La science quantique

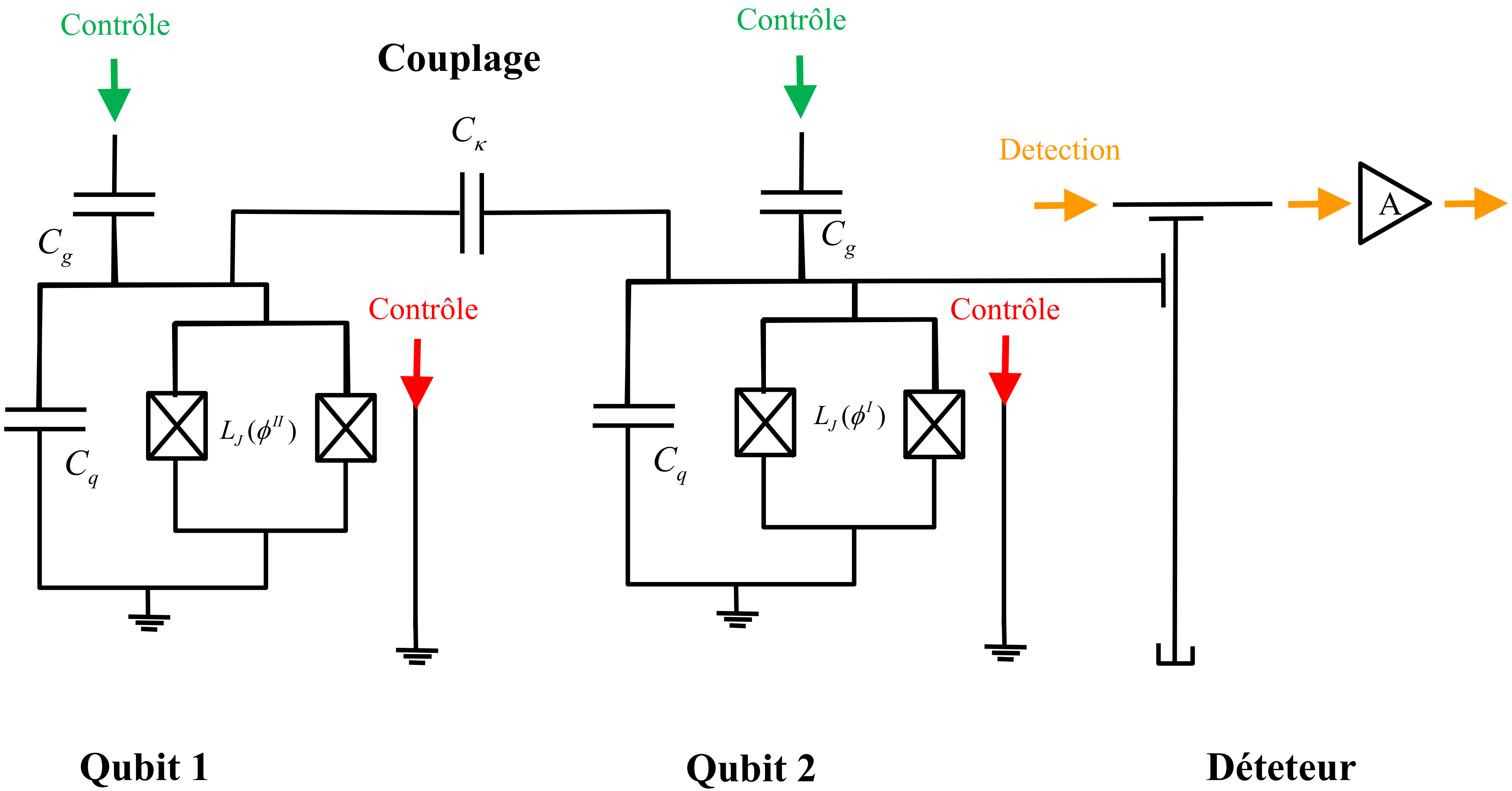
Une vision singulière

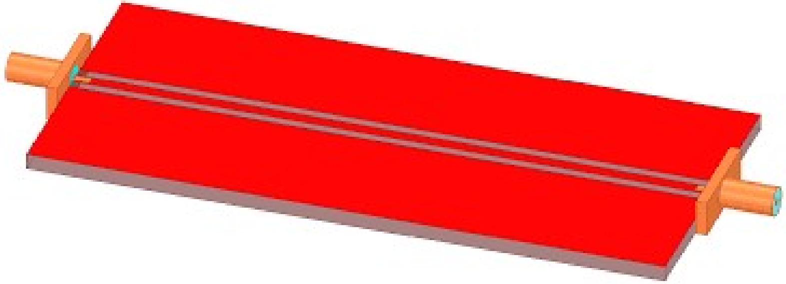
XIII) superconducting qubits

P.A. Besse

PAB

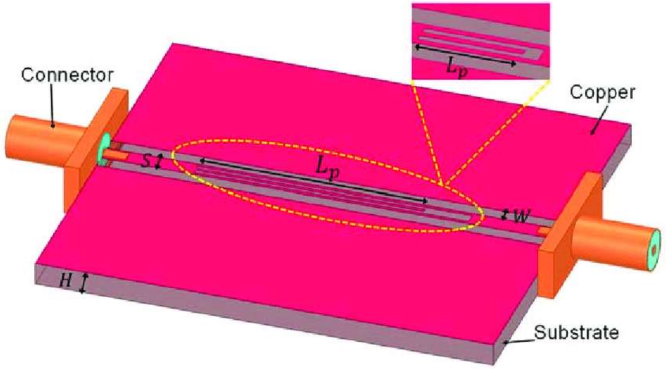
Schéma global: paire de qubits couplés





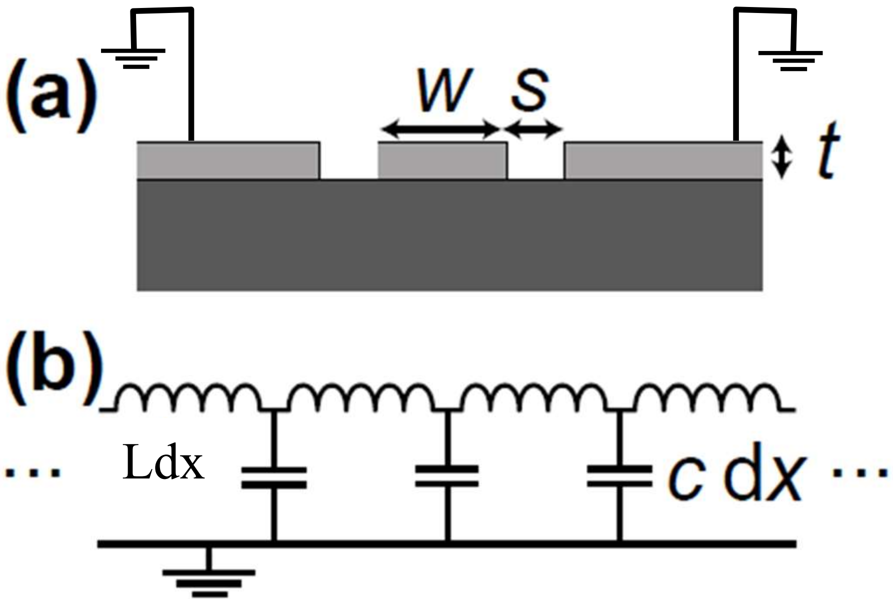
Guide d'onde coplanaire et

Résonateur harmonique LC

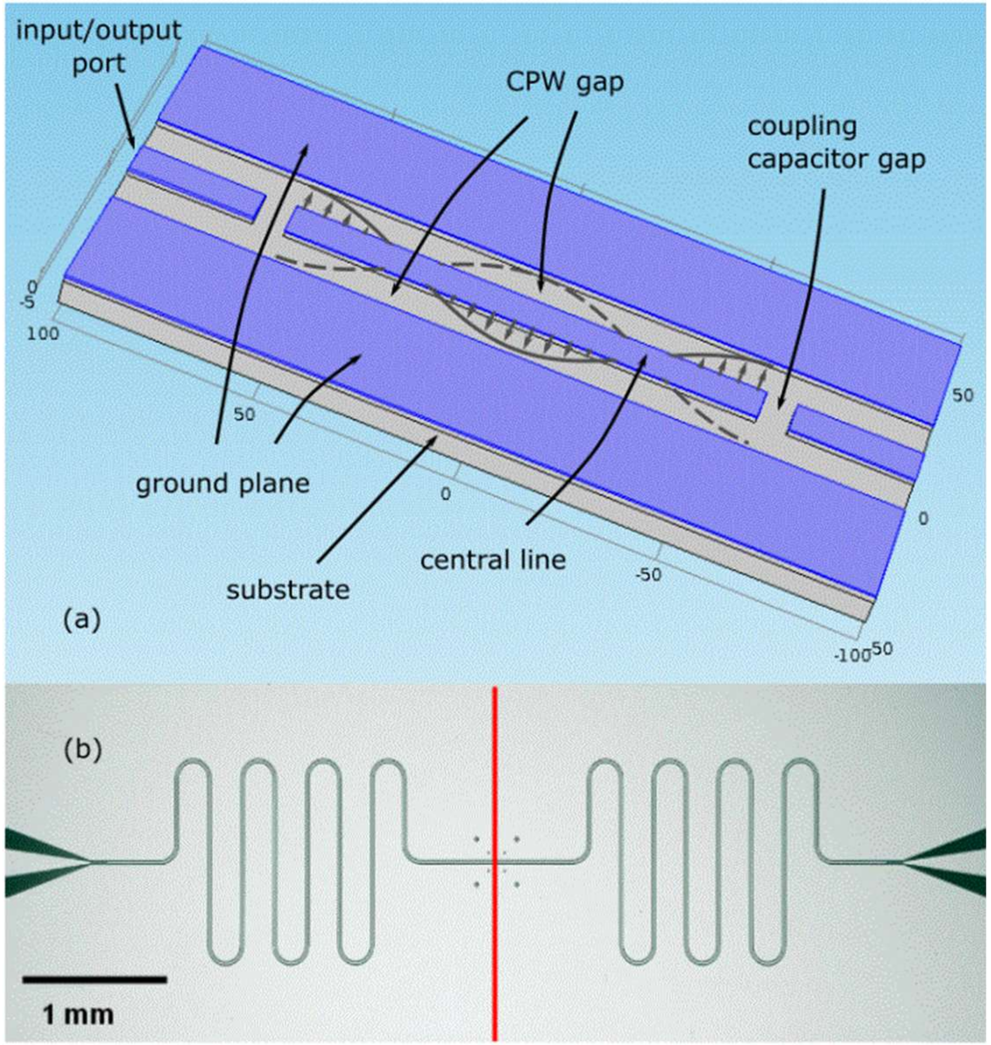


Coplanar Waveguide (CPW) Resonator

Similaire aux câbles coaxiaux:
Résonateur LC «distribué»

