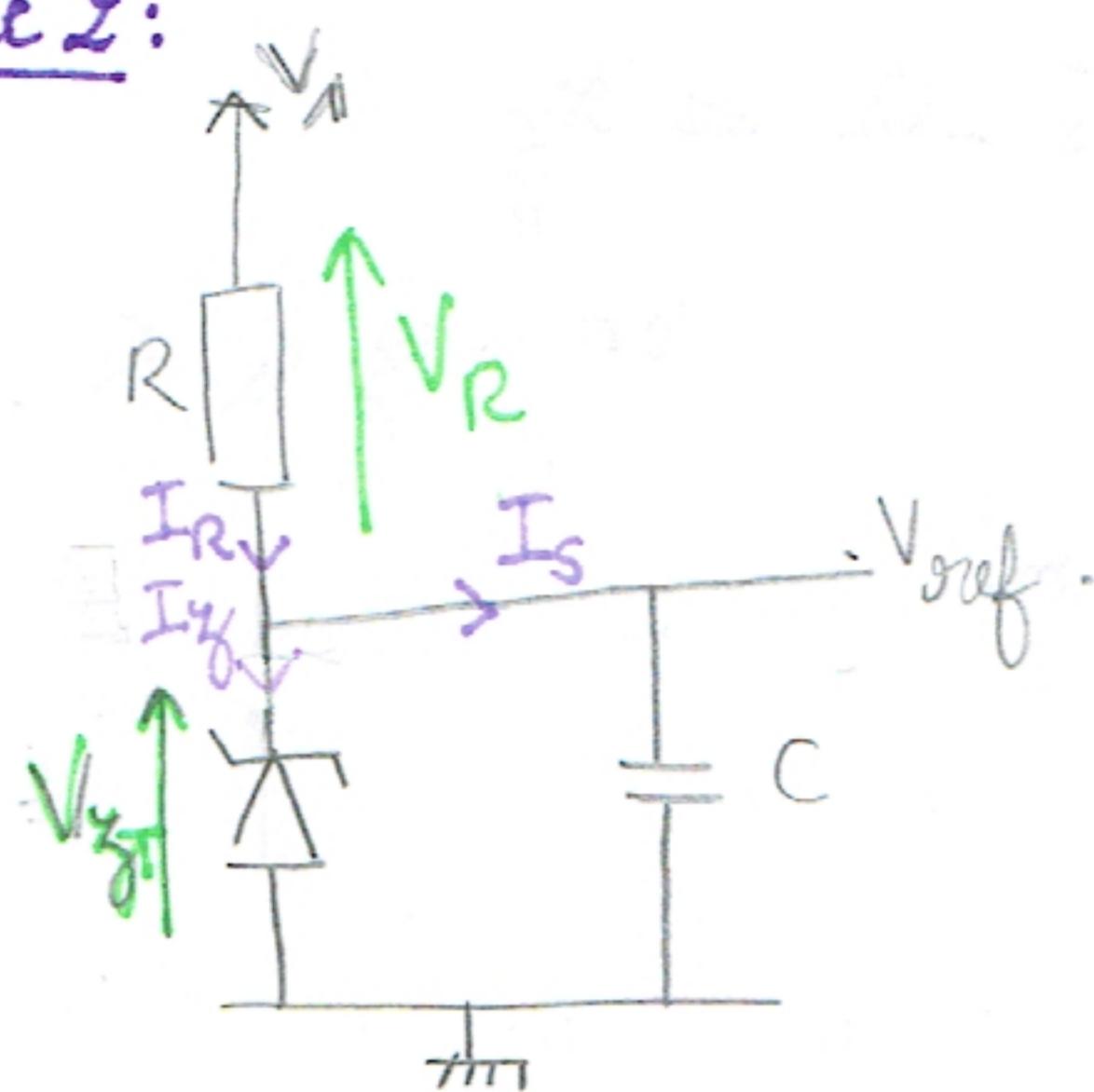


TP1 = Sources de courant et de tensionPartie 2:

avec  $* 4,8 < V_{zT} < 5,4 \text{ V}$  et  $\sigma_Z < 35 \Omega$ .

\*  $V_1 = 12 \text{ V DC} + 200 \text{ mV}_{pp}$  à  $f = 100 \text{ Hz}$ .

\*  $V_{ref} = 5,1 \text{ V}$  avec précision = 5%.

+  $10 \text{ mV}_{pp}$  à  $f = 100 \text{ Hz}$

\*  $I_Z = 5 \text{ mA}$ .

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

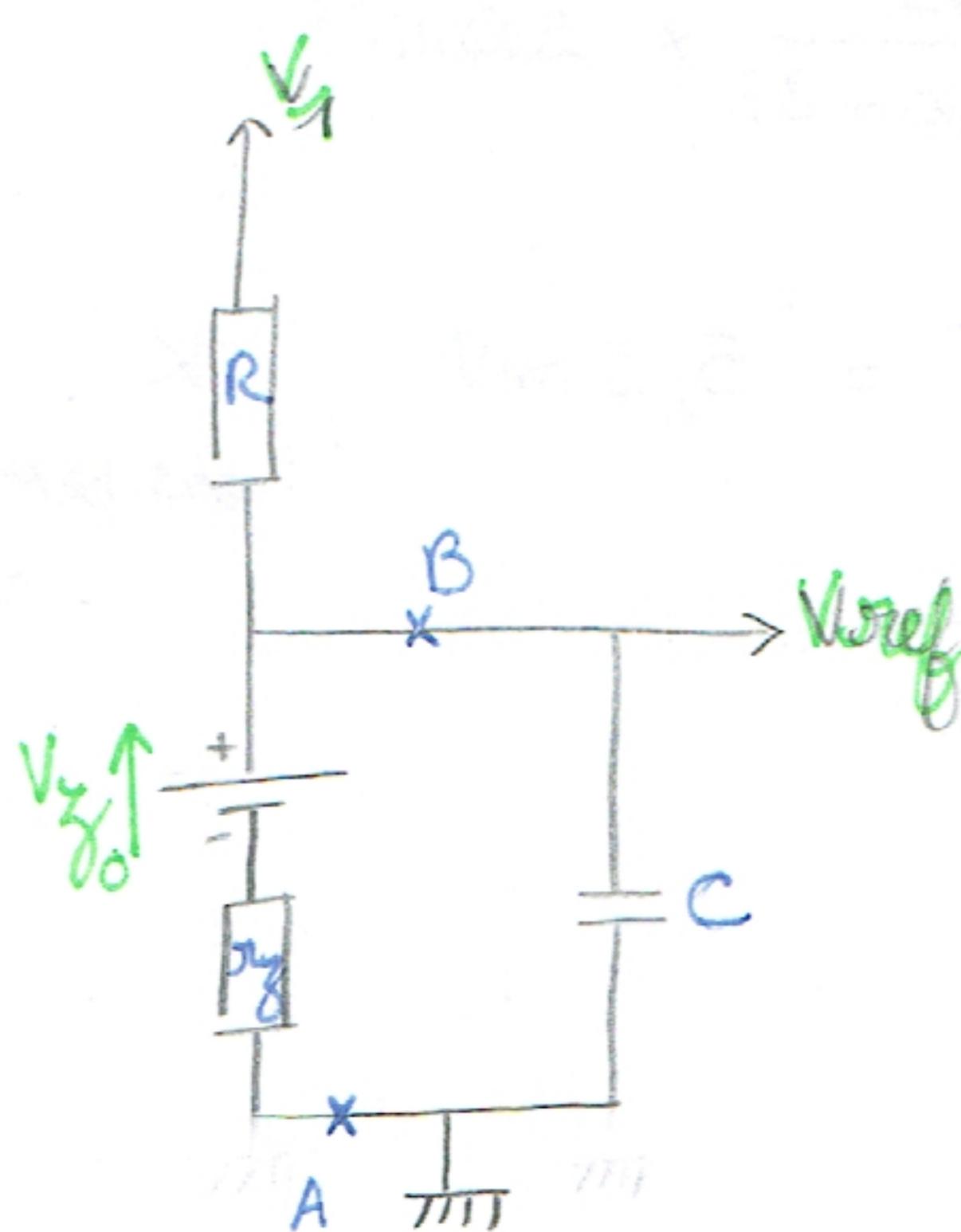
$$2/ I_s = 1 \text{ mA} . \quad I_Z = 5 \text{ mA} . \quad I_s = I_R - I_Z \Rightarrow I_R = I_s + I_Z = 6 \text{ mA} .$$

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

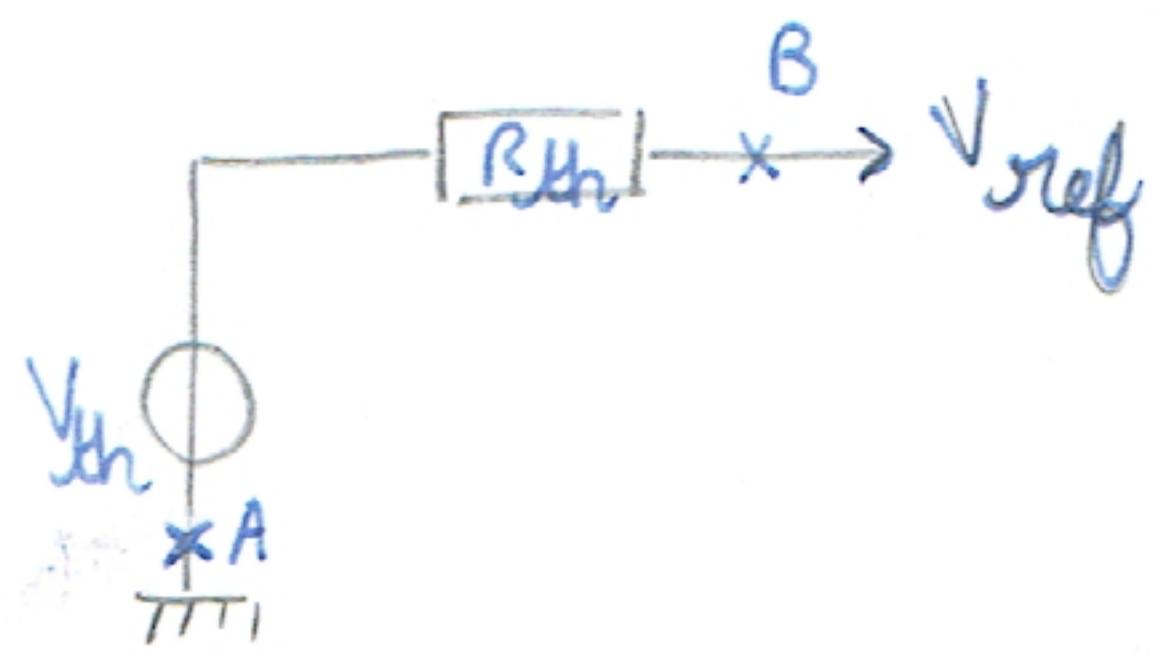
$$\text{d'où } R = 1150 \Omega .$$

$$3/ \sigma_Z < 35 \Omega .$$

$$V_{zT} = V_{z0} + \sigma_Z I_Z \Rightarrow V_{z0} = V_{zT} - \sigma_Z I_Z \\ = 5,1 - 35 \times 5 \cdot 10^{-3} \\ = 4,925 \text{ V} .$$



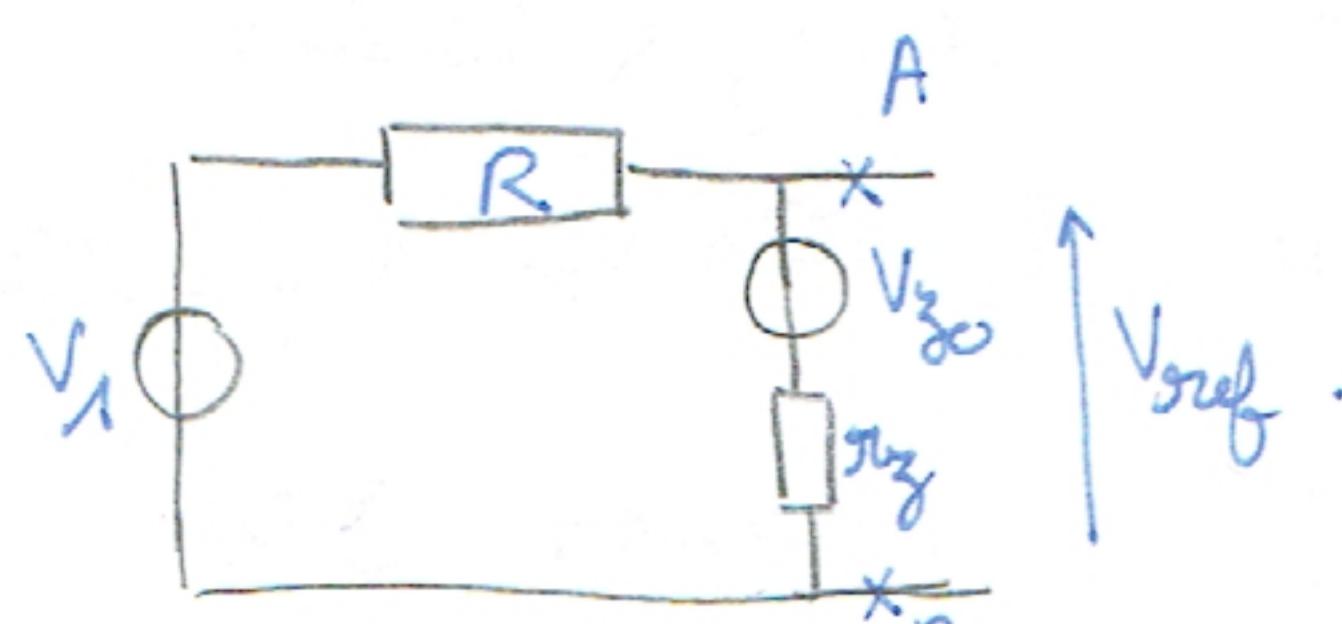
4/



$$R_{th} = r_z // R$$

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

car  $r_z \ll R$ .



= théorème de superposition.

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

$$V_{th_2}(V_{z_0}) = \frac{R}{r_z + R} V_{z_0}$$

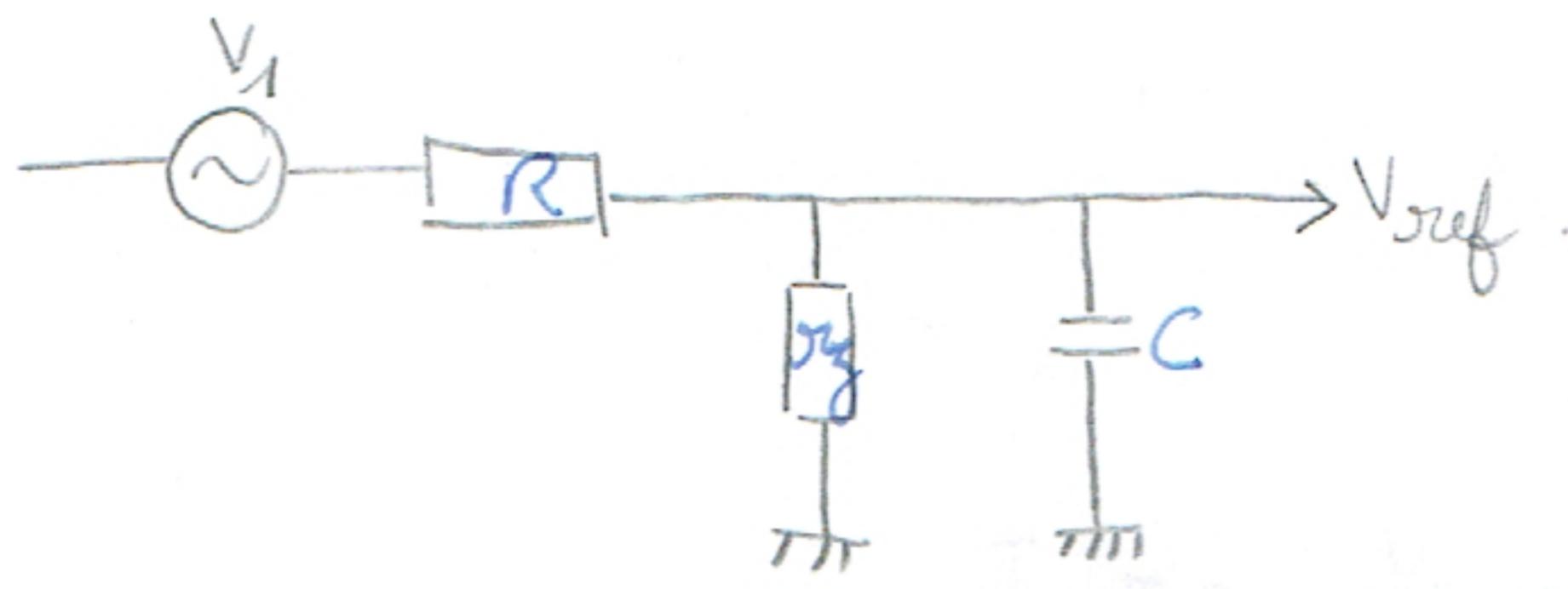
$$V_{th} = V_{th_1} + V_{th_2} = \frac{r_z V_1}{r_z + R} + \frac{R V_{z_0}}{r_z + R}$$

$$= \frac{r_z V_1 + R V_{z_0}}{r_z + R} = 4,925 \text{ V.}$$

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

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

6/



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

$$= 0,03 \times 200.10^{-3} = 5,9 \text{ mV. OK.}$$

$$3\% < 5\%$$

(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.

