R = V_{CC} - V_{R9} - V_{EC_7\,sat} = 10{,}8\,V$

$\Rightarrow$ $R = R_{10} + RV_2 = \frac{V_R}{4m} = 2\,700\,\Omega$

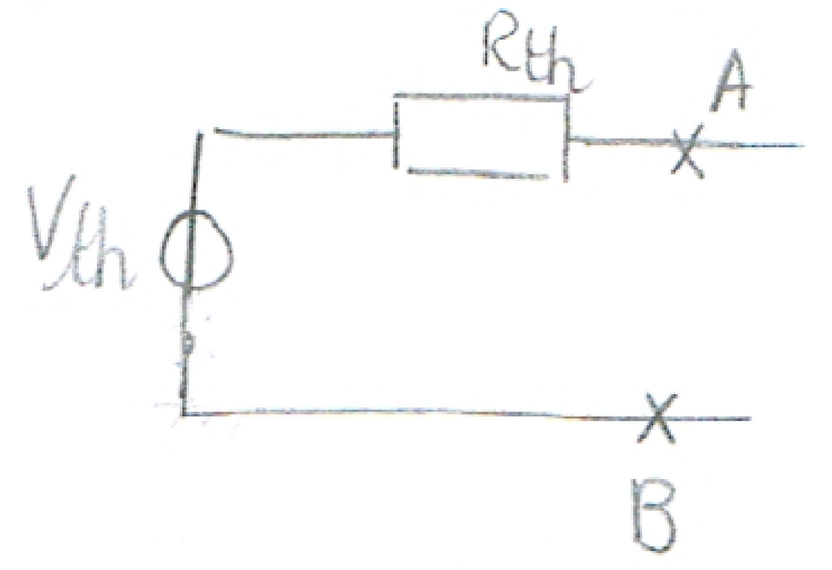
$\boxed{RV2 = 1k\,\Omega}$

$\boxed{R_{10} = 1700\,k\Omega}$

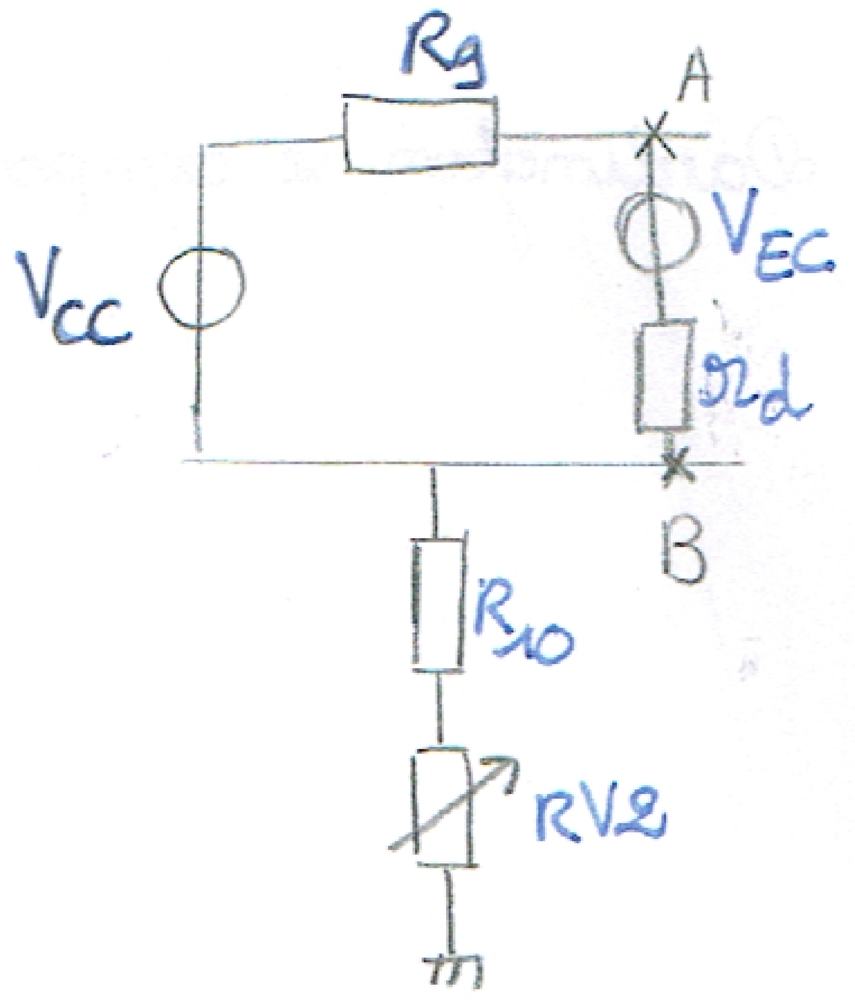
3/ * modélisation de Q_7 par une diode :