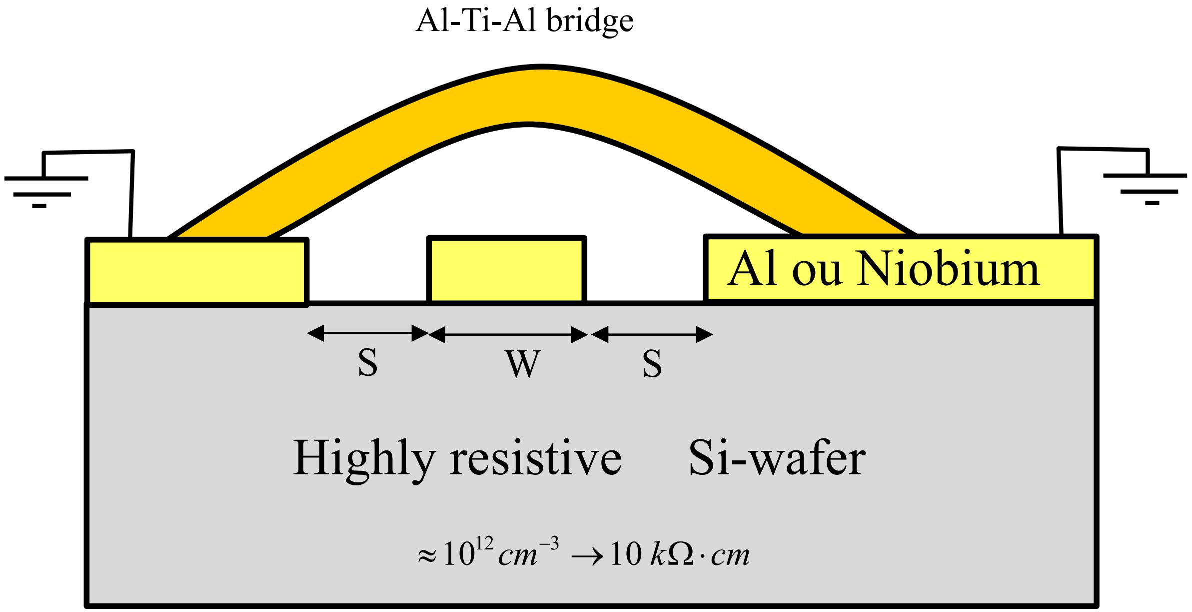


J.C Besse, ETH Thesis 27386



https://qudev.phys.ethz.ch/static/content/science/Documents/semester/Junxin_Chen_SemesterThesis_150318.pdf

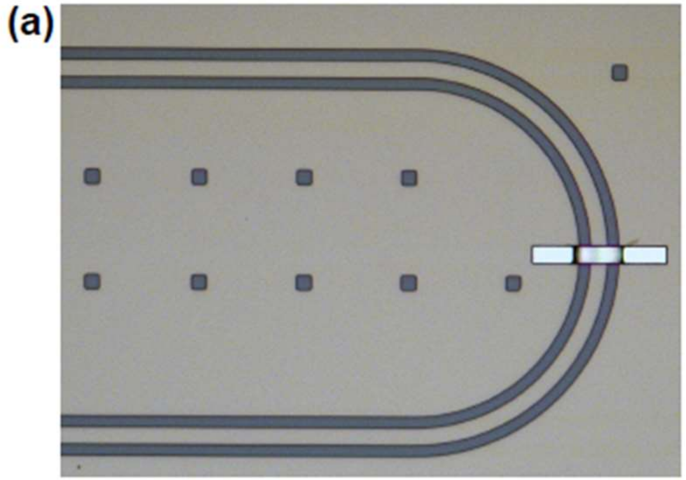
Coplanar Waveguide (CPW) Resonator



T<100mK

W=10um, S=5um

«câble coaxial»



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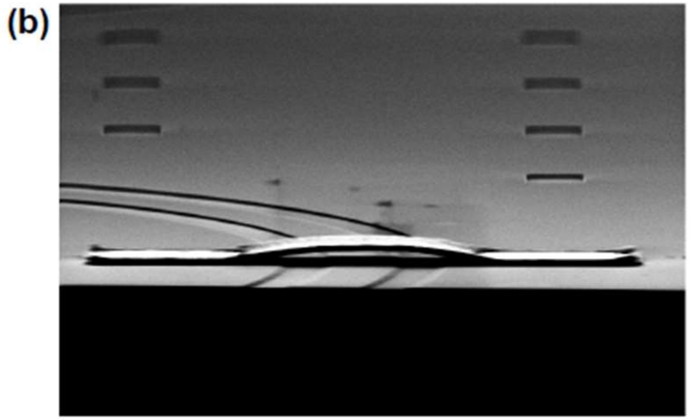

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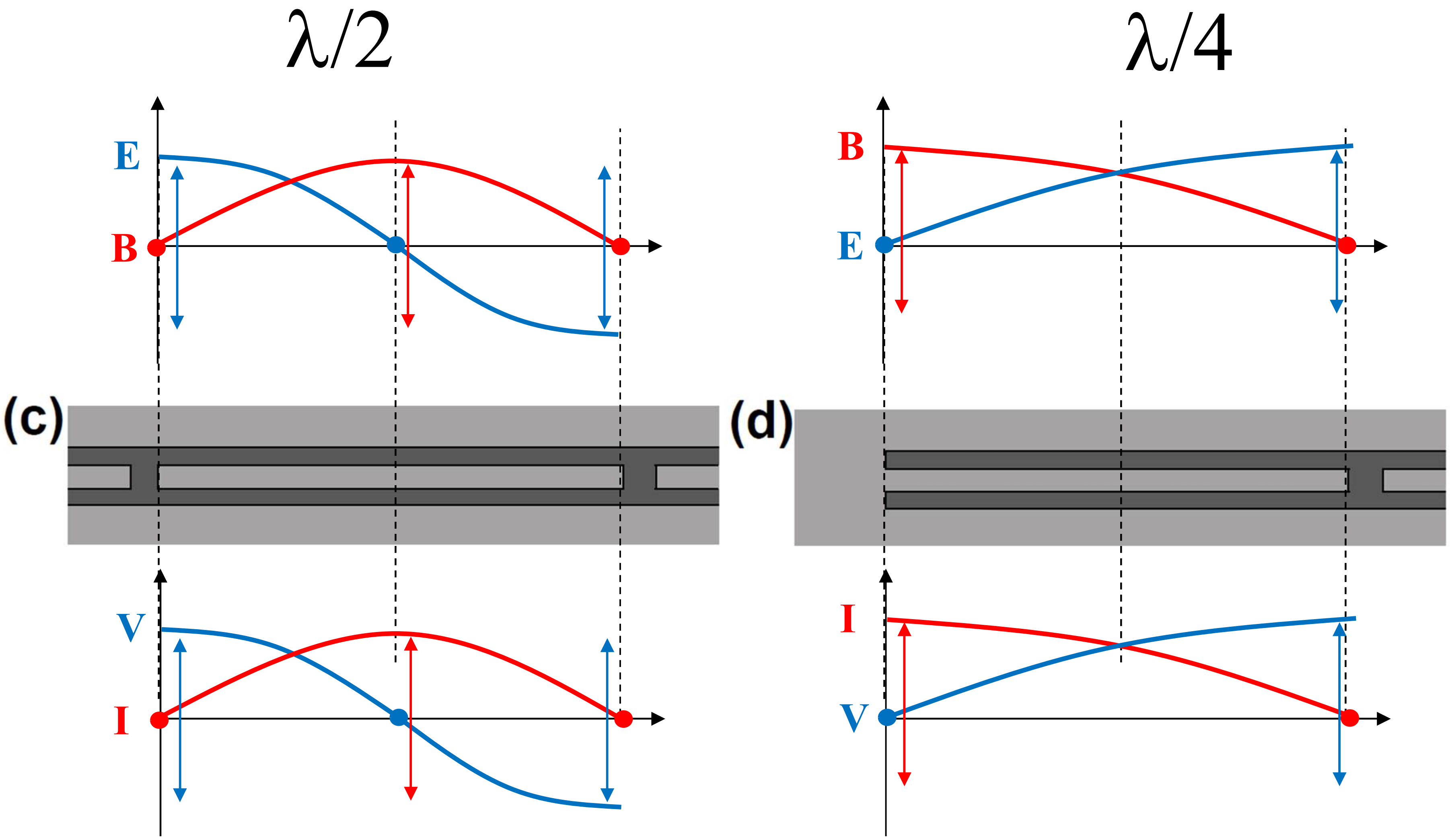
Résonateur