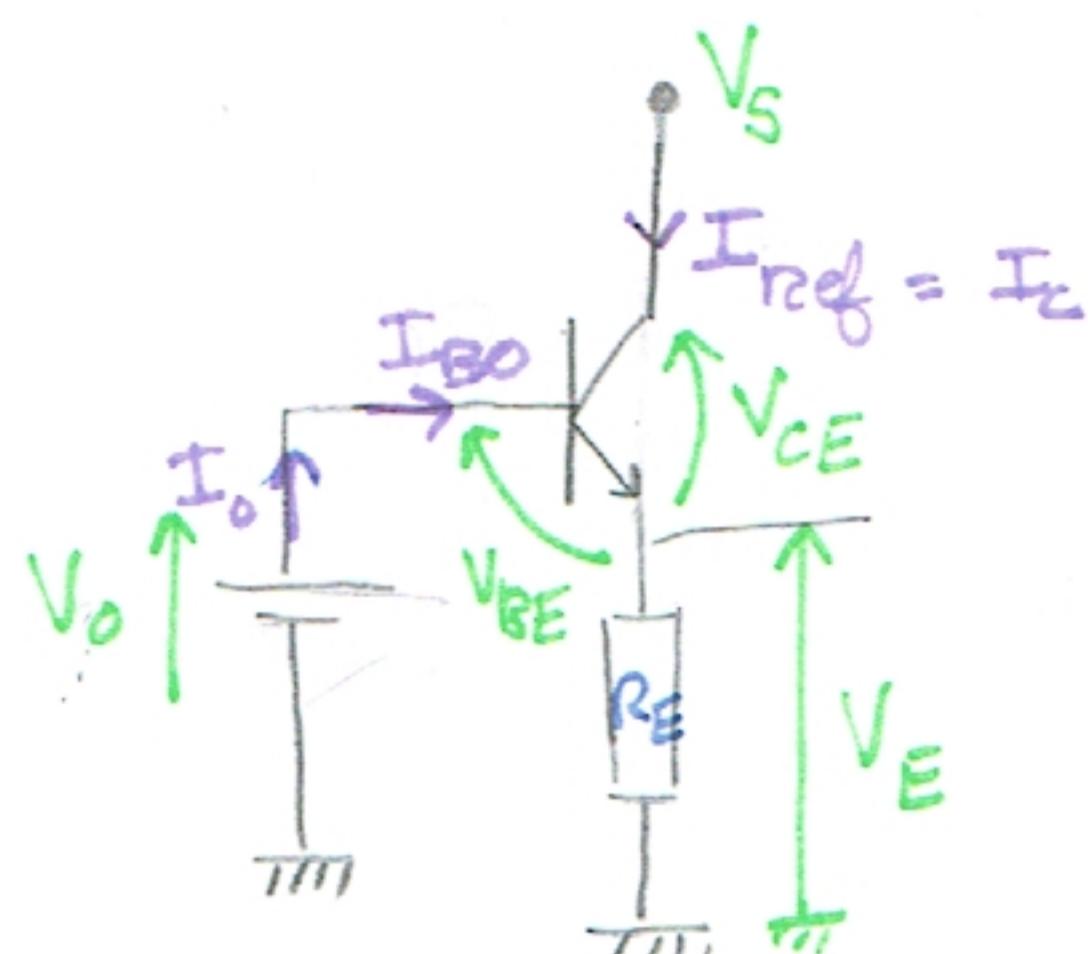
Partie 3 : Source de courant

3.3 Utilisation d'une référence de tension.

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

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

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



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

$$= 4 - 0,5$$

$$= 3,5 \text{ V} \Rightarrow R_E = \frac{V_E}{I_E}$$

$$= \frac{3,5}{1 \text{ mA}}$$

$$= 3500 \Omega$$

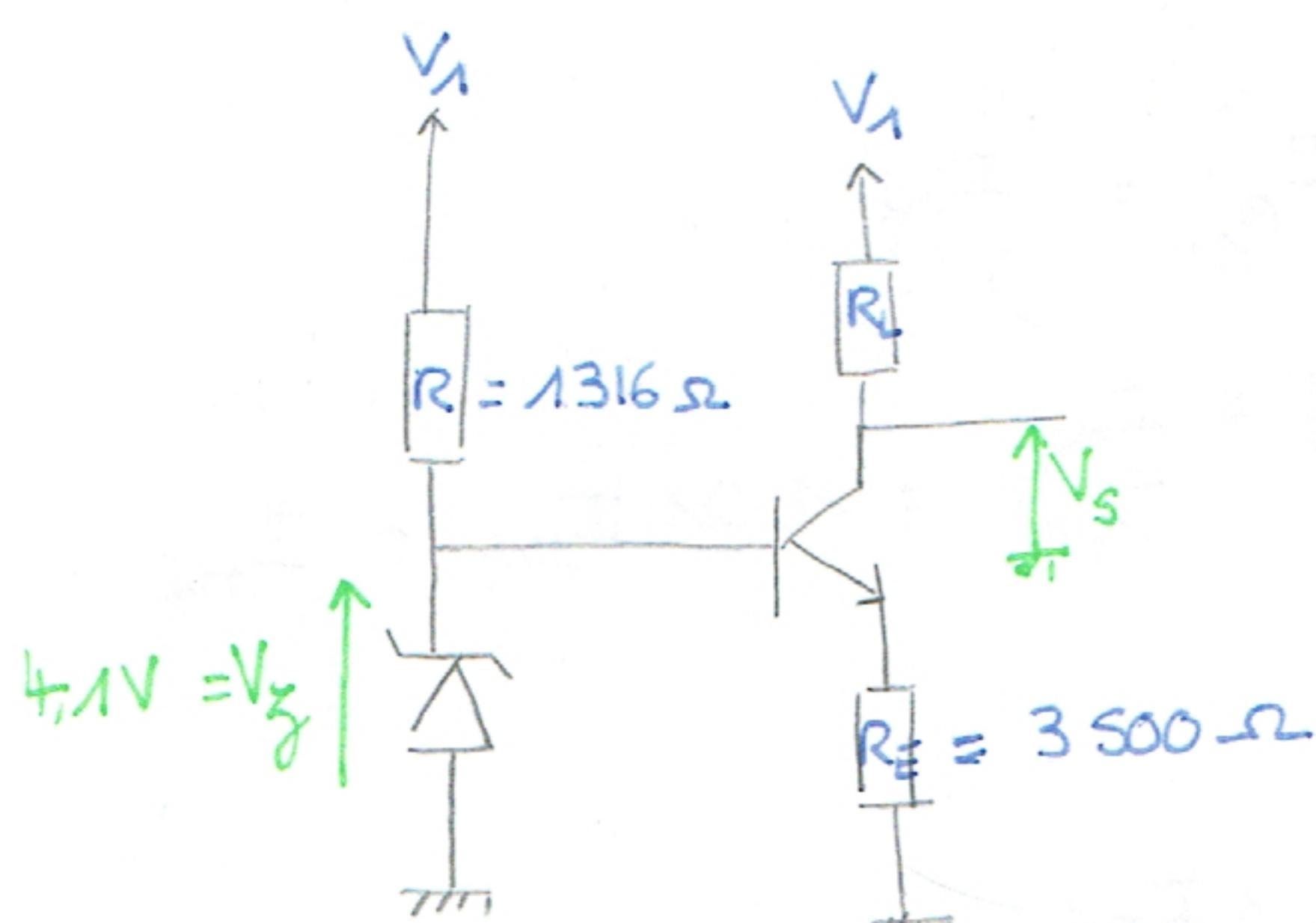
3/ on veut  $V_O = 4,1 \text{ V}$ ; on reprend le circuit de la partie 2.

\* calcul de  $R$ :

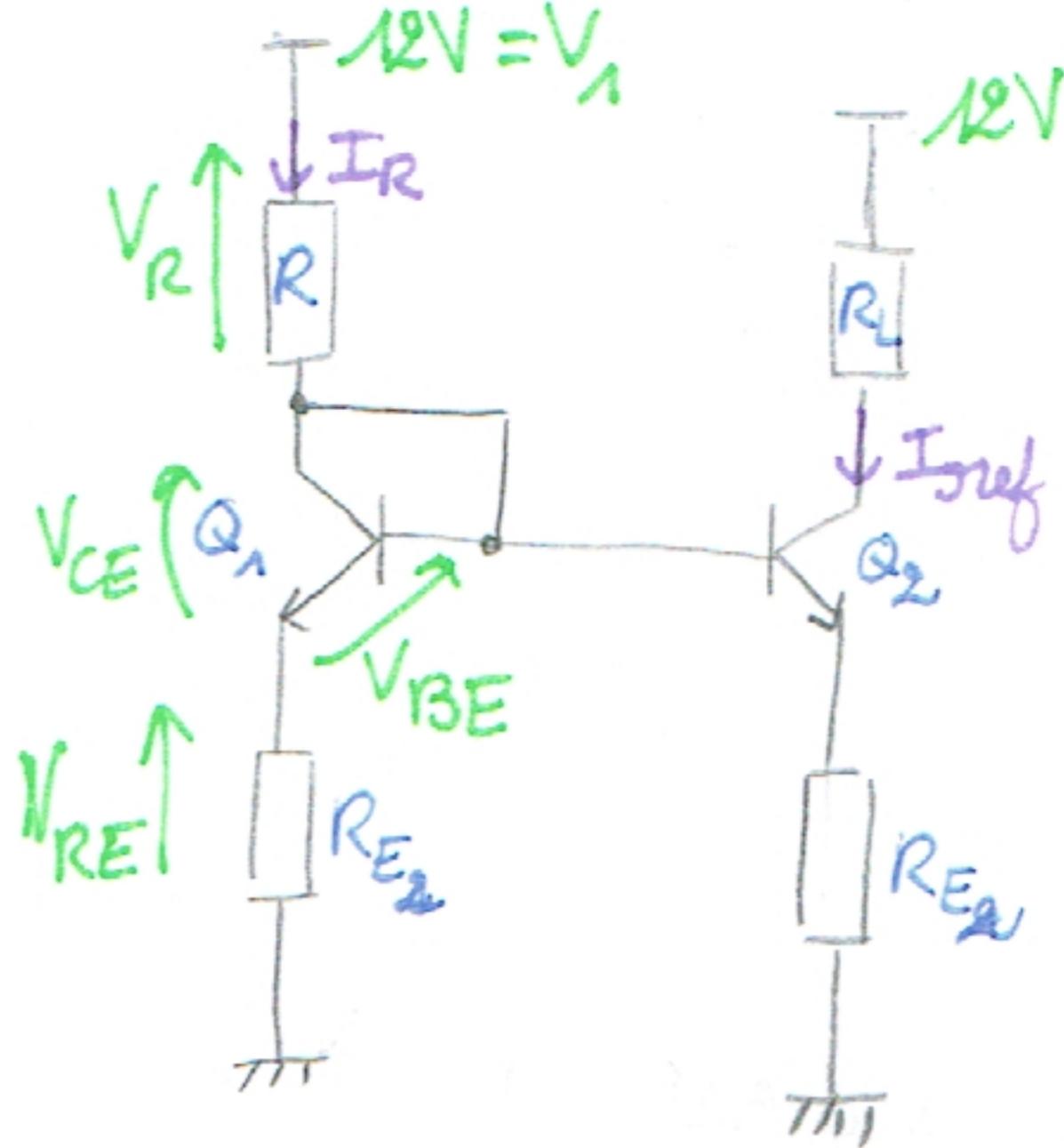
$$V_R = V_1 - V_2 = 12 - 4,1 = 7,9 \text{ V}$$

$$I_R = 6 \text{ mA}$$

$$\Rightarrow R = \frac{7,9}{6 \text{ mA}} = 1316 \Omega$$



### 3.5 Le miroir de courant.



$$R_{E1} = R_{E2} = R_E = 3500 \Omega$$

$$Q_1 = Q_2$$

$$I_{ref} = 1mA$$

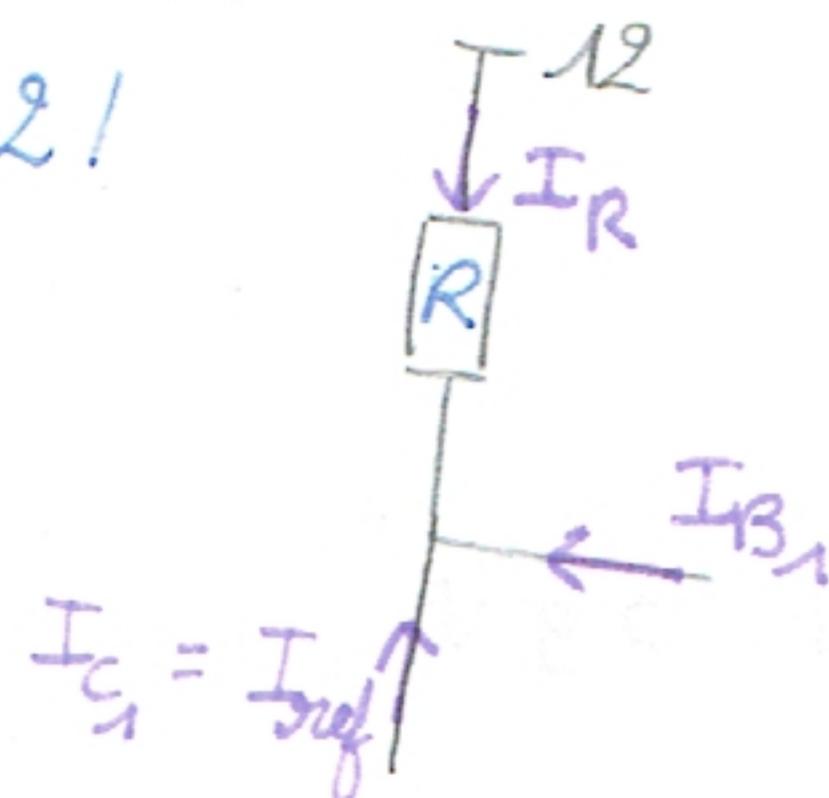
1/  $V_{B1}$ ?  $V_{B2}$ ?

on sait que  $Q_1 = Q_2$  et  $R_{E1} = R_{E2}$  donc  $V_{B1} = V_{B2}$ .

$$\text{donc } I_{B1} = I_{B2}$$

$$\text{donc } I_{C1} = I_{C2} = I_{ref}$$

2/



$$I_R = I_{ref} + I_{B1}$$

$$\text{Si } \beta = 100 \text{ alors } I_{B1} = \frac{I_{ref}}{100}$$

$$\Rightarrow I_R = I_{ref} + \frac{I_{ref}}{100} = 1,01 I_{ref}$$

$$= 1,01 I_{ref} \approx I_{ref}$$

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

$$V_R = V_1 - V_{BE} - V_{RE} = 12 - 0,6 - R_{E1} \times I_{ref}$$

$$= 7,9V$$

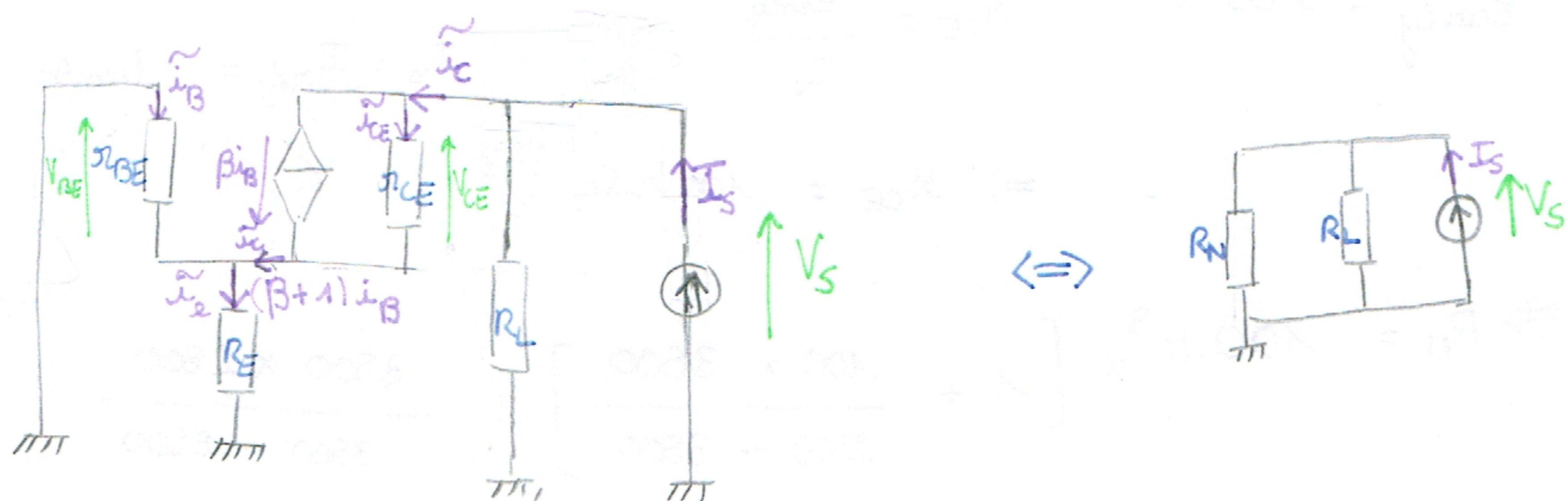
$$R = \frac{V_R}{I_R} = 7900 \Omega$$

TP1, suite

Partie 3, suite

3.7 Étude dynamique de la source de courant.