* on applique le théorème de Thèvenin entre A et B :



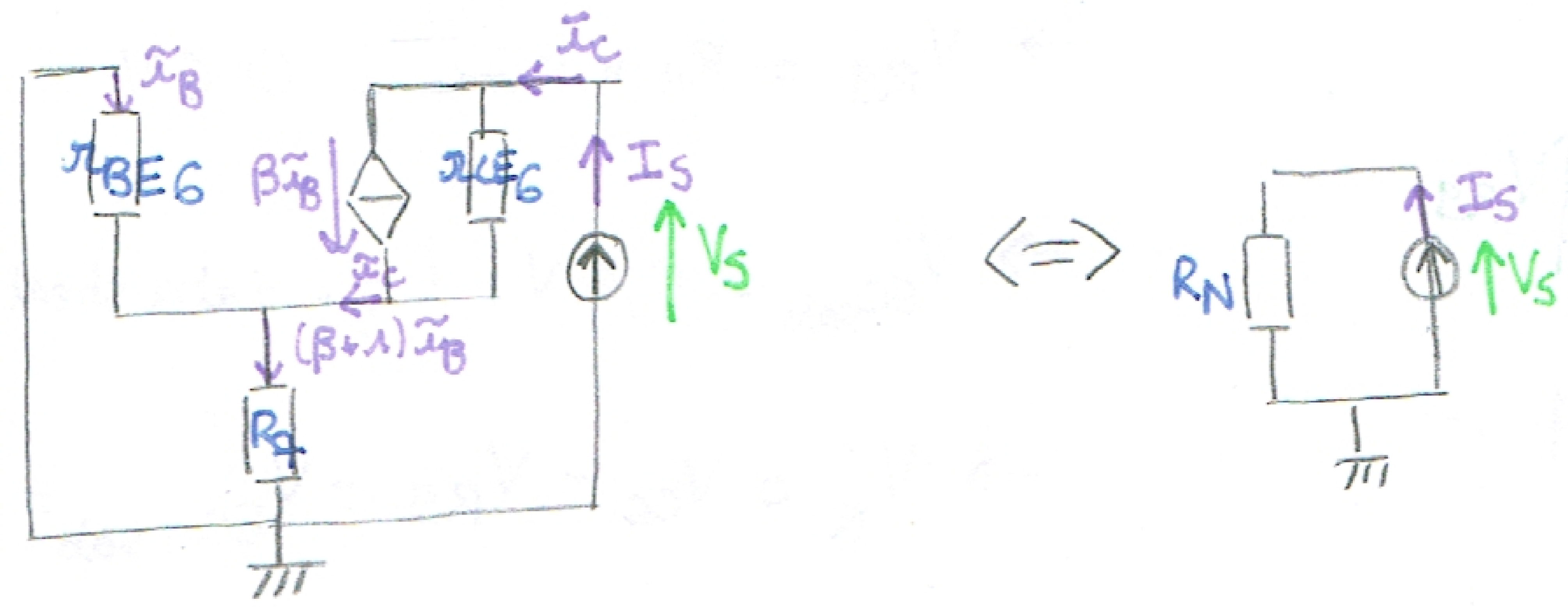
$$V_{th} = \frac{r_d V_{CC} + R_g V_{EC}}{r_d + R_g}$$