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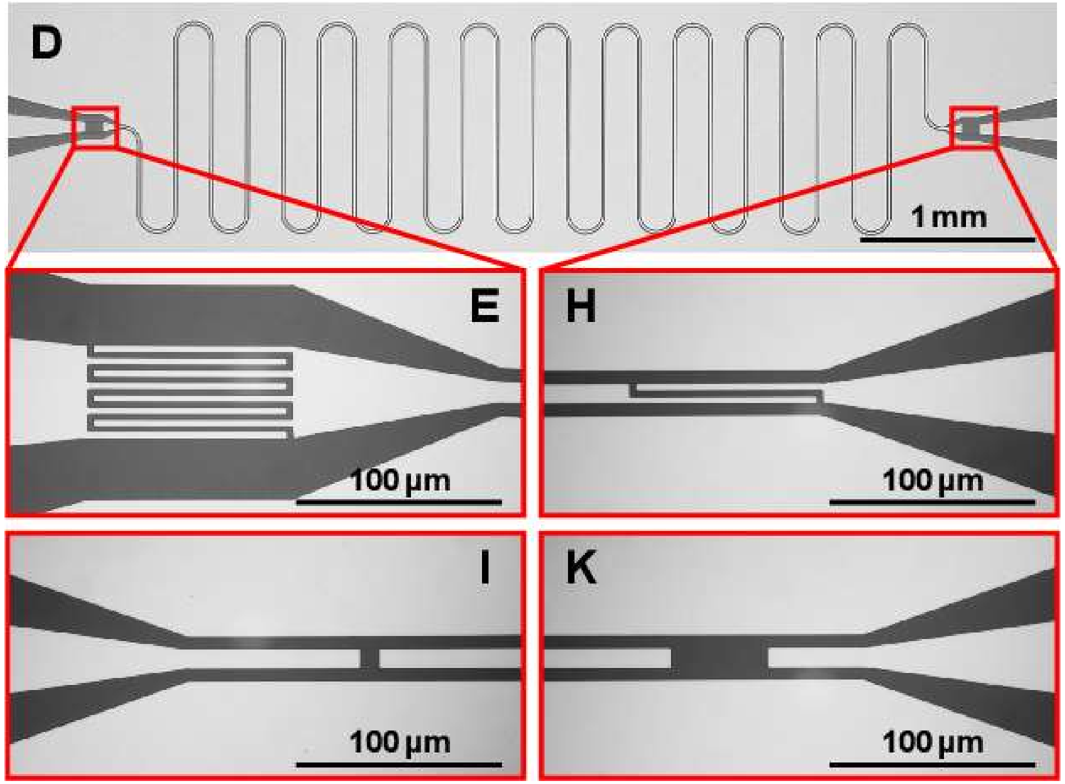
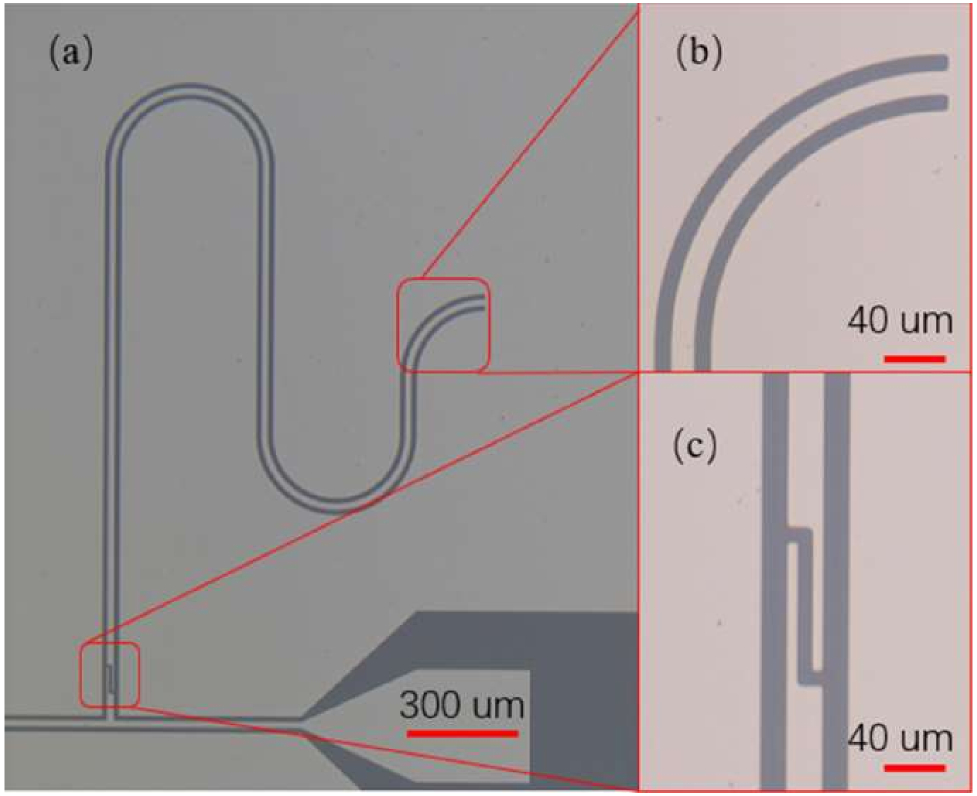
Coplanar waveguide resonator



Goppl, M. et al. "Coplanar waveguide resonators for circuit quantum electrodynamics." Journal of Applied Physics 104 (2008): 113904.

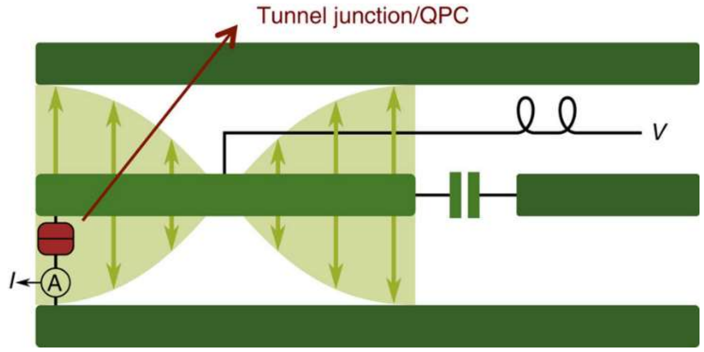


https://link.springer.com/article/10.1007/s42452-022-04956-7

PAB

Coplanar waveguide resonator

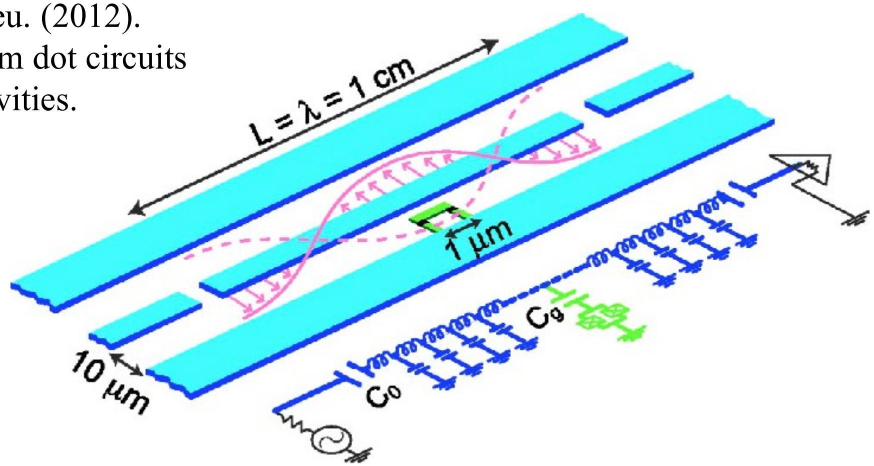
λ/2 wave



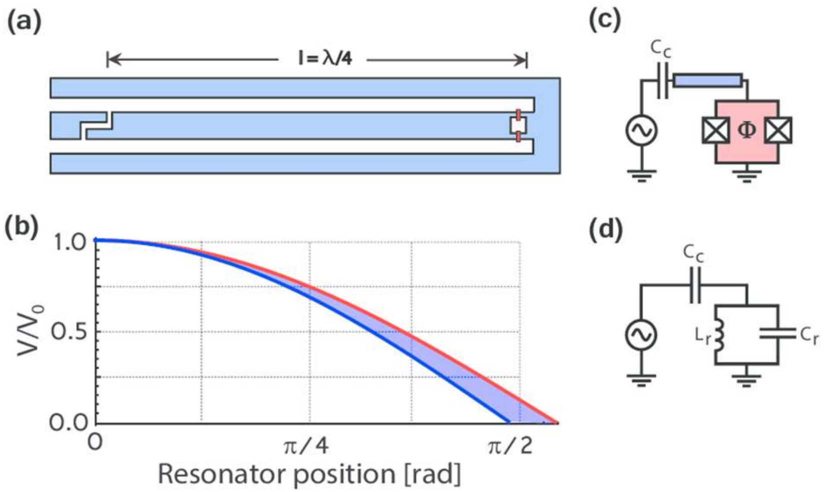
Souquet J.R. et al.. (2014). Photon-assisted tunneling with non-classical light. Nature communications. 5. 10.1038/ncomms6562.