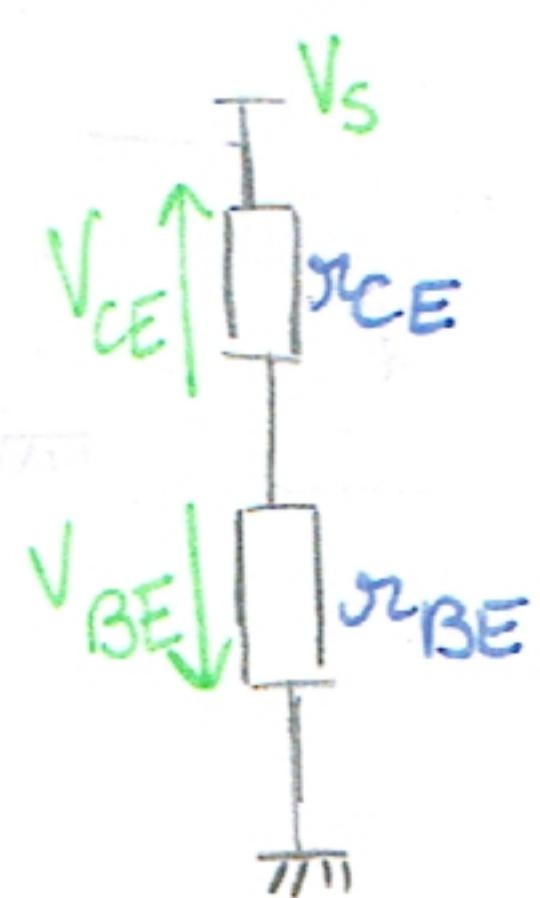
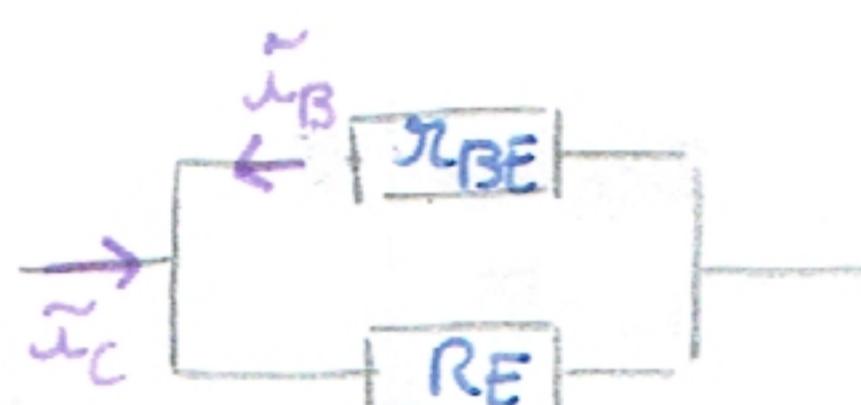
11



$$21 \quad R_N = \frac{V_s}{I_s}$$

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

$$\text{équation matrice} \quad i_B = \frac{R_E}{r_{BE} + R_E} i_C$$



$$V_s = V_{CE} - V_{BE} = \tilde{i}_C r_{CE} - \tilde{i}_B r_{BE}$$

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

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

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

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

$$3/ \alpha_{\mu_T} = 25 \text{ mV} \quad r_{BE} = \frac{\mu_T}{I_{BO}} \quad \text{avec} \quad I_{BO} = \frac{I_{CO}}{\beta} = \frac{I_{ref}}{\beta} = \frac{1\text{mA}}{100} = 10 \mu\text{A}$$

$$\Rightarrow r_{BE} = 2500 \Omega$$

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

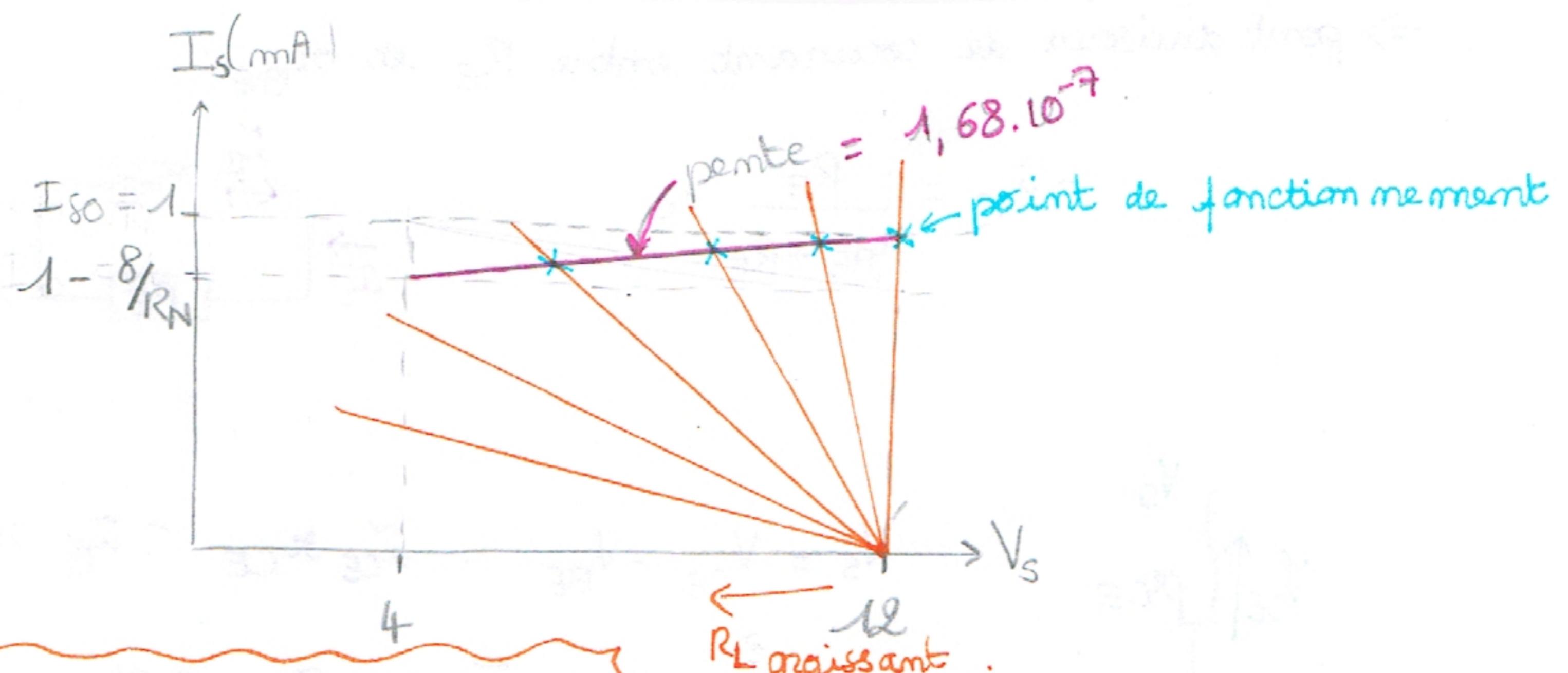
$$\Rightarrow r_{CE} = 100k\Omega$$

$$\Rightarrow R_N = 100 \cdot 10^3 \times \left[ 1 + \frac{100 \times 3500}{2500 + 3500} \right] + \frac{3500 \times 2800}{3500 + 2800}$$

$$4/ \text{pente} = \frac{1}{R_N} = 1,68 \cdot 10^{-7}$$

$$(I_{SO}, V_{SO}) = (1\text{mA}, 12\text{V}) \Rightarrow R_N = 5,935 \cdot 10^6 \Omega$$

$$= 5,9 \text{ M}\Omega$$

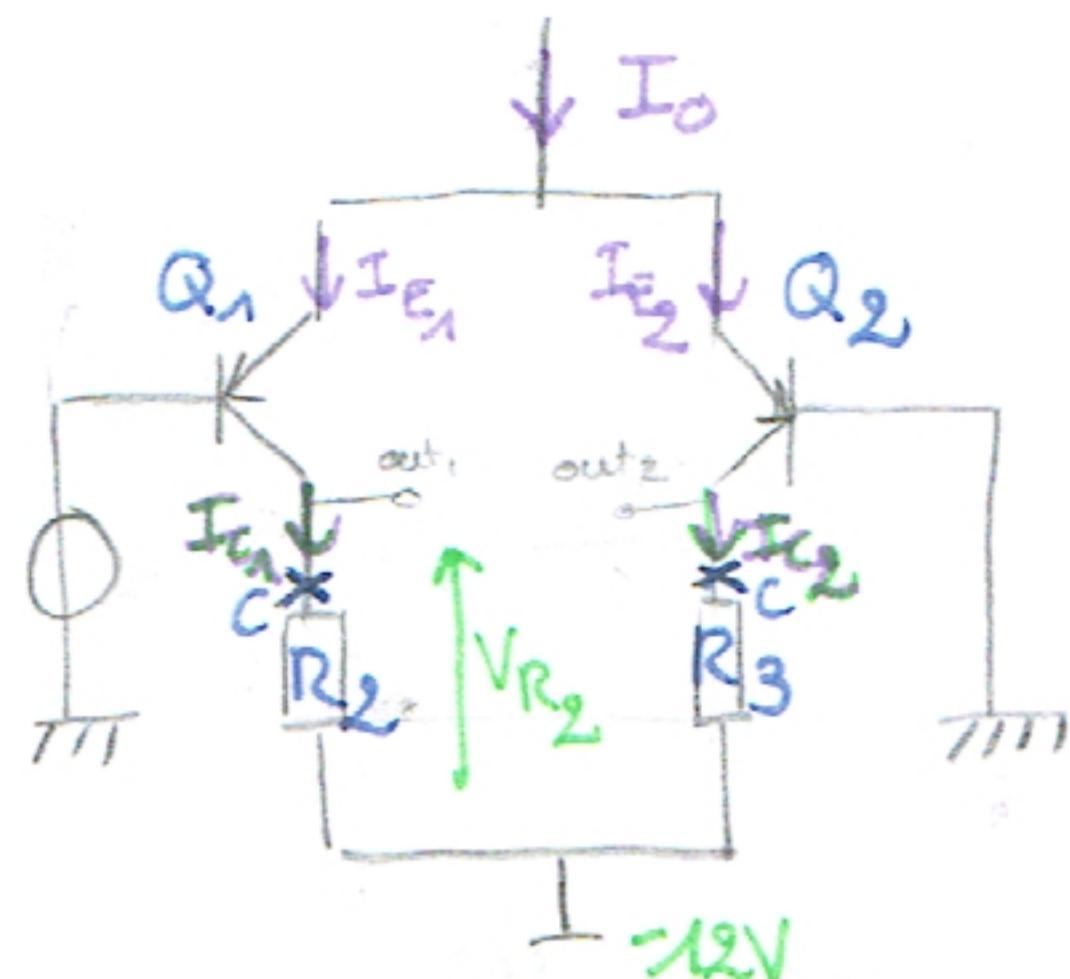


$$I_S = \frac{V_L - V_S}{R_L} = -\frac{V_S}{R_L} + \frac{V_L}{R_L}$$

## TP 2 = Etage différentiel.

### Partie 1 : Analyse et dimensionnement

1/

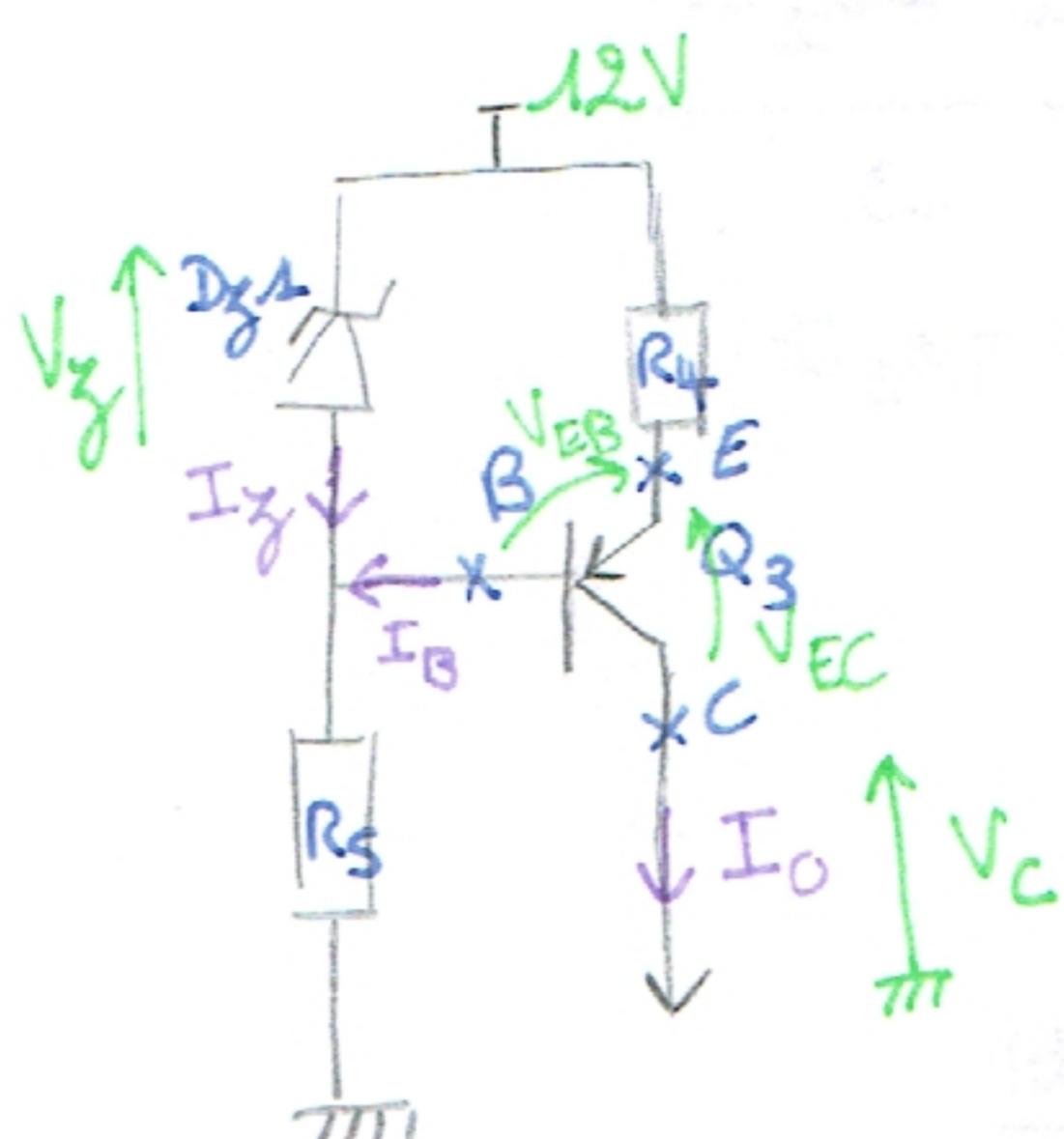


$$Q_1 = Q_2 = 2N2907.$$

$$I_{C1} = I_{C2} \Rightarrow R_2 = R_3 .$$

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

2/



= polarisation par diode zénier

⇒ générateur de courant au collecteur constant.