$$R_{th} = R_g // r_d // R_{10} + RV_2 \approx r_d$$

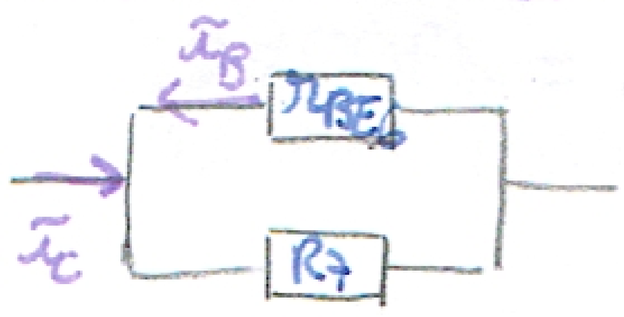
car $r_d \ll (R_g, R_{10}, RV_2)$.

* shéma équivalent dynamique (petit signaux) :



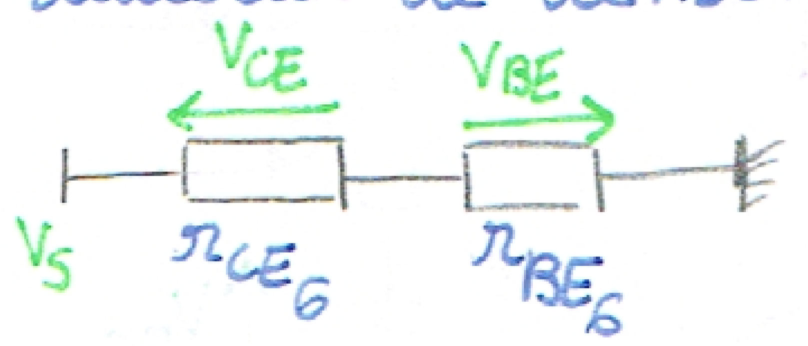
* déterminer l'expression de $R_N = \frac{V_s}{I_s}$.

→ pont diviseur de courant entre r_{BE_6} et R_7 :



$$-\tilde{i}_B = \frac{R_7}{r_{BE_6} + R_7} \tilde{i}_c \quad (1)$$

→ pont diviseur de tension entre r_{CE} et r_{BE} :



$$V_s = V_{CE} - V_{BE} = \tilde{i}_{CE} r_{CE_6} - \tilde{i}_B r_{BE_6} \quad \text{or} \quad \tilde{i}_{CE} = \tilde{i}_c - \beta \tilde{i}_B$$

$$V_s = (\tilde{i}_c - \beta \tilde{i}_B) r_{CE_6} - \tilde{i}_B r_{BE}$$

(1)

$$= \tilde{i}_c r_{CE_6} + \beta \frac{r_{CE_6} R_7}{r_{BE_6} + R_7} \tilde{i}_c + \frac{R_7}{r_{BE_6} + R_7} \tilde{i}_c .$$

TP3, suite,

BE Elec

10

Partie 3

$$R_N = \frac{V_s}{i_c} = r_{CE_6}\left[1 + \frac{\beta R_7}{r_{BE_6} + R_7}\right] + \frac{R_7\, r_{BE_6}}{R_7 + r_{BE_6}}$$

* application numérique :

$$\rightarrow r_{CE_6} = \frac{V_{early}}{I_0} = \frac{50}{4.10^{-3}} = 12\,500\ \Omega .$$

$$\rightarrow r_{BE_6} = \frac{U_T}{I_{B0}} = \frac{U_T}{I_0/\beta} = \frac{25.10^{-3} \times 100}{4.10^{-3}} = 625\ \Omega .$$

$$\Rightarrow R_N = 12\,500 \times \left(1 + \frac{100 \times 150}{625 + 150}\right) + \frac{150 \times 625}{150 + 625}$$

$$\boxed{R_N = 254,6\ k\Omega}$$