λ wave

Delbecq, Matthieu. (2012). Coupling quantum dot circuits to microwave cavities.

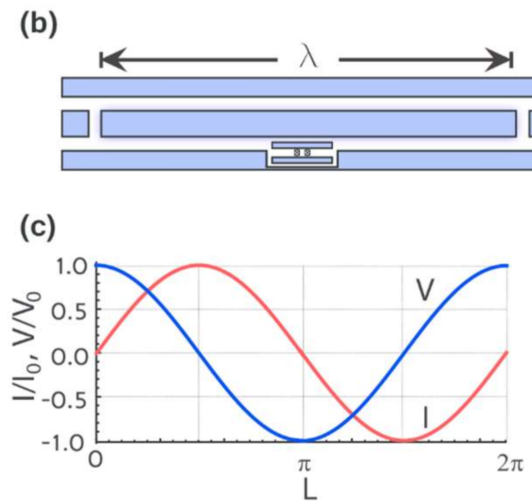


λ/4 wave



λ wave

Krantz, Philip. (2013). Parametrically pumped superconducting circuits. 10.13140/RG.2.1.1071.3041.



Harmonic oscillator

Hamiltonien:

$$H = \frac{1}{2C}\cdot Q^2 + \frac{1}{2L}\cdot \phi^2 = \hbar\omega\cdot\left(a^+a^- + \frac{1}{2}\right)$$

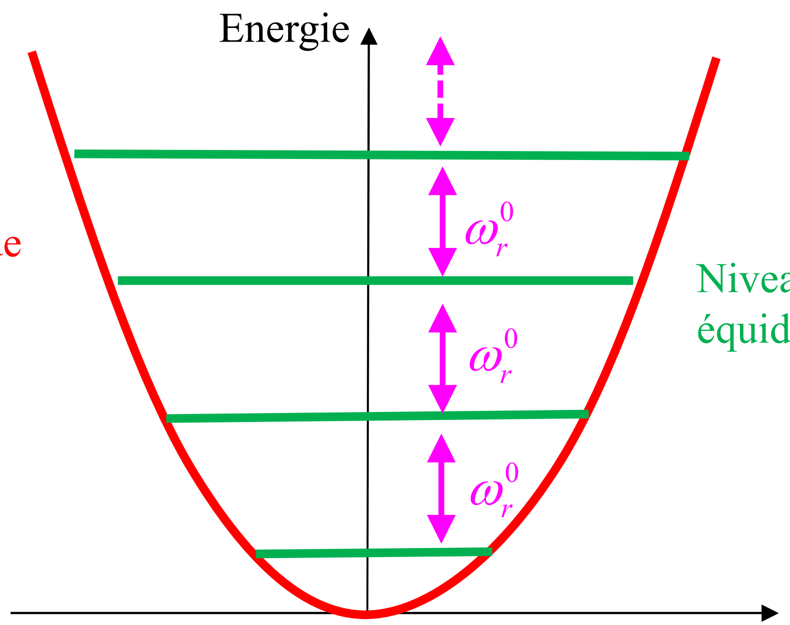
$$\omega_r \equiv \frac{1}{\sqrt{LC}}$$

Energie capacitive

Energie inductive

Oscillateur Harmonique LC

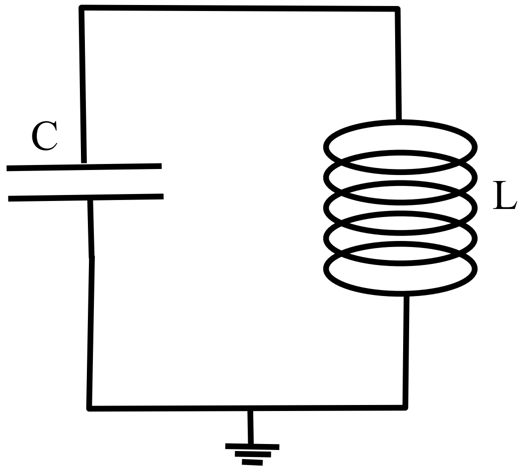
Potentiel quadratique



Niveaux équidistants

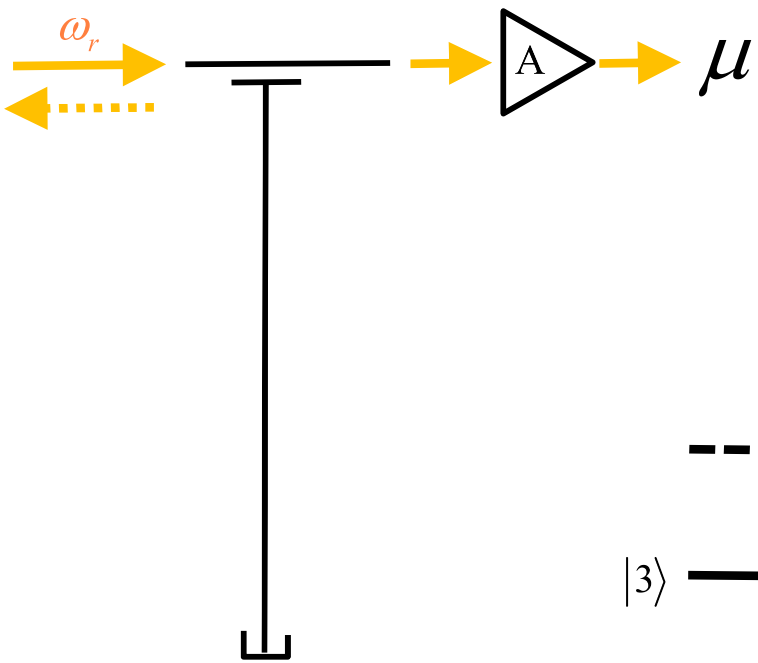
$$\phi = \frac{\hbar}{2q}\varphi$$

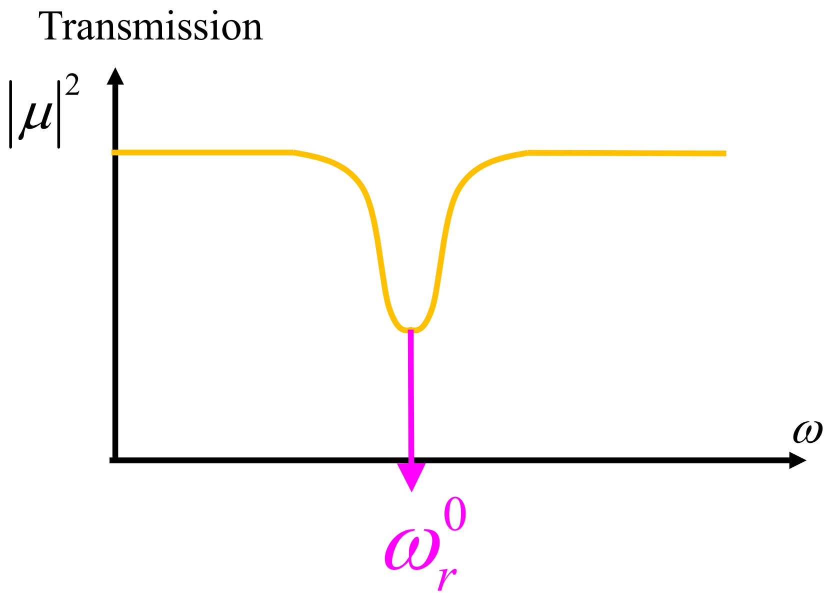
Flux (Berry phase)

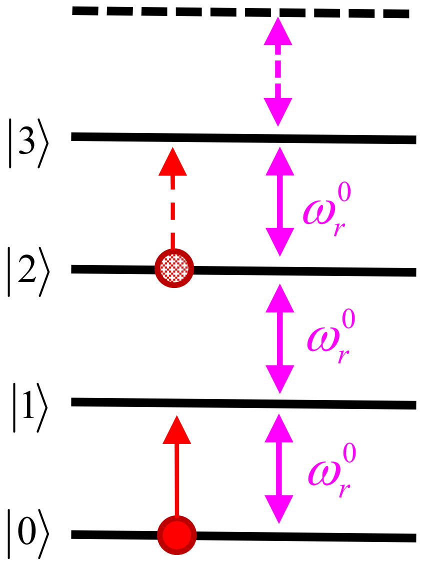


Résonateur harmonique

Resonator







Harmonic spectrum

Toutes les transitions sont aléatoirement possibles

- **Utilisé en sortie comme détecteur**
- **Autre device nécessaire comme qubit**