3/

$$I_0 = I_c = 280 \mu A$$

$$Q_3 = 2N2907$$

$$V_g = 5,1V$$

$$V_{EB} = 0,6V$$

$$I_B = 5mA$$

$$V_{ECsat} = 0,2V .$$

$$\beta = 100$$

$$\Rightarrow V_{ECmin} = 0,5V$$

$$* I_{R_S} = I_B + I_g = \frac{I_c}{\beta} + I_g = 5mA .$$

mégligeable

$$\Rightarrow R_S = \frac{V_{RS}}{I_{RS}} = 1380 \Omega$$

$$* V_{RS} = 12 - V_g = 6,9V .$$

$$* I_{R_4} = I_E \approx I_0 = 280 \mu A .$$

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

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

4/

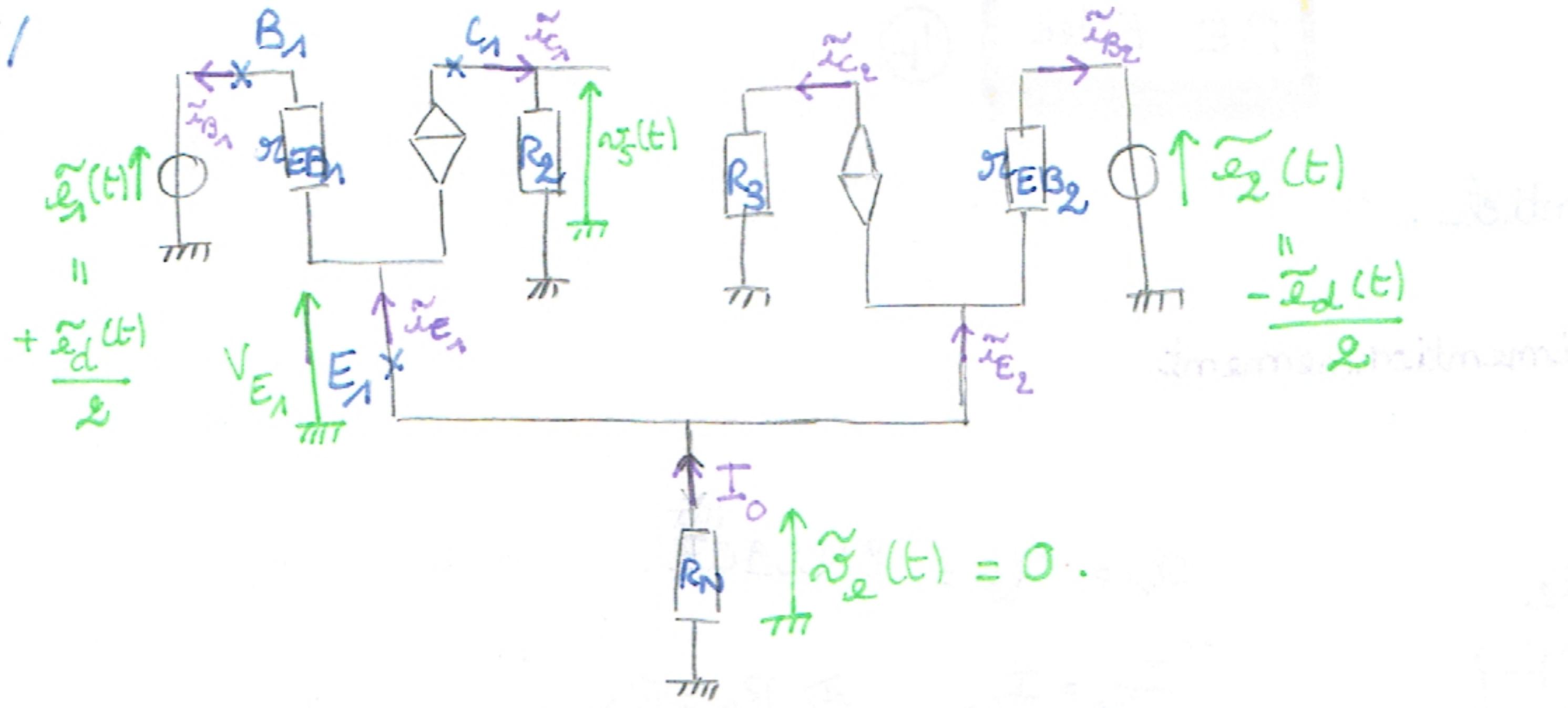
$$V_{Cmax} = 12 - V_{ECmin} - V_{R_4} = 7V .$$

5/

$$* V_{R_2} = 1,8V$$

$$* I_{R_2} = I_{C1} = I_0/2 = 125 \mu A \Rightarrow R_2 = R_3 = 14,4 k\Omega$$

6)

7)  $\rightarrow$  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  $e_1(t) = \frac{e_d(t)}{2}$        $e_2(t) = -\frac{e_d(t)}{2}$

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

avec  $\frac{\tilde{e}_d(t)}{2} + \tilde{i}_{B_1}r_{EB1} - \tilde{i}_{B_2}r_{EB2} + \frac{\tilde{e}_d(t)}{2} = 0$

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

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

Calcul du gain différentiel :

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

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

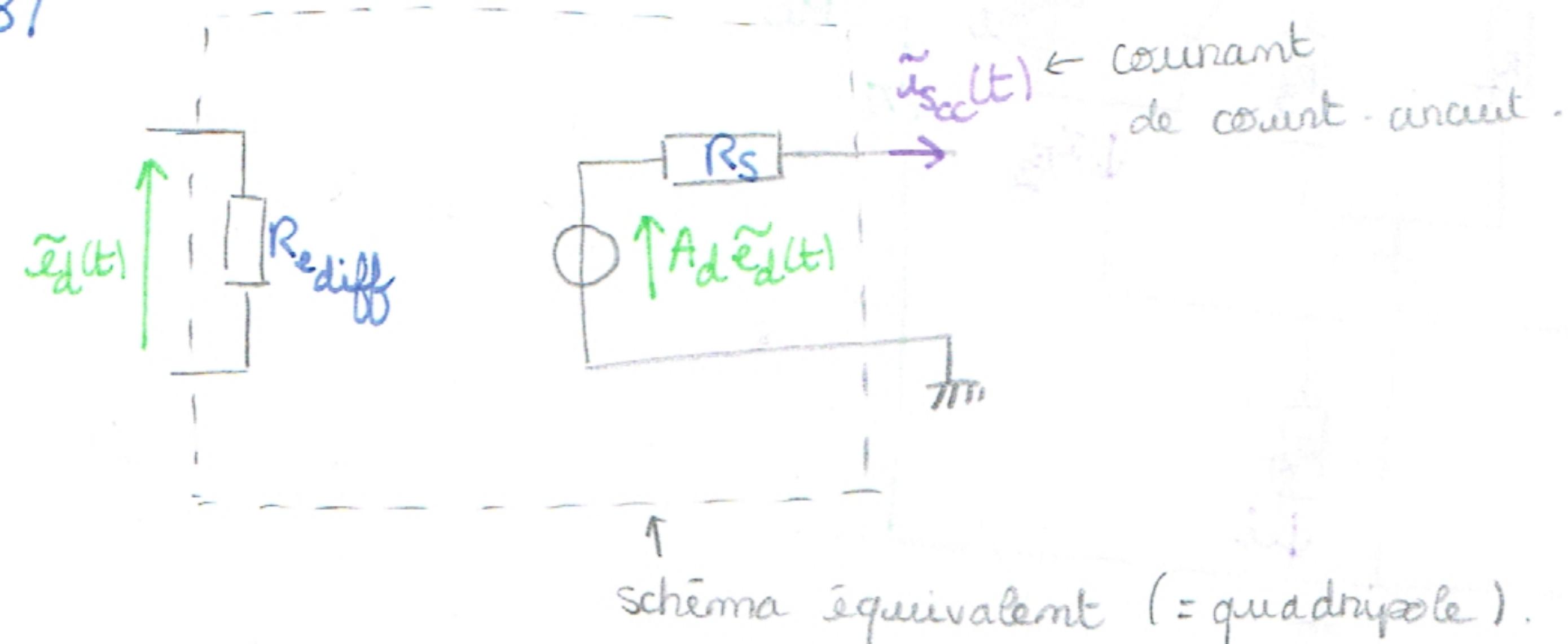
\*  $A_d = \frac{\tilde{v}_s(t)}{\tilde{e}_d(t)} = -R_2 \beta \times \frac{1}{2r_{BE}} = -R_2 \beta \frac{I_{BO}}{2U_T} = -R_2 \frac{I_{CO}}{2U_T} \stackrel{125 \mu A}{=} \text{ avec } U_T = 25 \text{ mV}$

$A_d = -36 \Rightarrow G = 20 \log(1/36) = -31,12$

TP2, suite

Partie 1, suite

8/



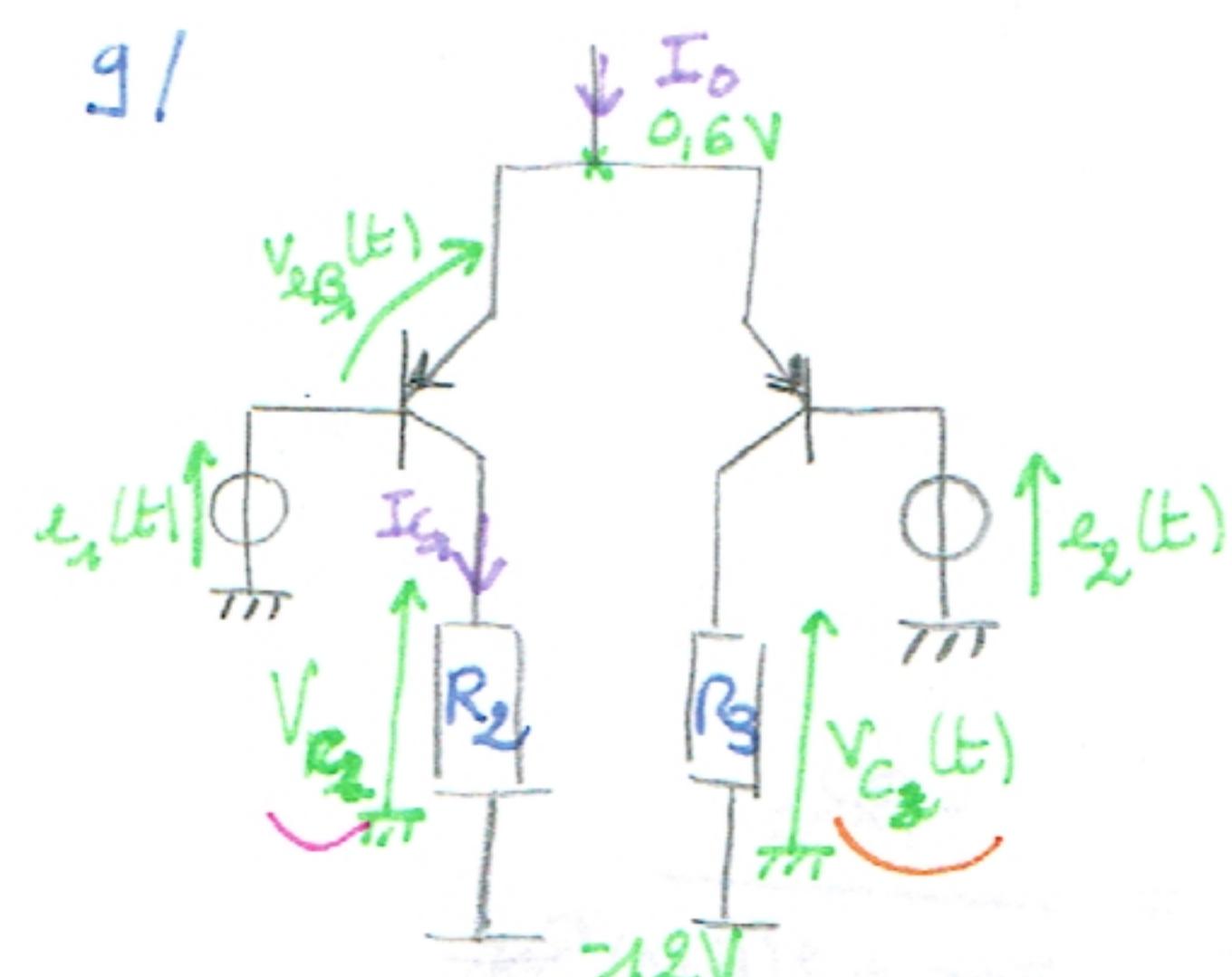
$$\tilde{i}_{S_{CC}}(t) = \frac{A_d \tilde{e}_d(t)}{R_s} \Rightarrow R_s = \frac{A_d \tilde{e}_d(t)}{\tilde{i}_{S_{CC}}(t)}$$

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

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

$$\text{d'où } R_s = -\frac{A_d 2r_{BE}}{\beta} \text{ avec } A_d = -\frac{R_2 \beta}{2r_{BE}} \Rightarrow R_s = R_2.$$

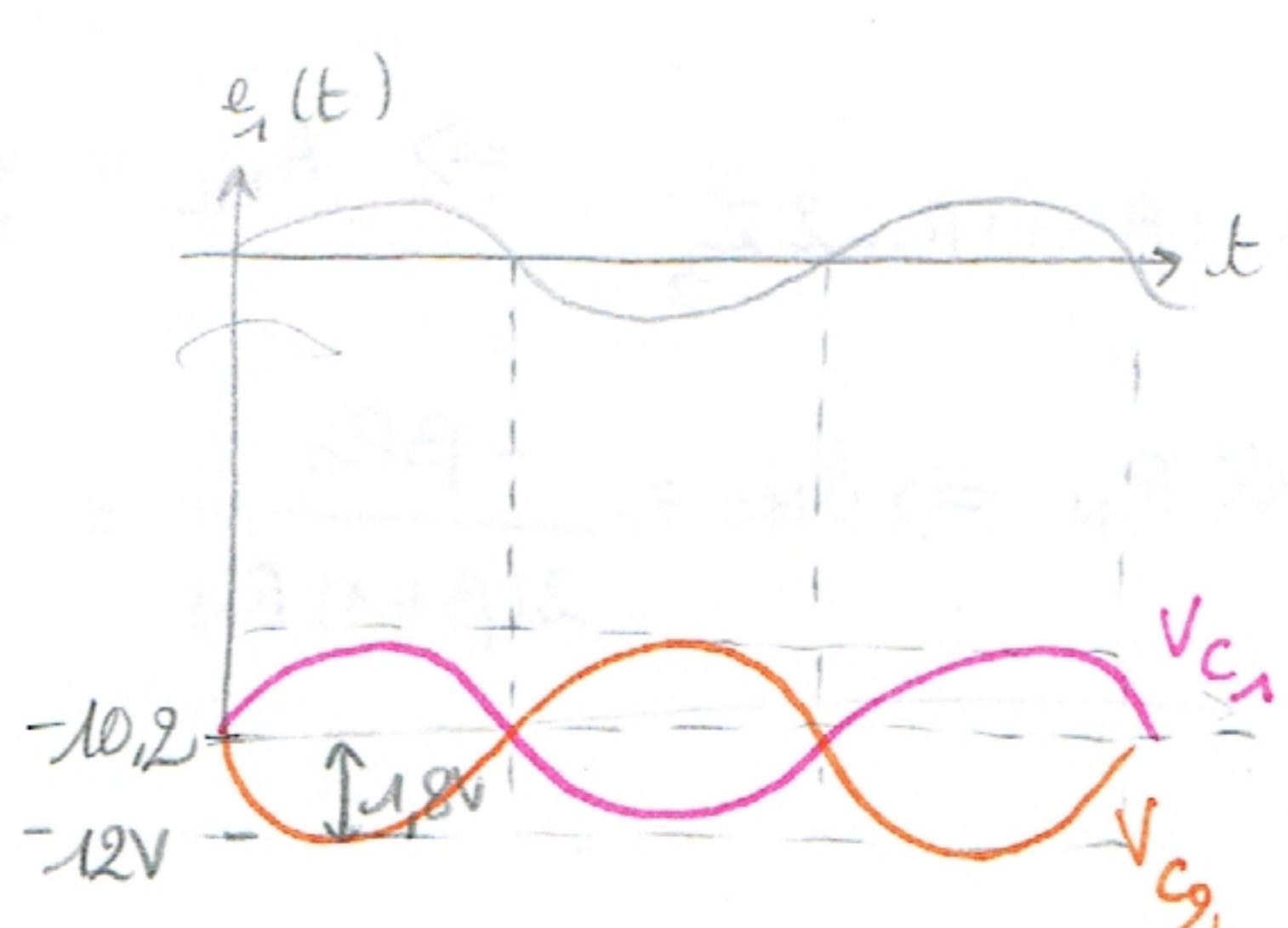
9/



si  $e_1(t) \rightarrow$  alors  $r_{EB_1} \downarrow$  donc  $T_1$  est  $\ominus$  passant.

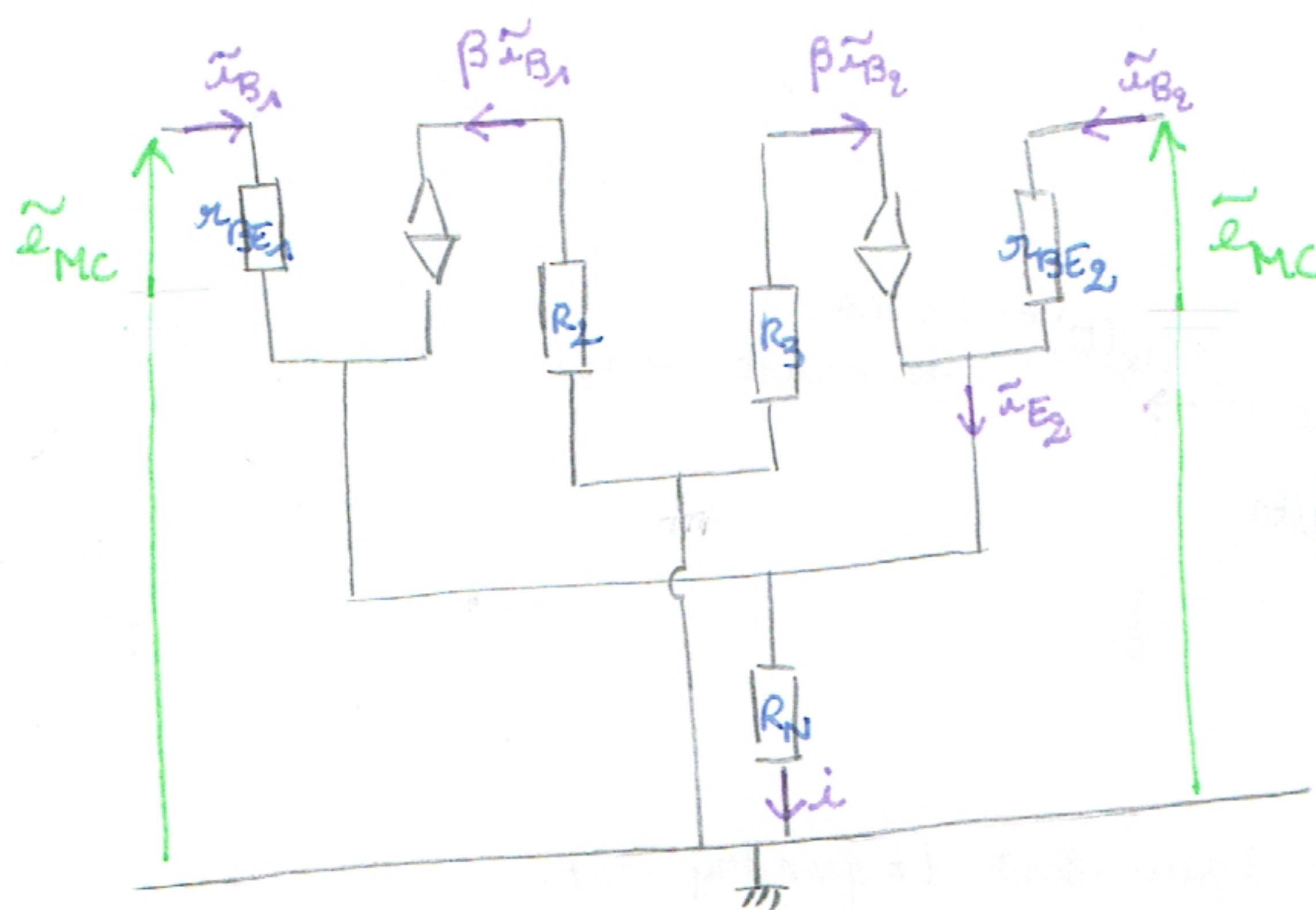
d'où  $I_{C_1} \downarrow$  d'où  $V_{R_2}$  diminue.

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: Etude du mode commun

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



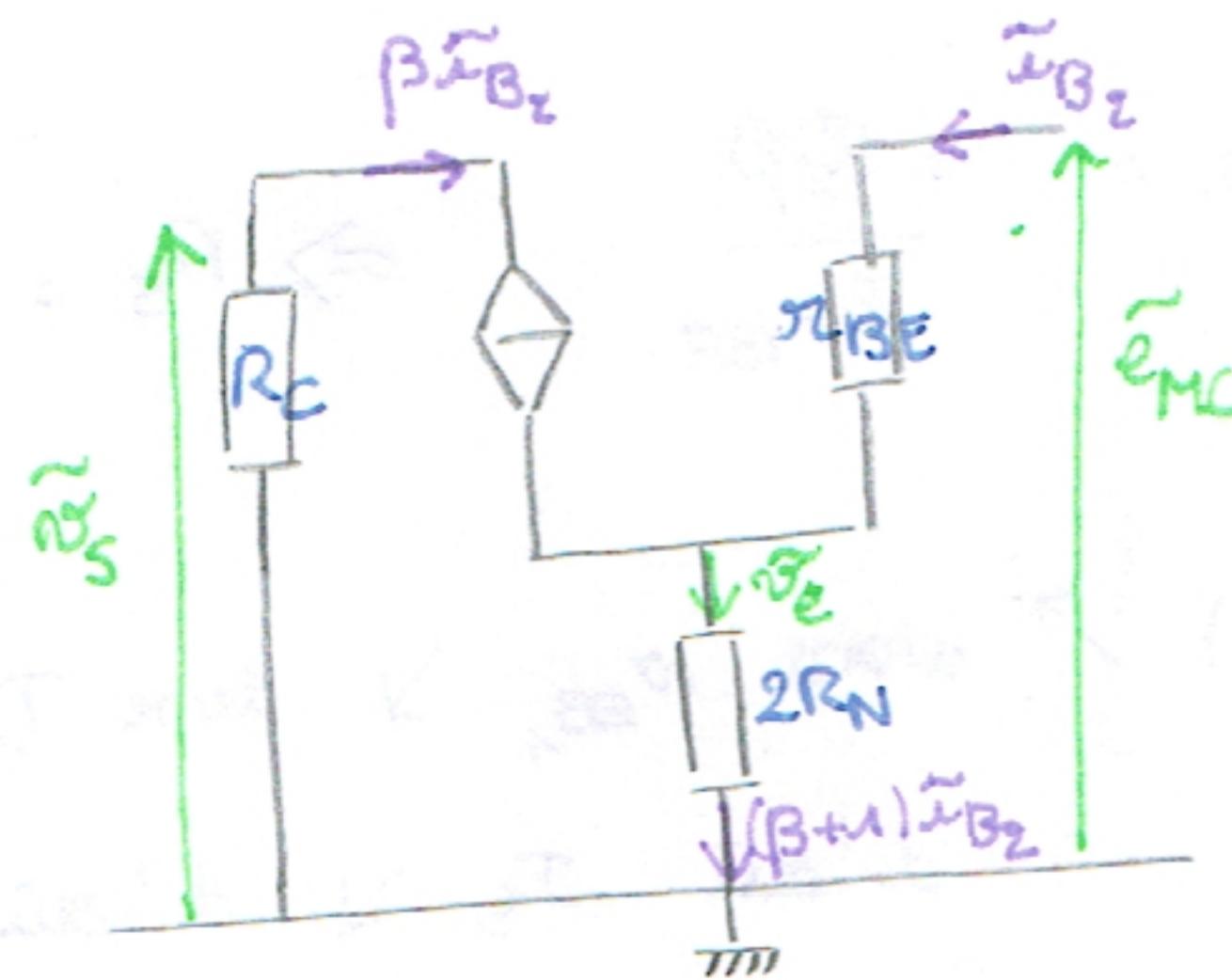
$$* i = (\beta+1) \tilde{i}_{B_1} + (\beta+1) \tilde{i}_{B_2}$$

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

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

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

$\Rightarrow$  demi-schéma



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

$$\bullet \tilde{e}_{MC} = \tilde{v}_{BE} \tilde{i}_{B_2} + (\beta+1) R_N 2 \tilde{i}_{B_2} \Rightarrow A_{MC} = \frac{-\beta R_C}{\tilde{v}_{BE} + 2(\beta+1) R_N}$$

$$\text{or } \tilde{v}_{BE} \ll R_N \Rightarrow A_{MC} = \frac{-\beta R_C}{2(\beta+1) R_N} = \frac{-R_C}{2R_N}$$

## TP2, suite

## Partie 4, suite

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

$$\star r_{CE} = \frac{V_{ce(sat)}}{I_0} = \frac{50}{280\mu} = 200 \text{ k}\Omega$$

$$\star \beta = 100$$

$$\star R_E = R_4 = 18 \text{ k}\Omega$$

$$\star r_{BE} = \frac{\mu}{I_0} = \frac{\beta \cdot r_T}{I_0} = \frac{100 \times 25 \text{ m}}{280\mu} = 10 \text{ k}\Omega$$

$$\Rightarrow R_N = 13 \text{ M}\Omega$$

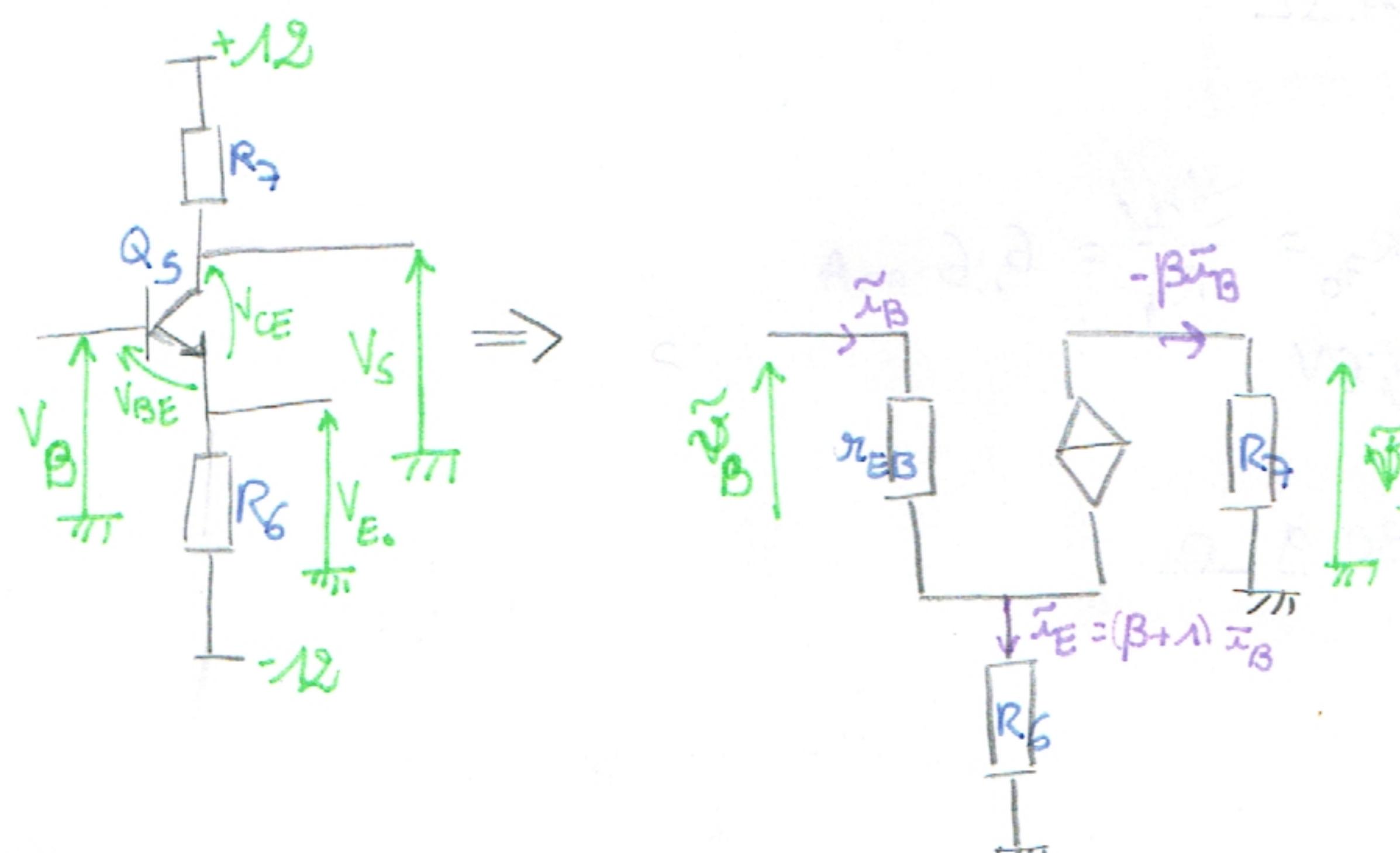
$$\text{d'où } A_{MC} = -\frac{R_C}{2R_N} = -\frac{R_2}{2R_N} = -\frac{14,4 \text{ k}}{2 \times 13 \text{ M}} = -5,5 \cdot 10^{-4}$$

$$TRMC = \frac{|Ad|}{|A_{MC}|} = \frac{36}{5,5 \cdot 10^{-4}} \Rightarrow TRMC = 65454 \text{ en dB.} \Rightarrow 96,32 \text{ dB.}$$

## TP3 = étage émetteur commun

## Partie 1 = étage simplifié

11



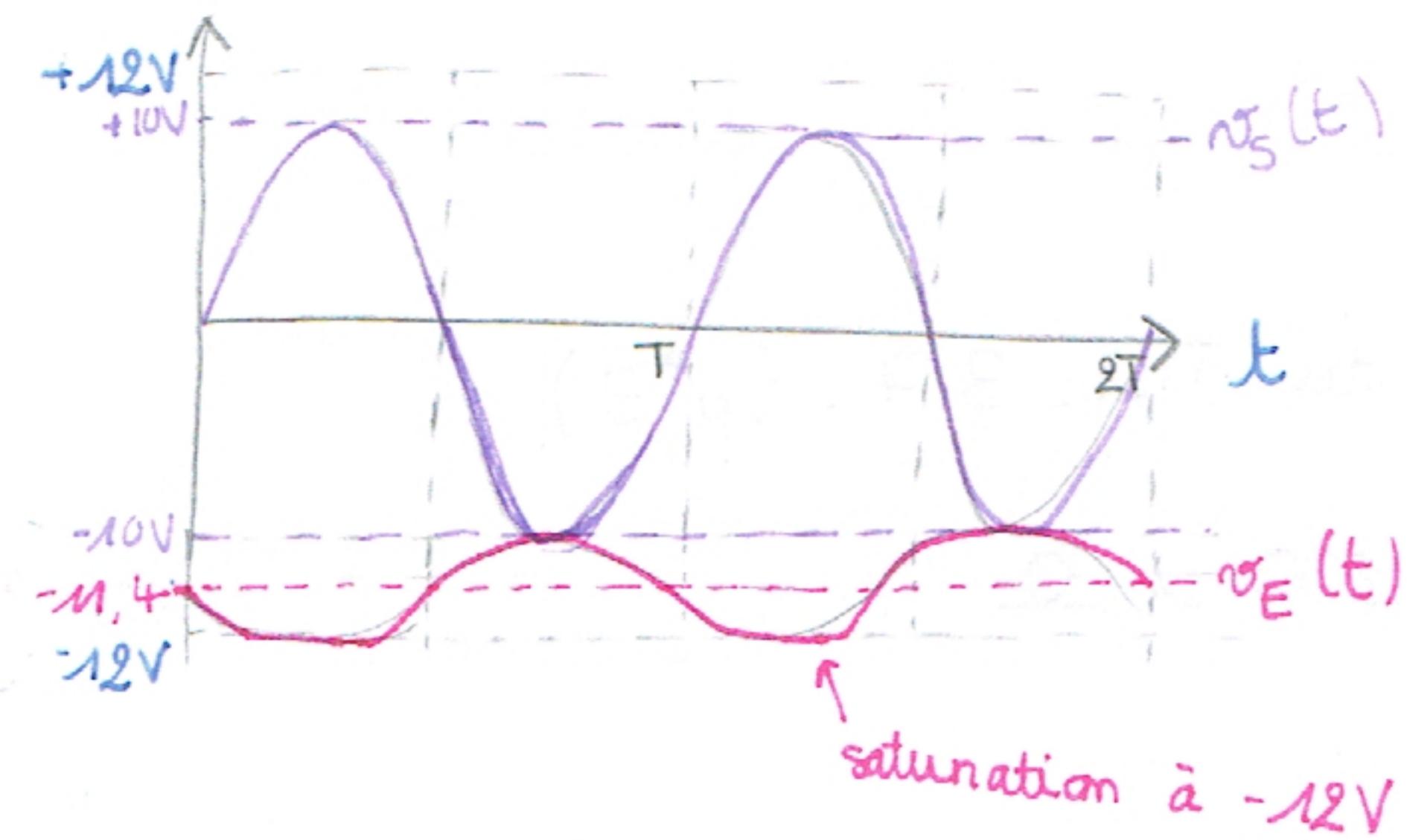
$$\star \tilde{v}_s(t) = -\beta \tilde{v}_B R_7$$

$$\star \tilde{v}_B(t) = r_{EB} \tilde{v}_B + R_6 \tilde{v}_B (\beta+1)$$

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

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

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

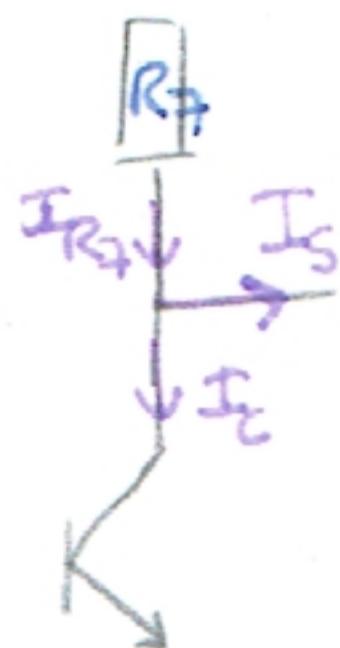


$$3/ \quad V_{CE_{sat}} = 0,3V$$

$$4/ \quad v_s \text{max} = 10V$$

$$R_L = 10k\Omega \quad \text{d'où } I_{Smax} = \frac{10}{10k} = 1mA$$

5/



$I_C = I_{R7} - I_S$  donc quand  $v_s$  est max,  $i_S$  est max donc  $I_C$  est min  
 $\Rightarrow$  risque de blocage.

$$6/ \quad * \quad I_{Cmin} = 100\mu A \quad I_{Smax} = 1mA \quad \Rightarrow \quad I_{R7min} = I_C + I_S = 1,1mA$$

$$* \quad V_{R7} = V_{CC} - V_s = 12 - 10 = 2V$$

$$\Rightarrow R_7 = 1,8k\Omega$$

$$* \quad \text{au repos, } I_{R6} = I_{C0} = I_{R70} = \frac{V_{CC}}{R_7} = 6,6mA$$

$$* \quad V_{R6} = V_{CC} - V_{E_0} = 0,6V$$

$$\Rightarrow R_6 = 90,9\Omega$$

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

TP3, suite :

Partie 2 = adapter les impédances, améliorer le gain

1/ 2.2.1 L'adaptation d'impédance statique.

$$* I_{C_1} = I_{C_2} = \frac{I_o}{2} = 125 \mu A.$$

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

2/  $I_{S_1} > I_{B_0}$  donc on a un courant trop grand en entrée de l'émetteur commun.