Jonctions de Josephson

et

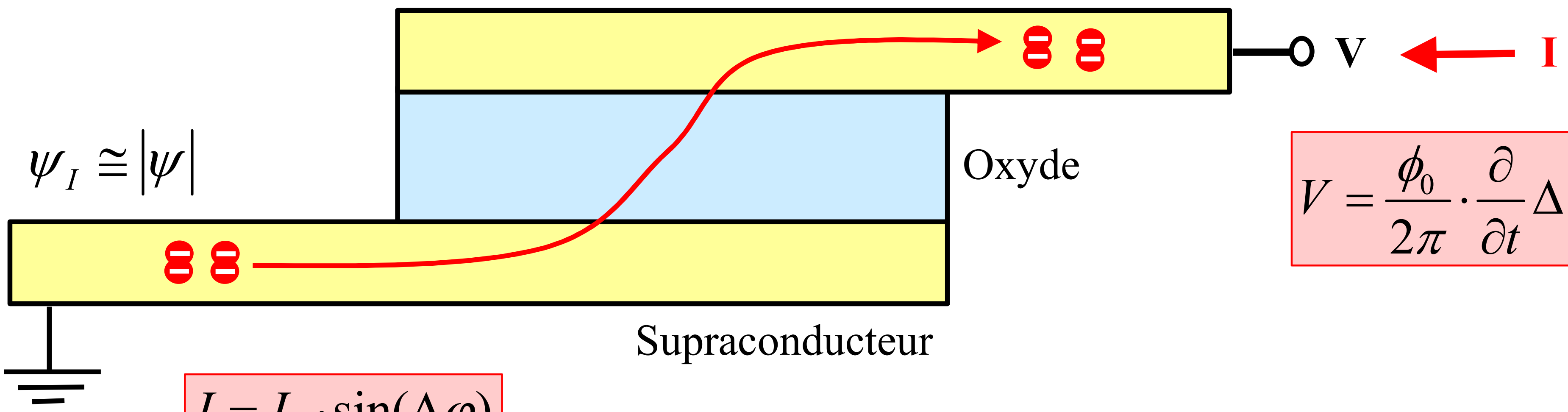
squids

Jonction de Josephson: résumé

Effet tunnel pour des paires de Cooper à des températures de mK.

$$\psi_{II} \cong |\psi| \cdot e^{i\Delta\varphi}$$

$$\psi_I \cong |\psi|$$



$$V = \frac{\phi_0}{2\pi} \cdot \frac{\partial}{\partial t} \Delta\varphi$$

$$I = I_0 \cdot \sin(\Delta\varphi)$$

$$I_0 \equiv 4\pi \frac{T}{\phi_0} |\psi|^2$$

$$\frac{1}{L_J} = \frac{1}{L_0} \cdot |\cos(\Delta\varphi)|$$

$$E_J = \frac{1}{2\pi} \cdot I_0 \phi_0 \cdot (1 - \cos(\Delta\varphi))$$

Quantum Flux

$$\phi_0 \equiv \frac{h}{2q}$$

$$\frac{1}{L_0} \equiv 2\pi \frac{I_0}{\phi_0}$$

Hamiltonien «inductif» d'une jonction de Josephson

anharmonicité

Pour une jonction de Josephson:

$$H_J \equiv E_J = \frac{1}{2\pi} I_0 \phi_0 \left(1 - \cos(\Delta\varphi)\right) \cong \frac{1}{2}\frac{1}{L_0} \cdot \left(\frac{\phi_0}{2\pi}\right)^2 \Delta\varphi^2 - O\left(\Delta\varphi^4\right)$$

Pour une bobine inductive supraconductrice:

Flux magnétique

$$H_J = \frac{1}{2}\frac{1}{L} \cdot \phi^2 = \frac{1}{2}\frac{1}{L} \cdot \left(\frac{\phi_0}{2\pi}\right)^2 \Delta\varphi^2$$

Phase de Berry:

$$\Delta\varphi = \frac{(2q)}{\hbar} \cdot \oint \vec{A} \cdot d\vec{l} = 2\pi \cdot \frac{\phi}{\phi_0}$$

Résonateur anharmonique

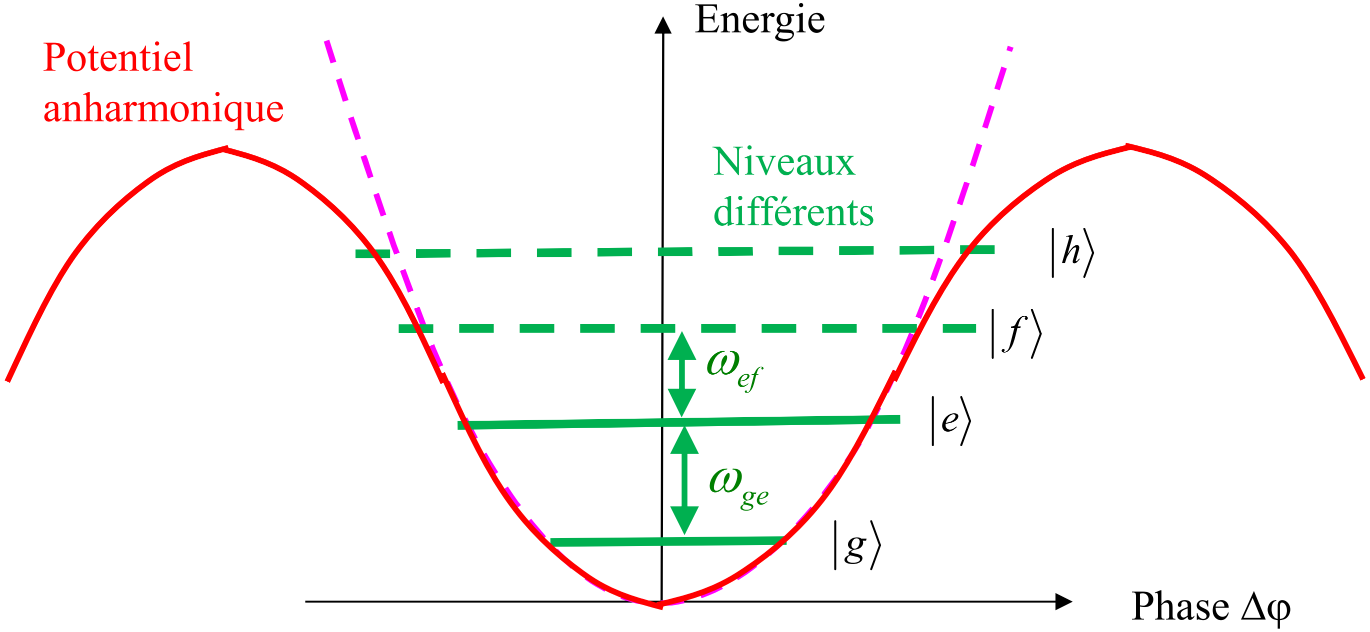
Energie cinétique

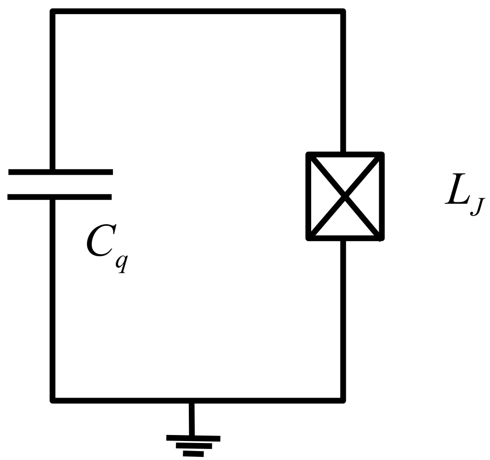
Energie potentielle

fixe

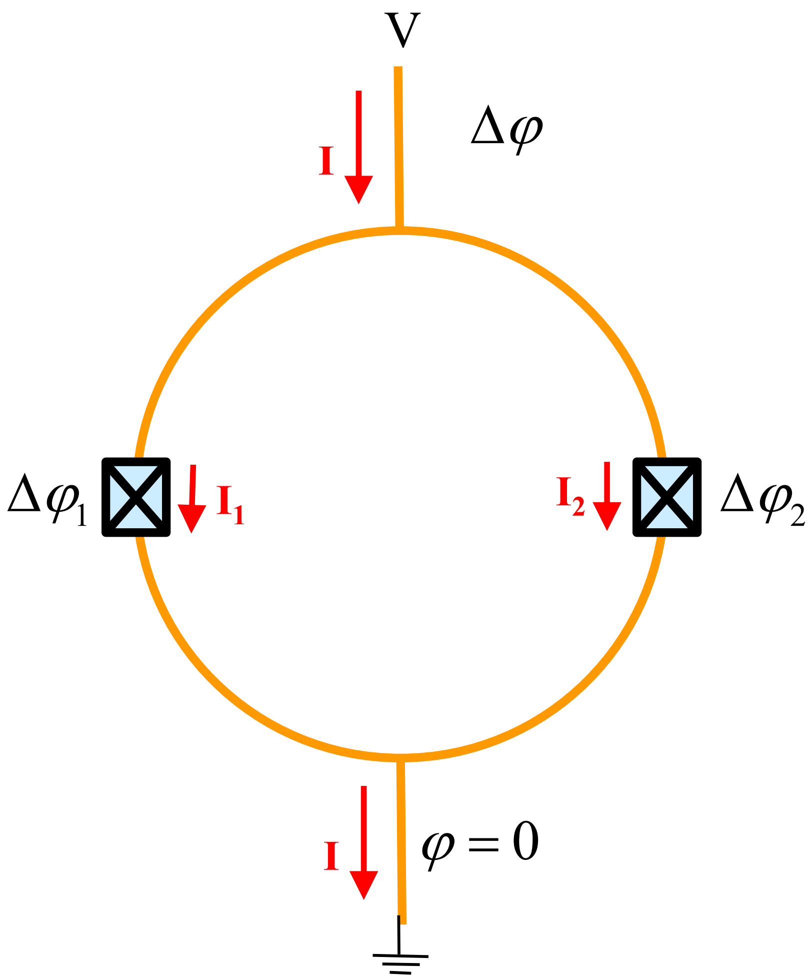
anharmonicité

$$H = \frac{1}{2C_q} \cdot Q^2 + \frac{1}{2\pi} I_0 \phi_0 \cdot (1 - \cos(\Delta\varphi)) \cong \frac{1}{2C_q} \cdot Q^2 + \frac{\phi_0}{4\pi} \cdot I_0 \cdot \Delta\varphi^2 - O\left(\Delta\varphi^4\right)$$