2.2.2 L'adaptation d'impédance dynamique.

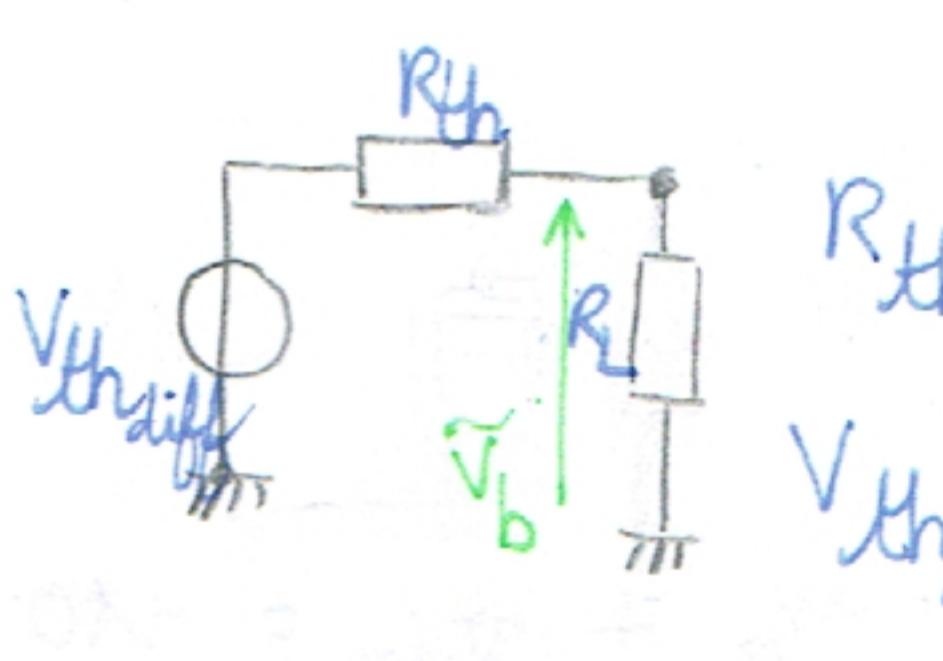
$$3/ R_S = R_2 = 14,4 k\Omega.$$

$$4/ R_e = \frac{r_B}{\beta} = r_{BE} + R_C (\beta + 1)$$

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

$$R_e = 9468 \Omega.$$

5/

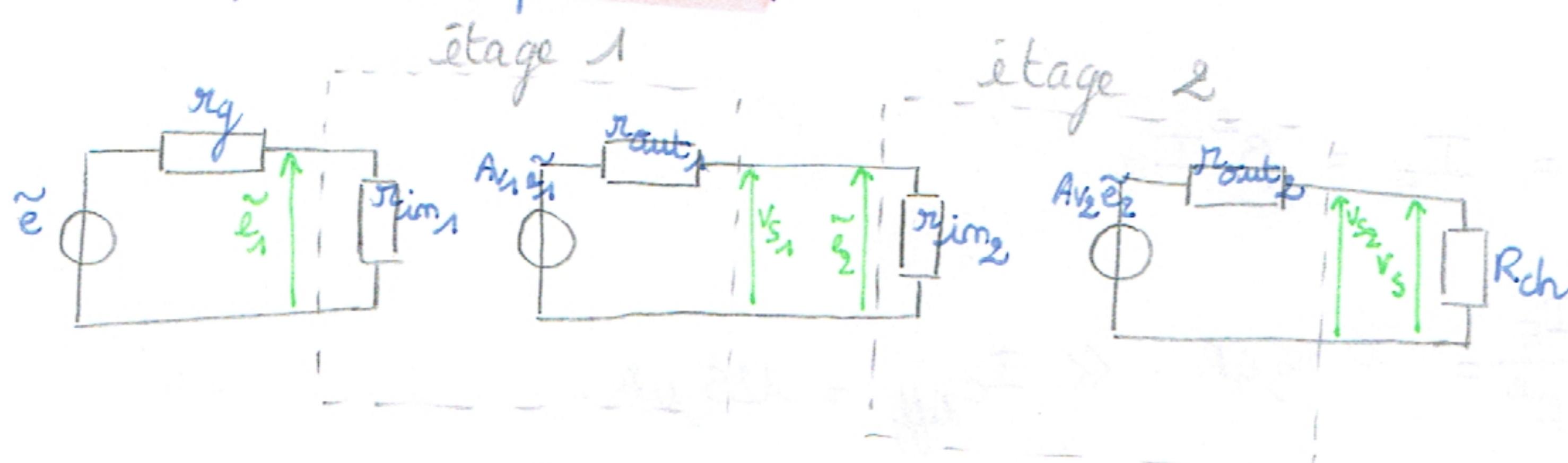


$$R_{th} = R_S = 14,4 k\Omega$$

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

$$R_L = R_e = 9468 \Omega.$$

Bilan adaptation impédance :



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

↪ OK

↪ pas OK  $\Rightarrow$  Darlington

$$\tilde{v}_S = \frac{R_{ch}}{R_{ch} + R_{S2}} \times A_{V2} \times \frac{r_{in_2}}{r_{in_2} + r_{out_1}} \times A_{V1} \times \frac{r_{in_1}}{r_{in_1} + r_g} \times \tilde{e}$$

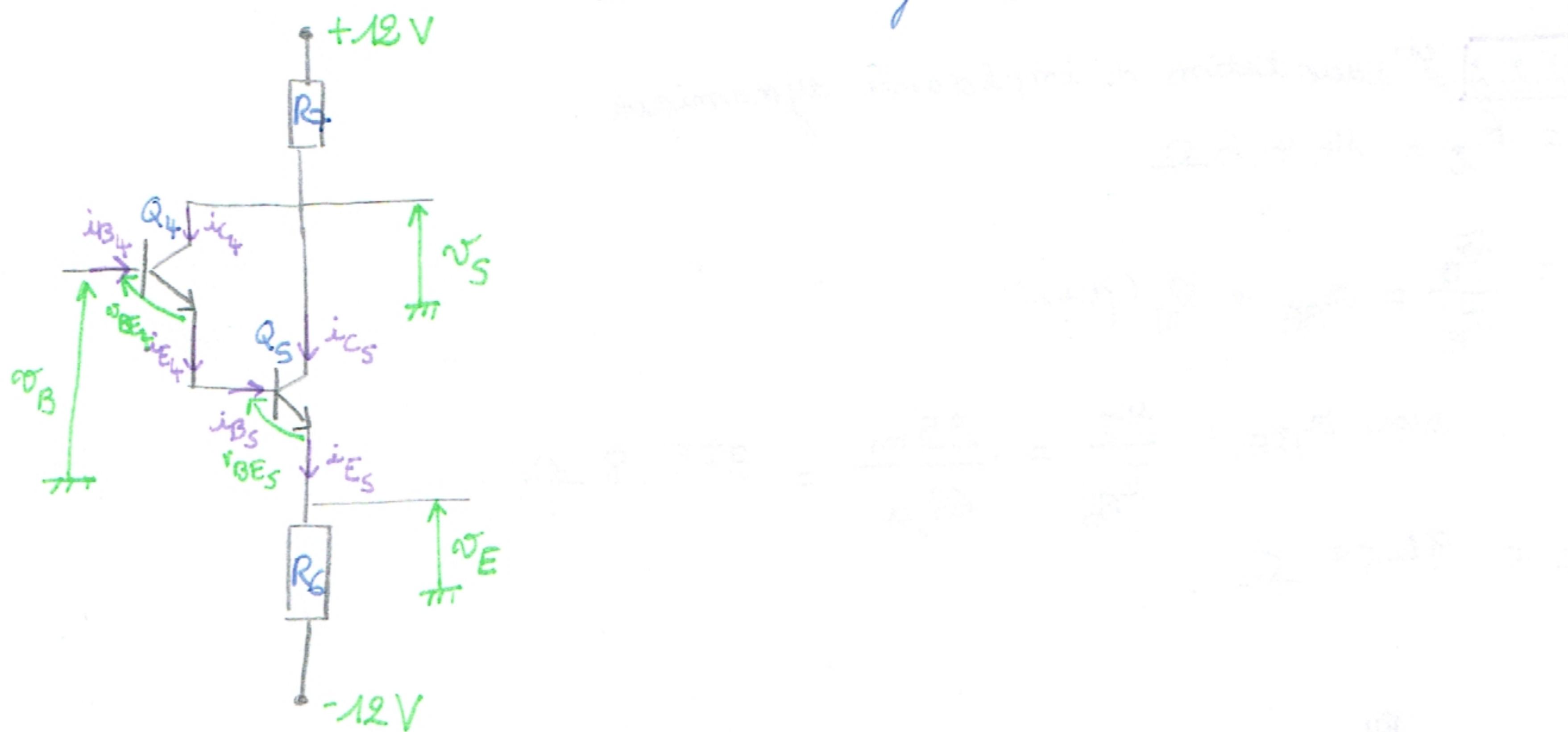
6/ point diviseur de tension schéma q° 5 Thévenin =

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

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

2.4. mise en œuvre d'un étage de Darlington.

1/



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

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

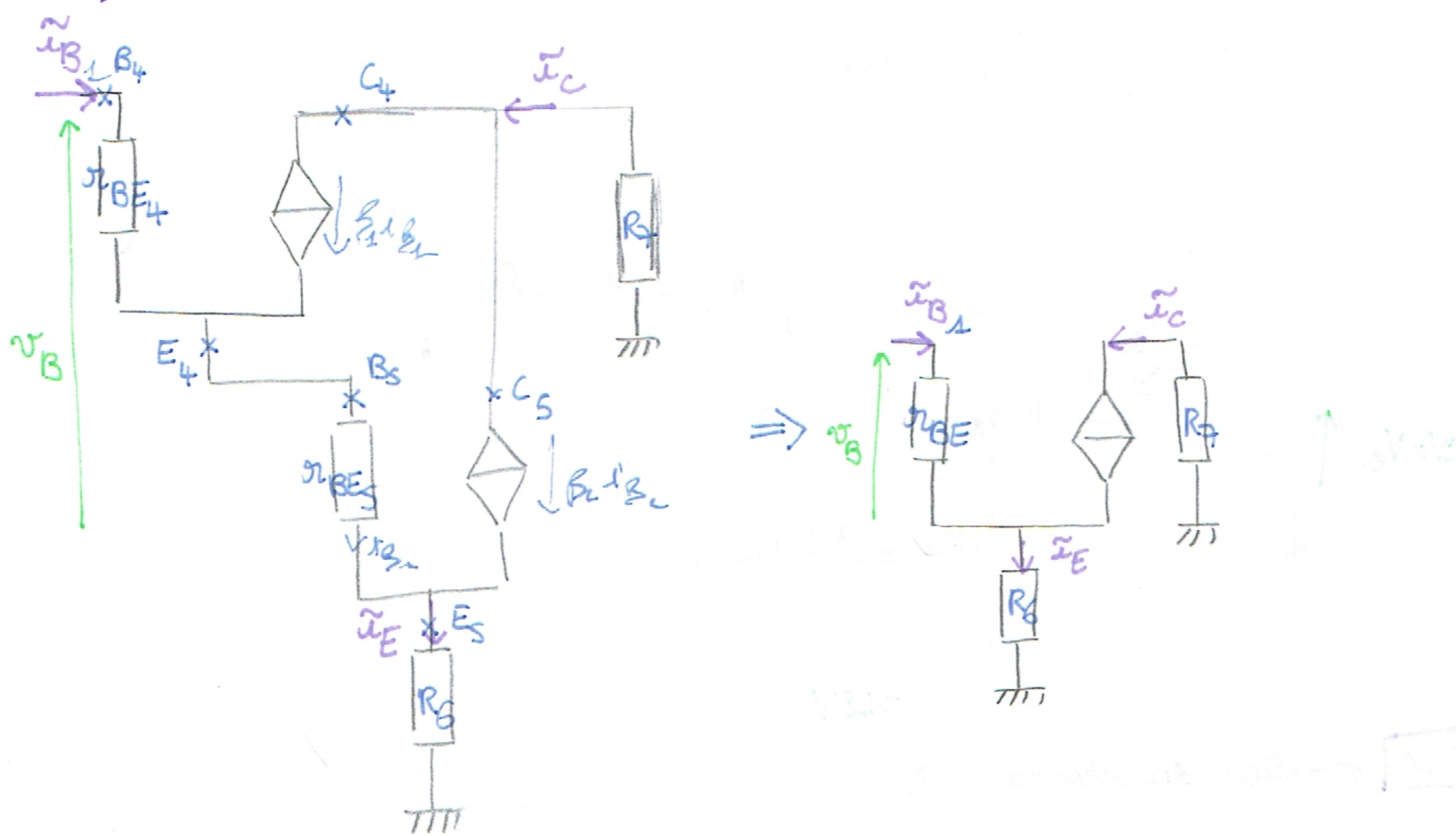
$$3/ I_{R_L} = 6,6 \text{ mA} = I_E = \beta^2 I_B$$

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

## TP3, suite

## Partie 2, suite

4/



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

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

$$* i_C = \beta_1 \tilde{i}_{B_1} + \beta_2 \tilde{i}_{B_2} = \beta_1 \tilde{i}_{B_1} + \beta_2 (\beta_1 + 1) \tilde{i}_{B_1} = \beta \tilde{i}_{B_1}$$