Squid sans champ magnétique: deux jonctions de Josephson en parallèle



Phases

$$\Delta\varphi_1 = \Delta\varphi_2 = \Delta\varphi$$

Courants

$$I_1 = I_2$$

$$I = 2I_0 \cdot \sin(\Delta\varphi)$$

Inductance

$$\frac{1}{L_J} = \frac{1}{L_0} \cdot \left|\cos(\Delta\varphi)\right|$$

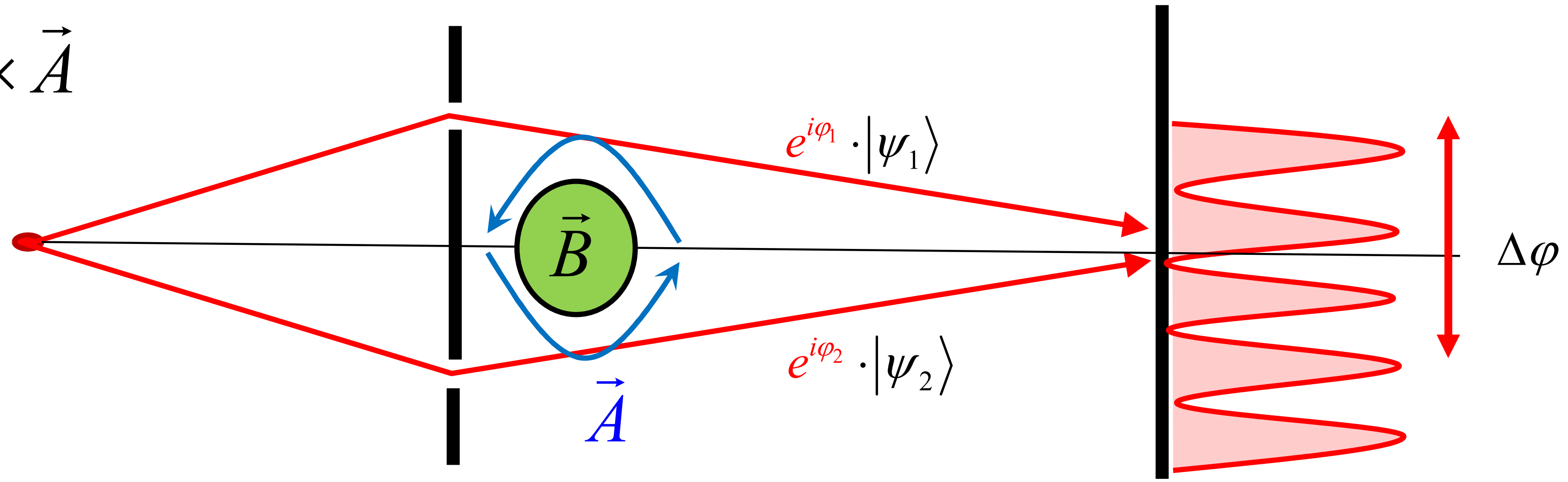
$$\frac{1}{L_0} \equiv 2\pi \frac{2I_0}{\phi_0}$$

Energie

$$E_J = \frac{1}{2\pi} \cdot 2I_0 \cdot \phi_0 \cdot \left(1 - \cos(\Delta\varphi)\right)$$

Rappel: Effet Aharonov-Bohm

$$\vec{B} = \vec{\nabla} \times \vec{A}$$



Hamiltonien:

$$H = \frac{1}{2m_e}\left(\frac{\hbar}{i}\vec{\nabla} - q\vec{A}\right)^2$$

Modes propres: $e^{i\varphi_1} \cdot |\psi_1\rangle$ $e^{i\varphi_2} \cdot |\psi_2\rangle$

Phase de Berry $\varphi = \frac{q}{\hbar} \cdot \int_0^x \vec{A} \cdot d\vec{l}$

$$\Delta\varphi \equiv \varphi_1 - \varphi_2 = \frac{q}{\hbar} \cdot \oint \vec{A} \cdot d\vec{l} = \frac{q}{\hbar} \cdot \iint \vec{B} \cdot d\vec{S} = 2\pi \cdot \frac{q}{h} \cdot \phi_{mag}$$

Squid avec champ magnétique

$$\sin(x-y)+\sin(x+y)=2\cos(y)\cdot\sin(x)$$

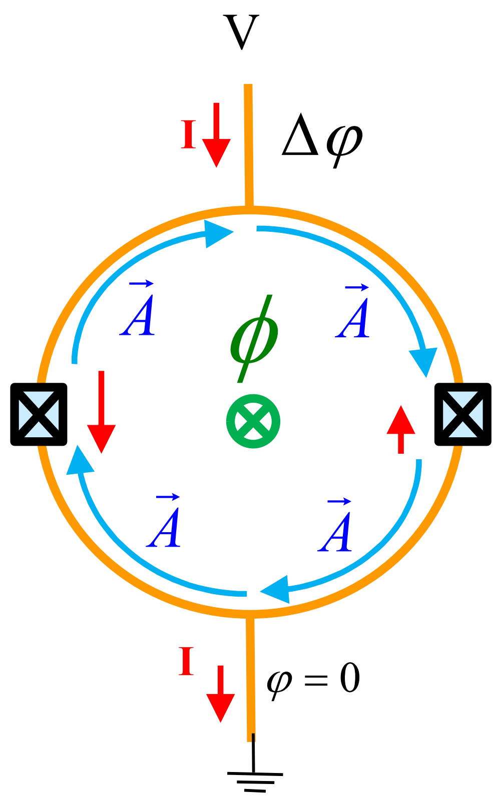
$$I=\widetilde{I}_0(\phi)\cdot\sin\left(\Delta\varphi\right)$$

$$V=\frac{\phi_0}{2\pi}\cdot\frac{\partial}{\partial t}\Delta\varphi$$

$$\frac{1}{L_J}=\frac{1}{L_0}\cdot\left|\cos(\Delta\varphi)\right| \qquad \frac{1}{L_0}\equiv 2\pi\cdot\frac{\widetilde{I}_0(\phi)}{\phi_0}$$

$$I_1=I_0\cdot\sin\left(\Delta\varphi_1\right)$$

$$\Delta\varphi_1=\Delta\varphi-\pi\cdot\frac{\phi}{\phi_0}$$



$$I_2=I_0\cdot\sin\left(\Delta\varphi_2\right)$$

$$\Delta\varphi_2=\Delta\varphi+\pi\cdot\frac{\phi}{\phi_0}$$

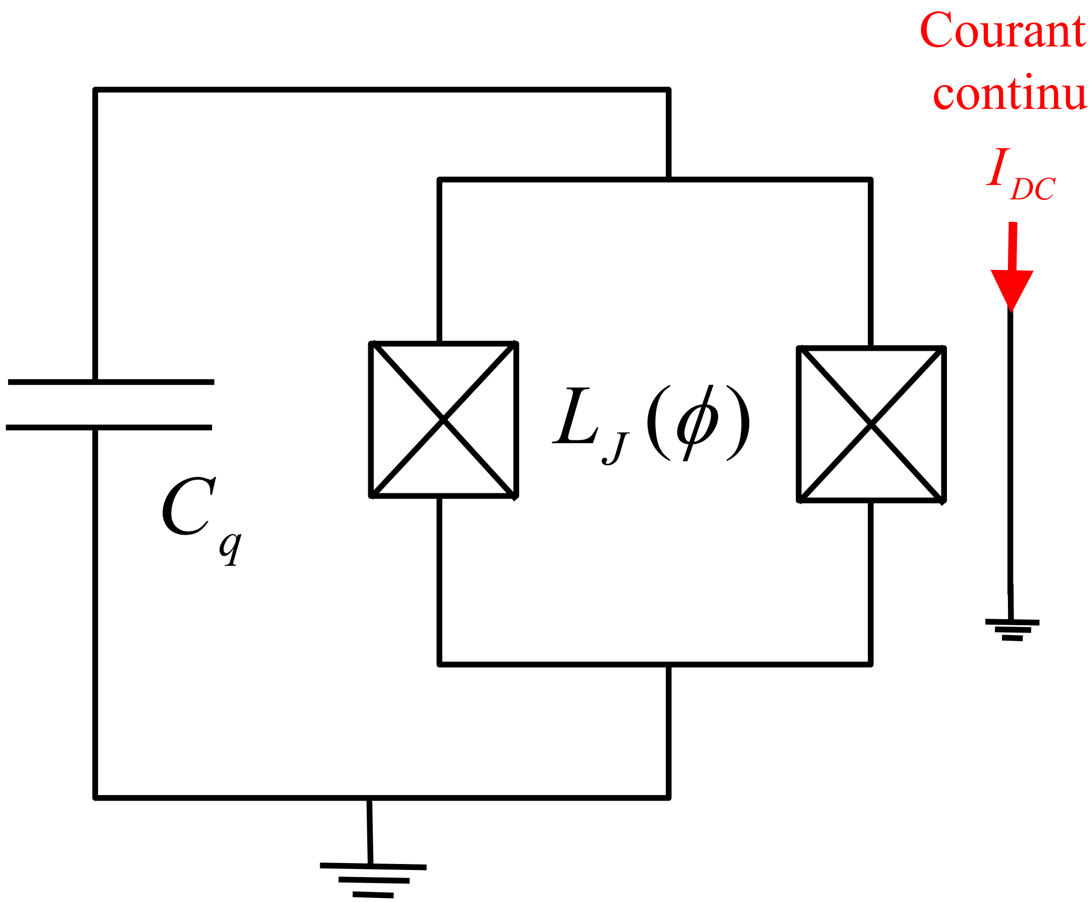
$$E_J(\phi,\varphi)=\frac{1}{2\pi}\cdot\widetilde{I}_o(\phi)\cdot\phi_0\cdot\left(1-\cos(\Delta\varphi)\right)\cong\frac{1}{4\pi}\cdot\widetilde{I}_o(\phi)\cdot\phi_0\cdot\Delta\varphi^2$$

contrôlable

$$\widetilde{I}_0(\phi)=2I_0\cos\left(\pi\cdot\frac{\phi}{\phi_0}\right)$$

Résonateur anharmonique:
Qubit supraconducteur

Résonateur anharmonique: Principe



$$\frac{1}{L_J(\Delta\varphi,\phi)} \equiv \frac{1}{L_0(\phi)} \cdot \left|\cos(\Delta\varphi)\right|$$

$$\frac{1}{L_0(\phi)} \equiv 2\pi \frac{\tilde{I}_0(\phi)}{\phi_0}$$

Fréquence

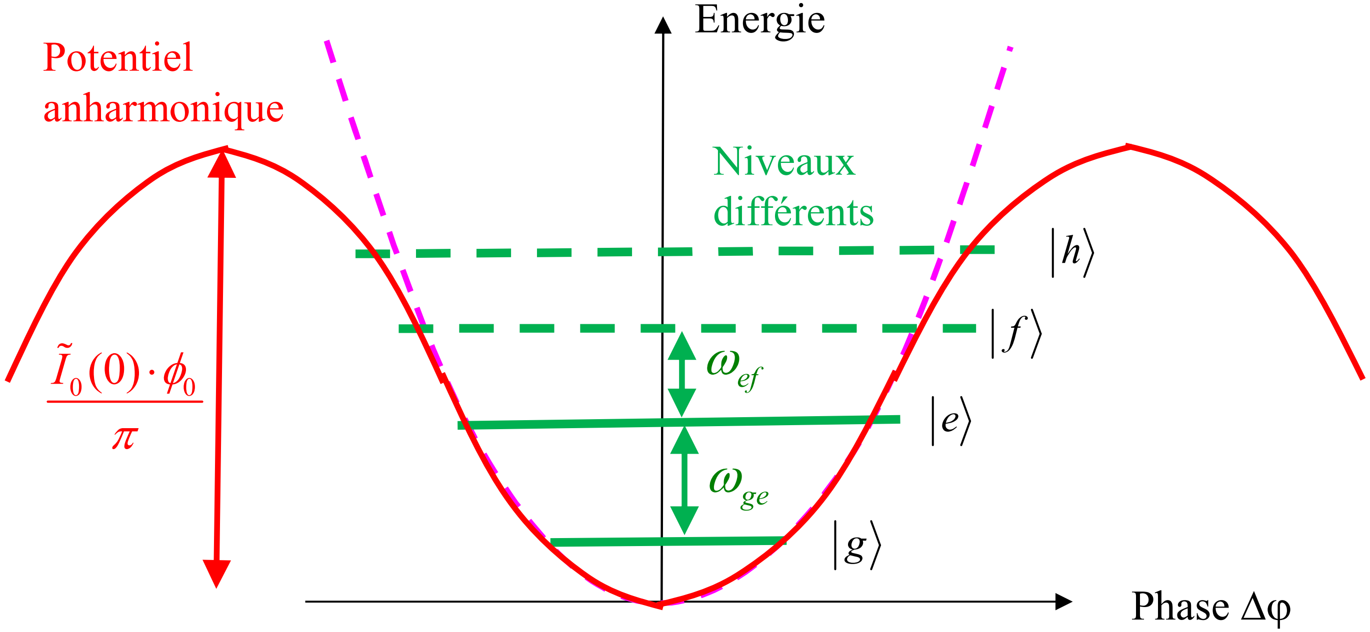
$$\omega_q(\phi) \equiv \frac{1}{\sqrt{L_0(\phi)C_q}} \approx \sqrt{\left|\cos\left(\pi \cdot \frac{\phi}{\phi_0}\right)\right|}$$

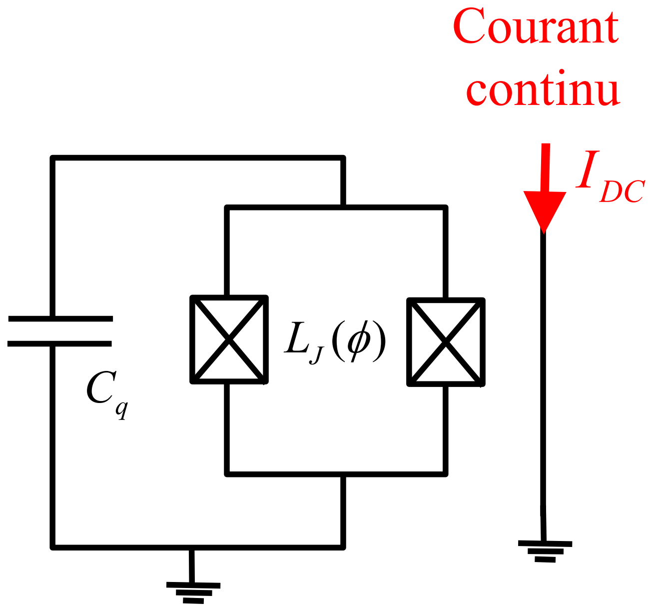
Résonateur anharmonique: étude

Energie cinétique

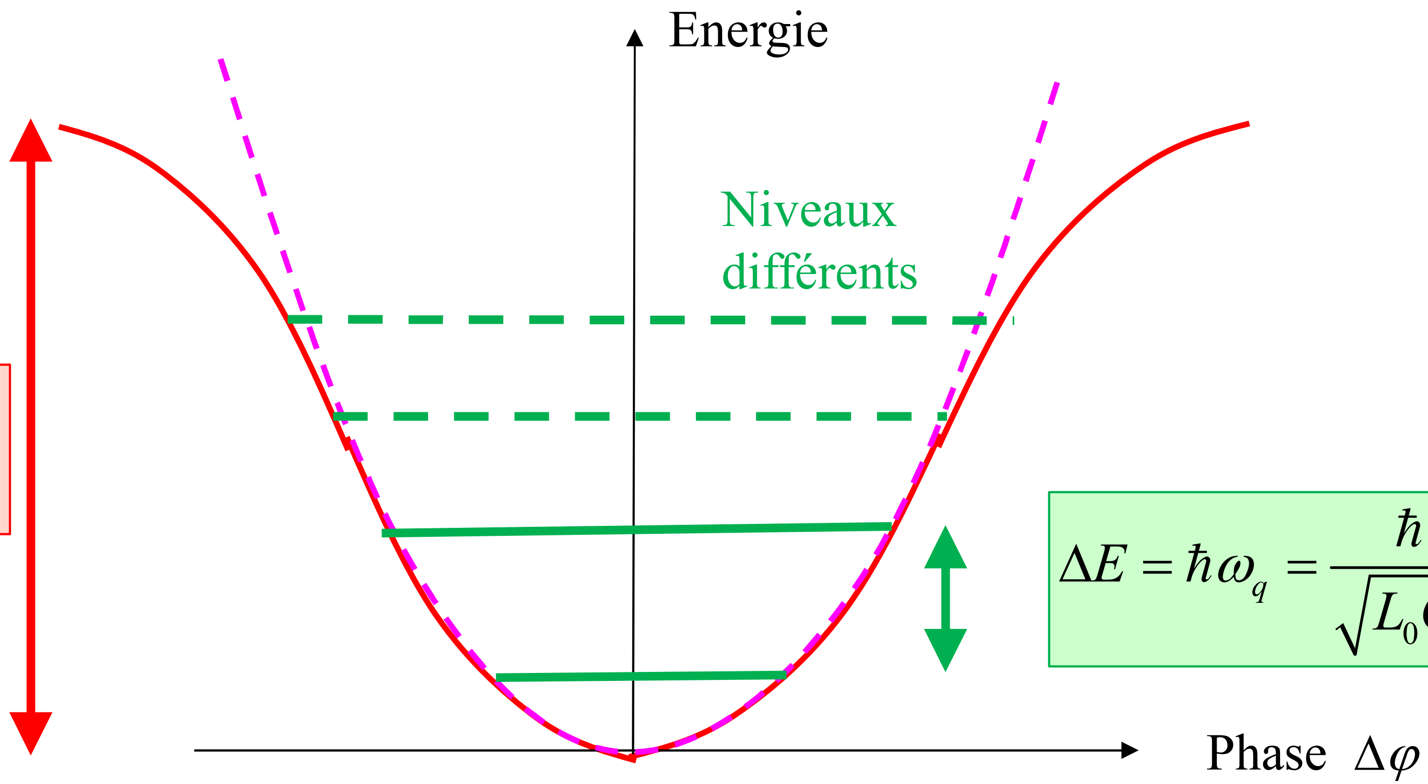
Energie potentielle

$$H = \frac{1}{2C_q} \cdot Q^2 + \frac{\widetilde{I_0}(\phi) \cdot \phi_0}{\pi} \cdot \frac{(1 - \cos(\Delta\varphi))}{2} \cong \frac{1}{2C_q} \cdot Q^2 + \left(\frac{\phi_0}{4\pi} \cdot \widetilde{I_0}(\phi) \right) \cdot \Delta\varphi^2 - O\left(\Delta\varphi^4\right)$$