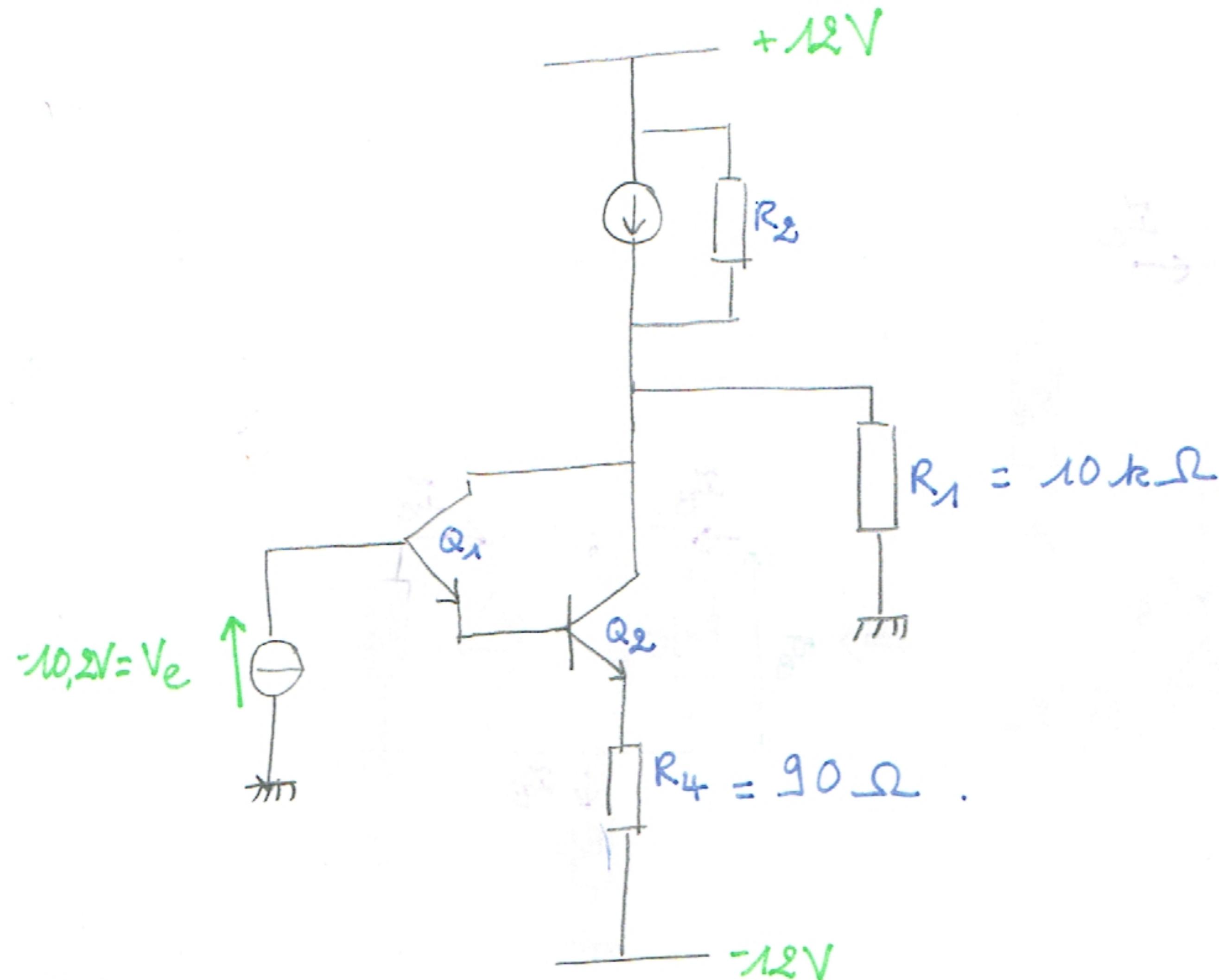
$$\Rightarrow \beta = \beta_1 + \beta_1 \beta_2 \approx \beta_1 \beta_2$$

5/

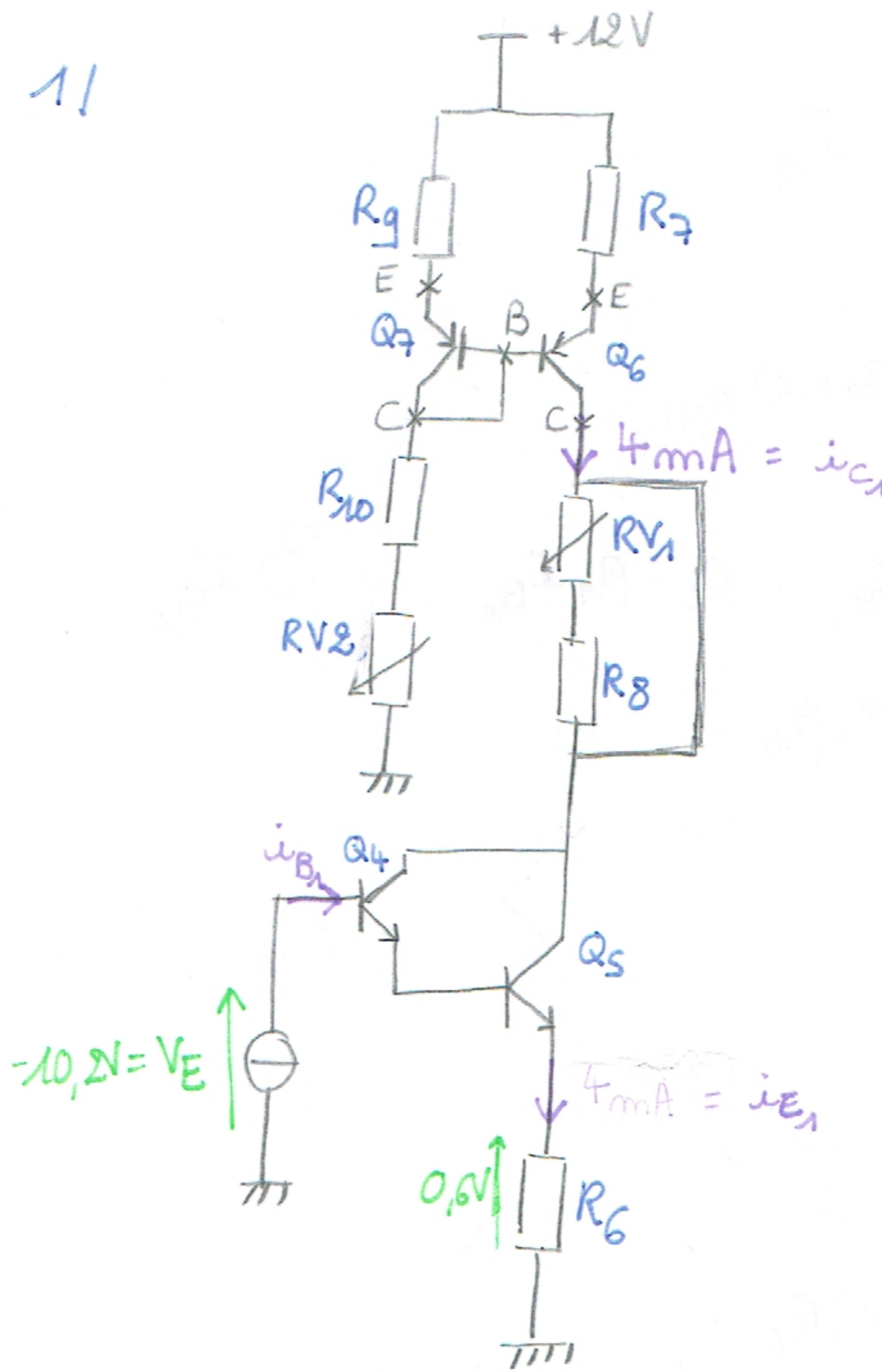
$$R_{in} = \frac{v_B}{i_B} = r_{BE} + (\beta + 1) R_G$$

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

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



3.1. Analyse du schéma réel.



TP3, suite :

Partie 3, suite :

2/ \* on cherche  $R_6$  : on en déduit  $R_7$  et  $R_9$

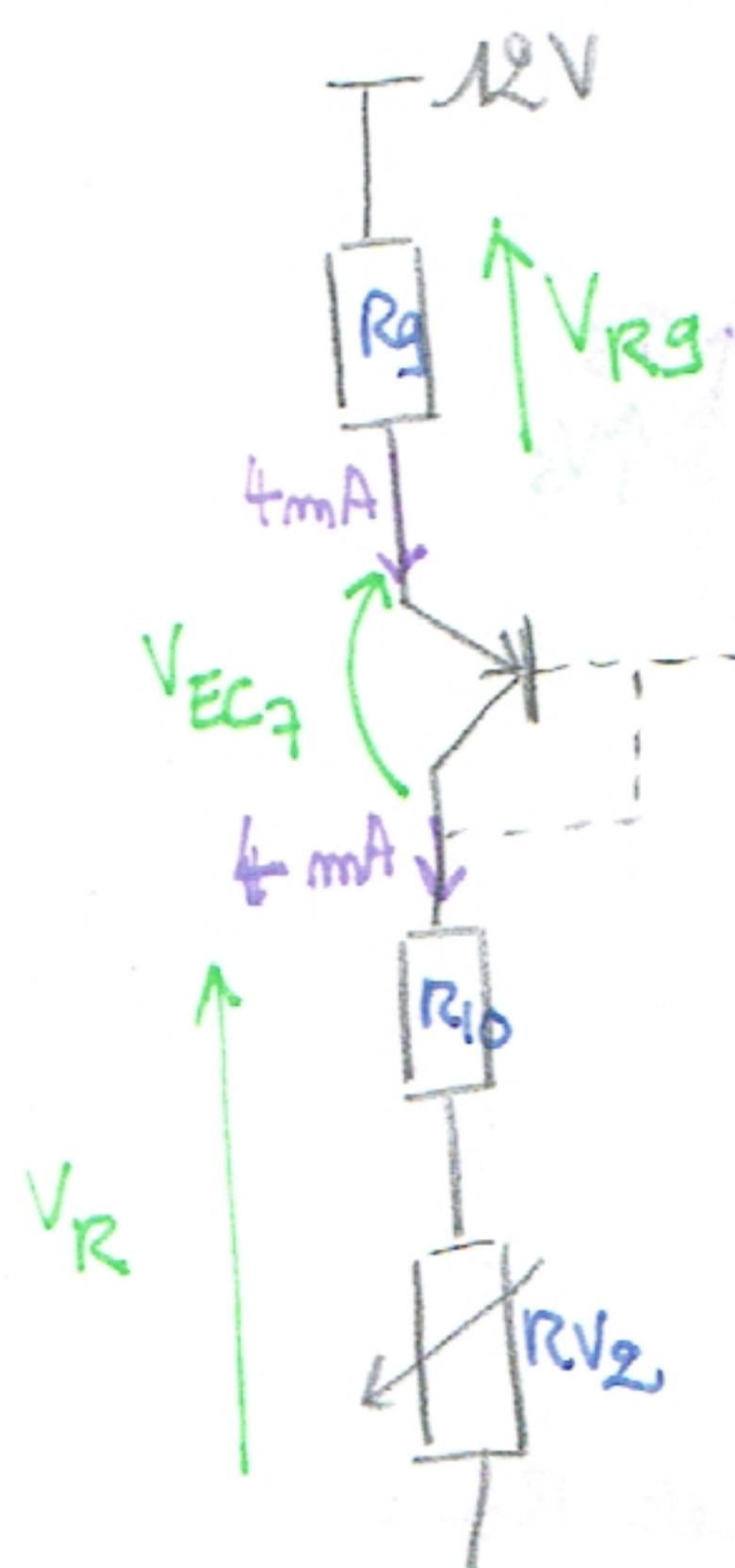
→ on considère que les 2 transistors de Darlington se comportent comme un grand transistor

$$\text{d'où } I_{C_1} = I_{E_1} = 4 \text{ mA.}$$

$$\rightarrow \text{on a } V_{R_6} = 0,6 \text{ V}$$

$$\Rightarrow R_6 = R_7 = 150 \Omega = R_9$$

\* on cherche  $R_{10}$  et  $RV_2$ :



$$\rightarrow V_{Rg} = R_g \times 4 \text{ mA} = 0,6 \text{ V.}$$

$$\rightarrow V_{EC7sat} = 0,6 \text{ V} \text{ (cf. data sheet).}$$

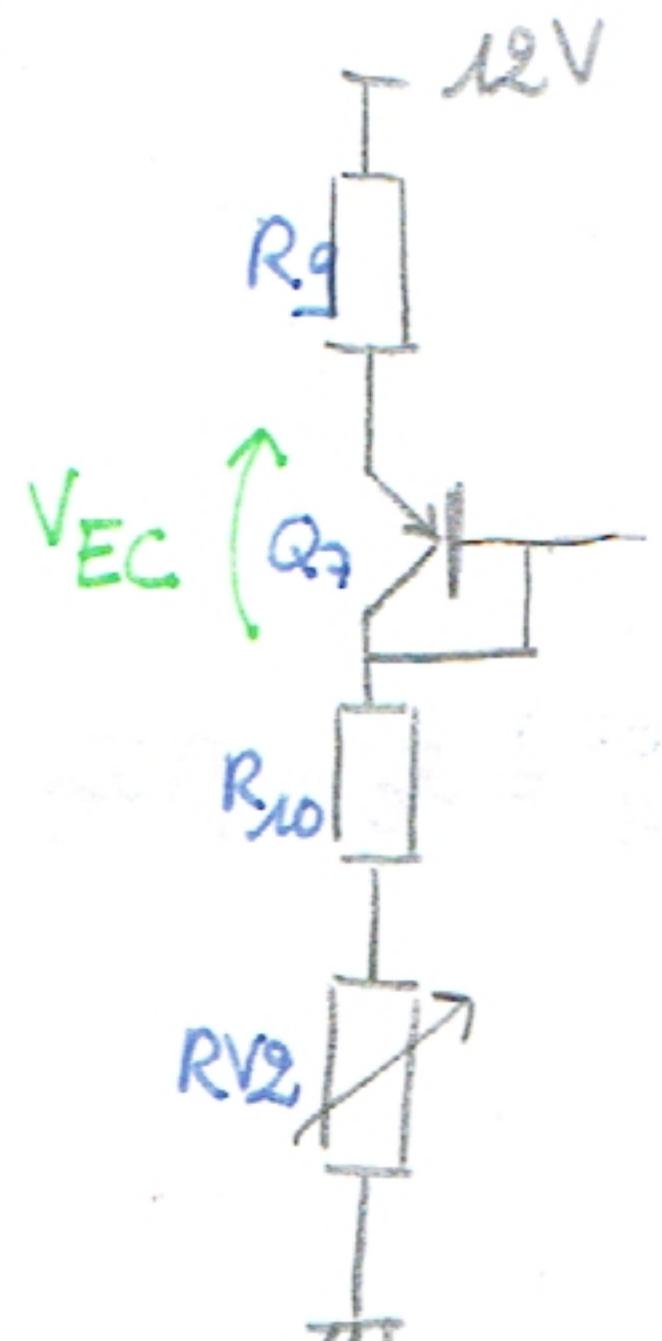
$$\rightarrow V_R = V_{CC} - V_{Rg} - V_{EC7sat} = 10,8 \text{ V}$$

$$\Rightarrow R = R_{10} + RV_2 = \frac{V_R}{4 \text{ mA}} = 2700 \Omega$$

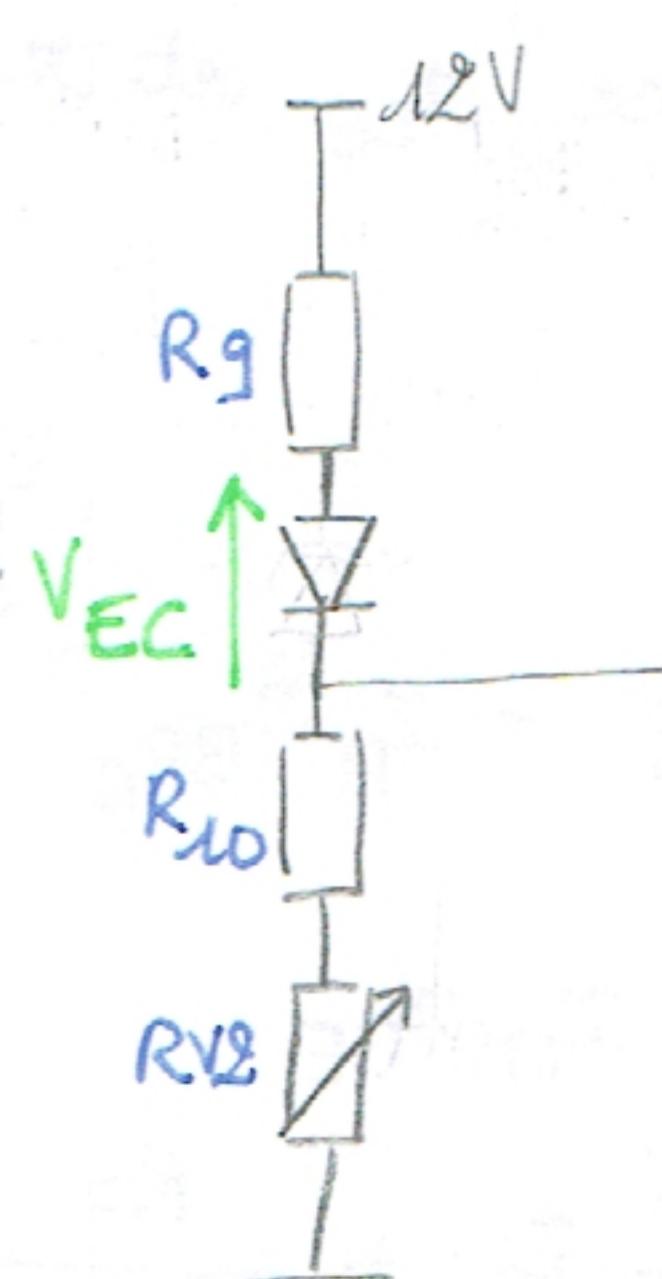
$$RV_2 = 1k \Omega$$

$$R_{10} = 1700 \Omega$$

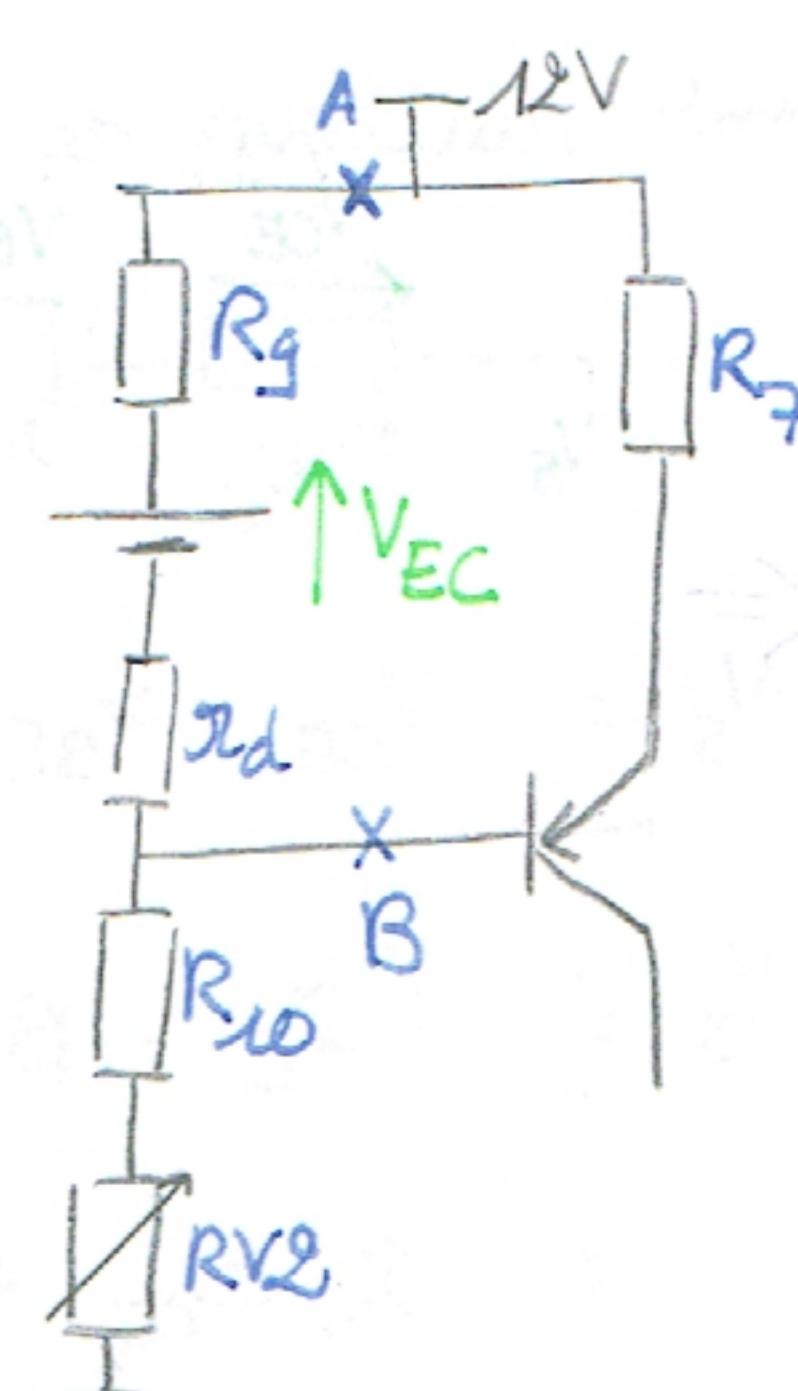
3/ \* modélisation de  $Q_7$  par une diode :



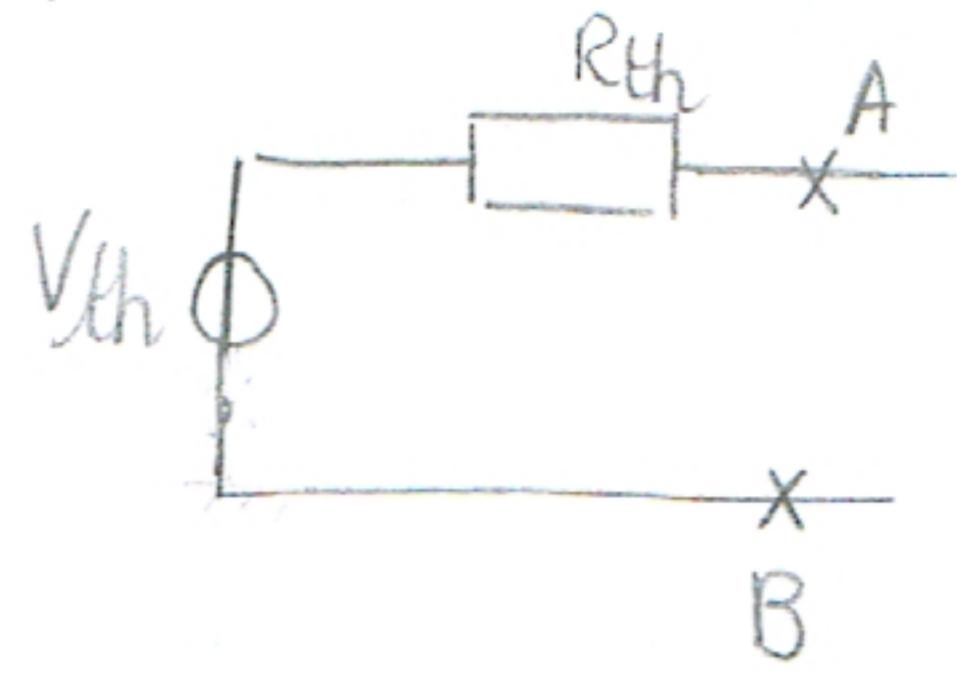
⇒



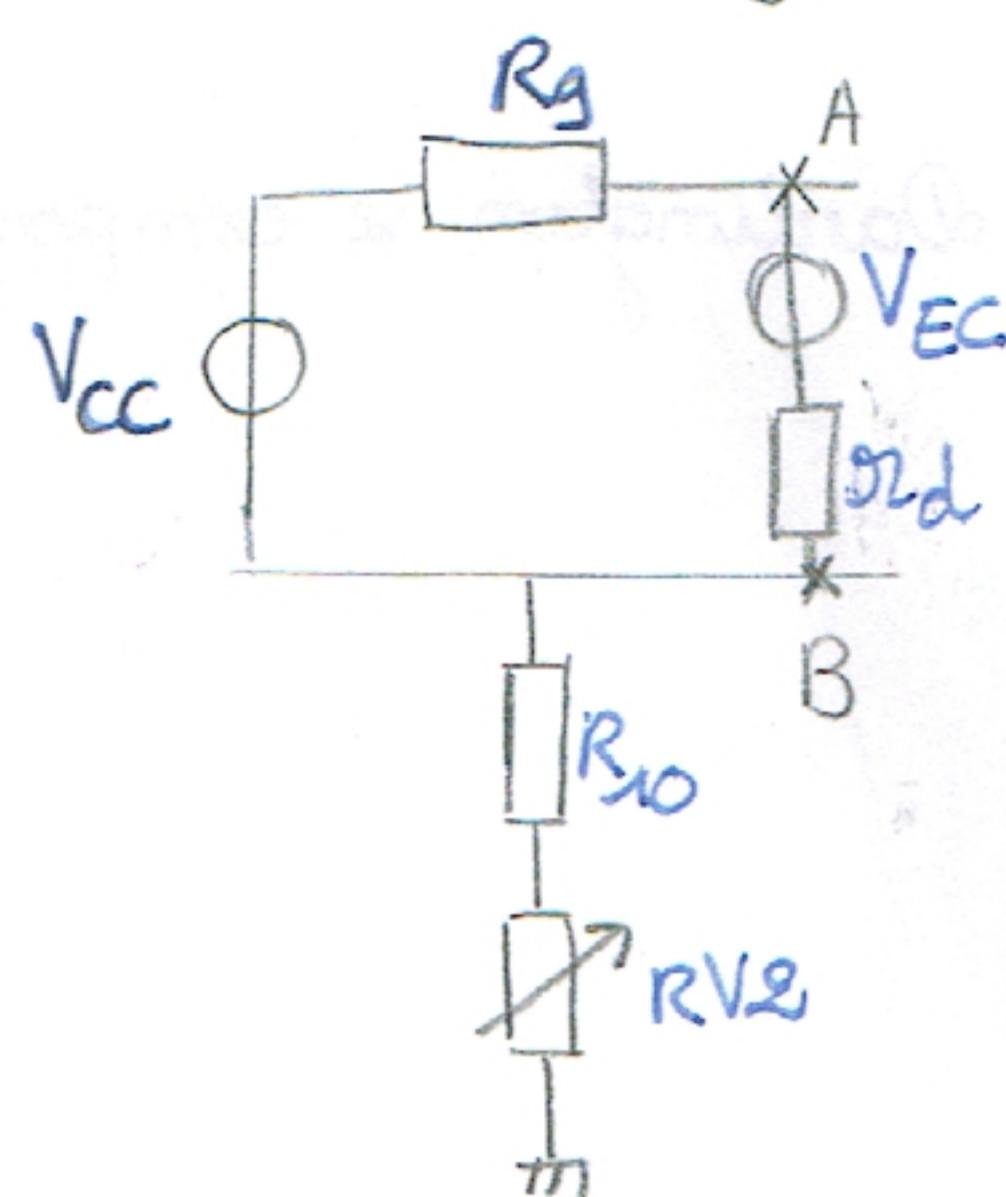
⇒



\* on applique le théorème de Thévenin entre A et B :



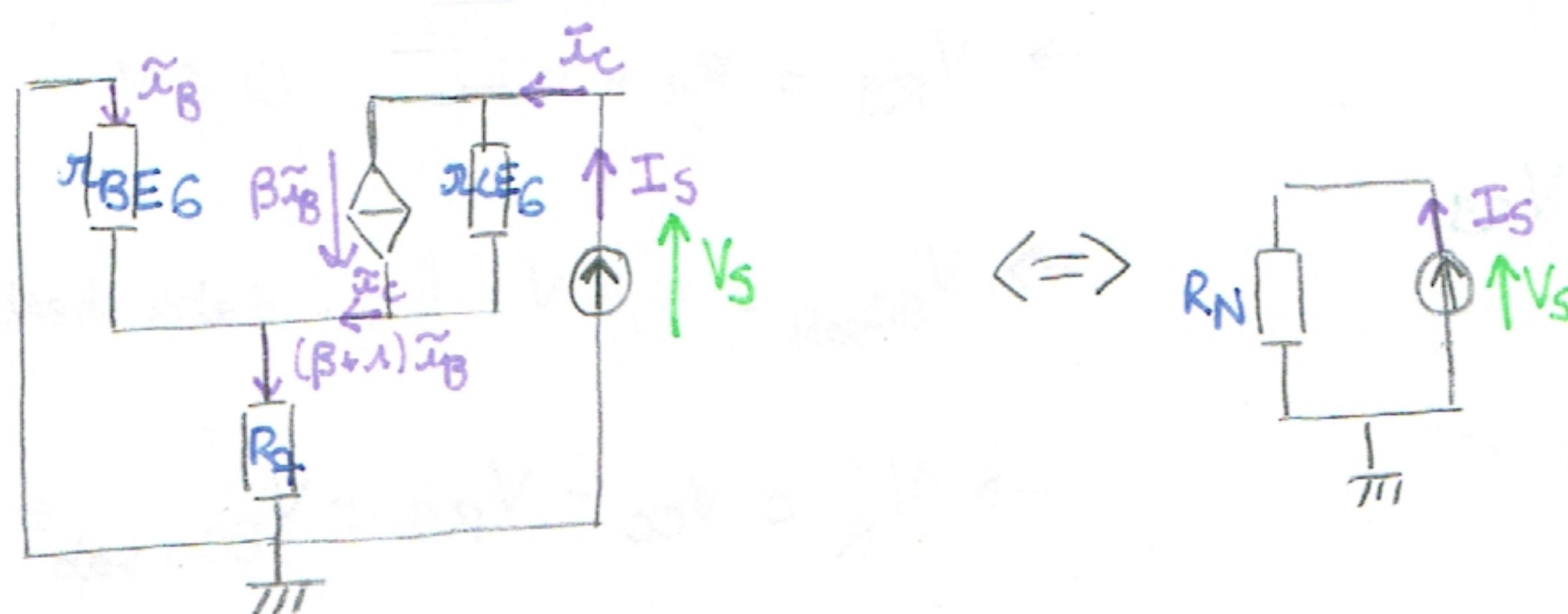
$$V_{th} = \frac{r_d V_{cc} + R_g V_{EC}}{r_d + R_g}$$



$$R_{th} = R_g \parallel r_d \parallel R_{10} + R_{V2} \approx r_d$$

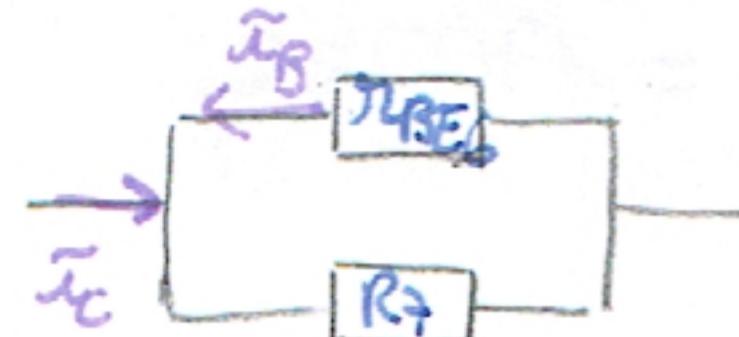
car  $r_d \ll (R_g, R_{10}, R_{V2})$ .

\* schéma équivalent dynamique (petit signaux) :



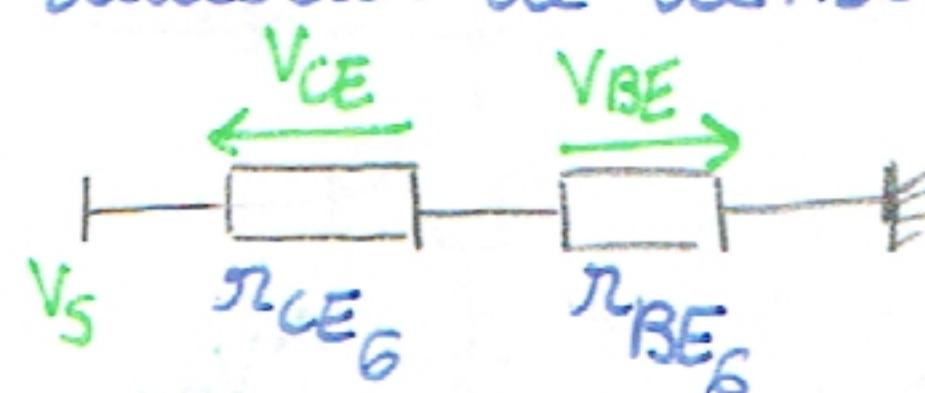
$$\text{determiner l'expression de } R_N = \frac{V_s}{I_s}.$$

→ point diviseur de courant entre  $r_{BE6}$  et  $R_7$  :



$$-\tilde{i}_B = \frac{R_7}{r_{BE6} + R_7} \tilde{i}_C \quad \textcircled{1}$$

→ point diviseur de tension entre  $r_{CE6}$  et  $r_{BE}$  :



$$V_s = V_{CE} - V_{BE} = \tilde{i}_{CE} r_{CE6} - \tilde{i}_B r_{BE6} \quad \text{or } \tilde{i}_{CE} = \tilde{i}_C - \beta \tilde{i}_B$$

$$\textcircled{1} \quad V_s = (\tilde{i}_C - \beta \tilde{i}_B) r_{CE6} - \tilde{i}_B r_{BE6}$$

$$= \tilde{i}_C r_{CE6} + \beta \frac{r_{CE6} R_7}{r_{BE6} + R_7} \tilde{i}_C + \frac{R_7}{r_{BE6} + R_7} \tilde{i}_C.$$

$$R_N = \frac{V_S}{I_C} = r_{CE6} \left[ 1 + \frac{\beta R_7}{r_{BE6} + R_7} \right] + \frac{R_7 r_{BE6}}{R_7 + r_{BE6}}$$

\* application numérique :

$$\rightarrow r_{CE6} = \frac{V_{early}}{I_0} = \frac{50}{4 \cdot 10^{-3}} = 12\,500 \Omega .$$

$$\rightarrow r_{BE6} = \frac{U_T}{I_{SO}} = \frac{U_T}{I_0/\beta} = \frac{25 \cdot 10^{-3} \times 100}{4 \cdot 10^{-3}} = 625 \Omega .$$

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

$$R_N = 254,6 \text{ k}\Omega .$$