Design des transmons avec squid



$$\frac{\tilde{I}_0(0)\cdot\phi_0}{\pi} = \frac{\phi_0^2}{2\pi^2 L_0} = N\cdot\Delta E$$

$$\Delta E = \hbar\omega_q = \frac{\hbar}{\sqrt{L_0 C_q}}$$

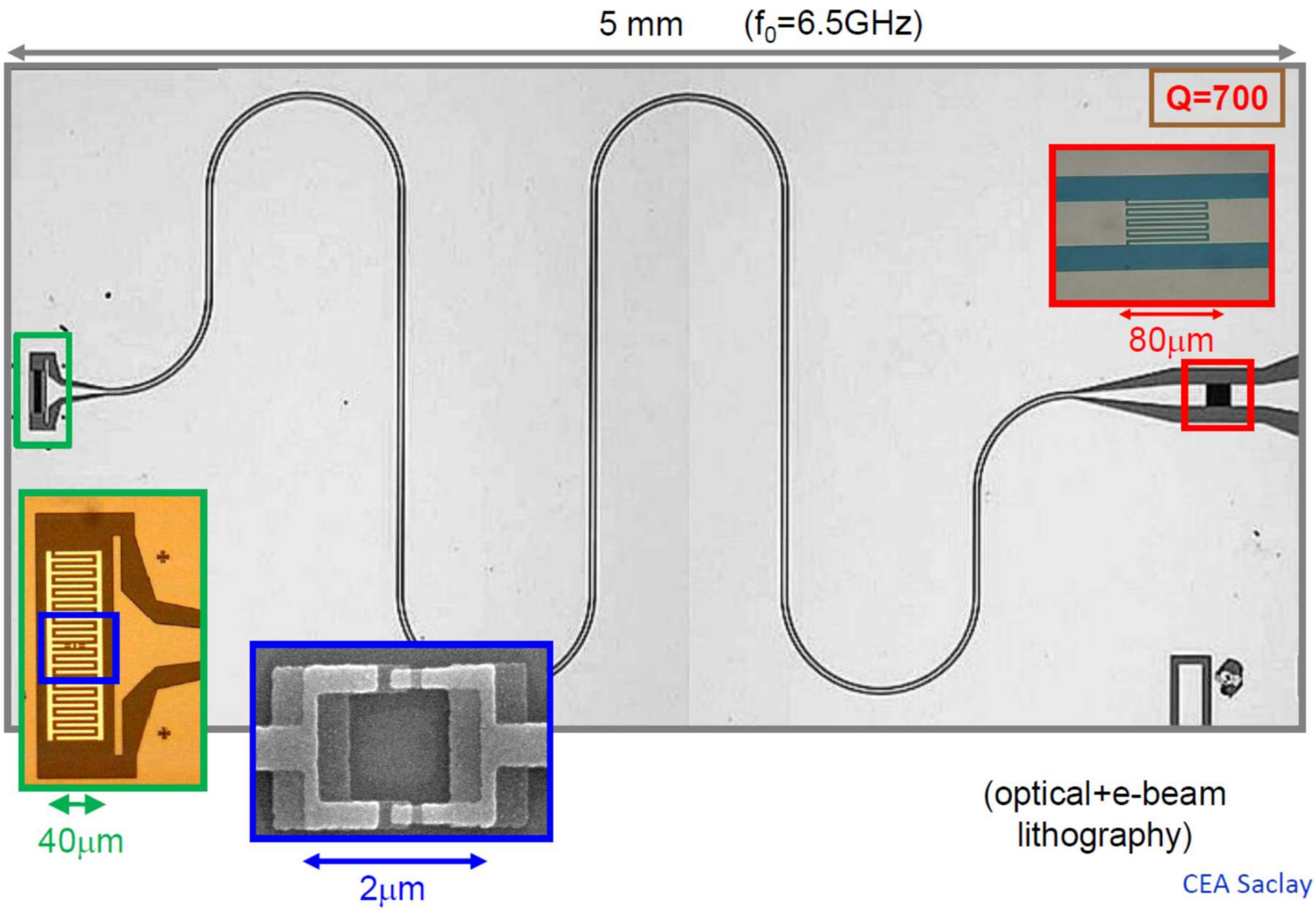
Choisir: $\dfrac{\omega_q}{2\pi} \cong 7\ GHz$, $N = 10$

$$L_0 \cong \frac{\phi_0^2}{2\pi^2\cdot N\cdot\hbar\omega_q} \cong 5\ nH$$

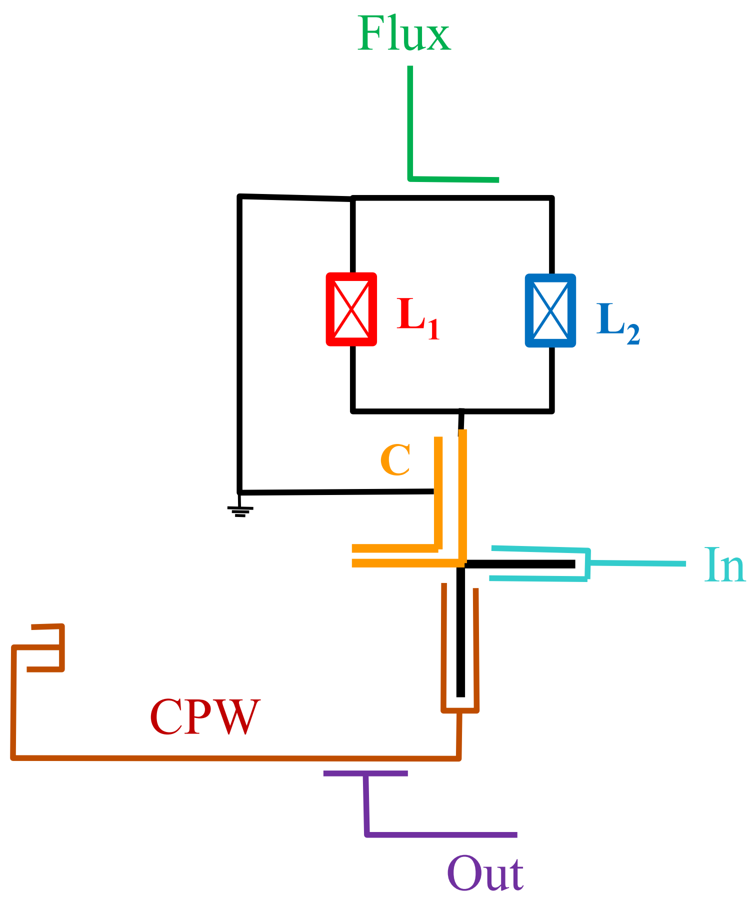
et

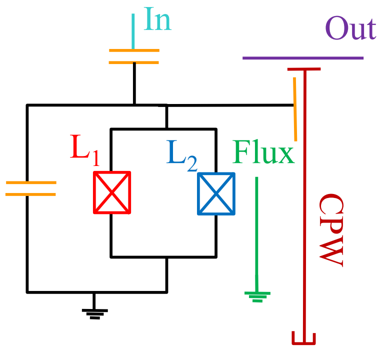
$$C_q \cong \frac{1}{L_0\cdot\omega_q^2} \cong 100\ fF$$

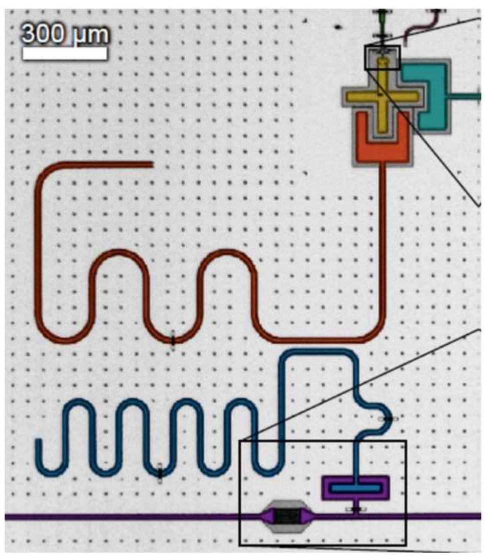
Exemples de transmons

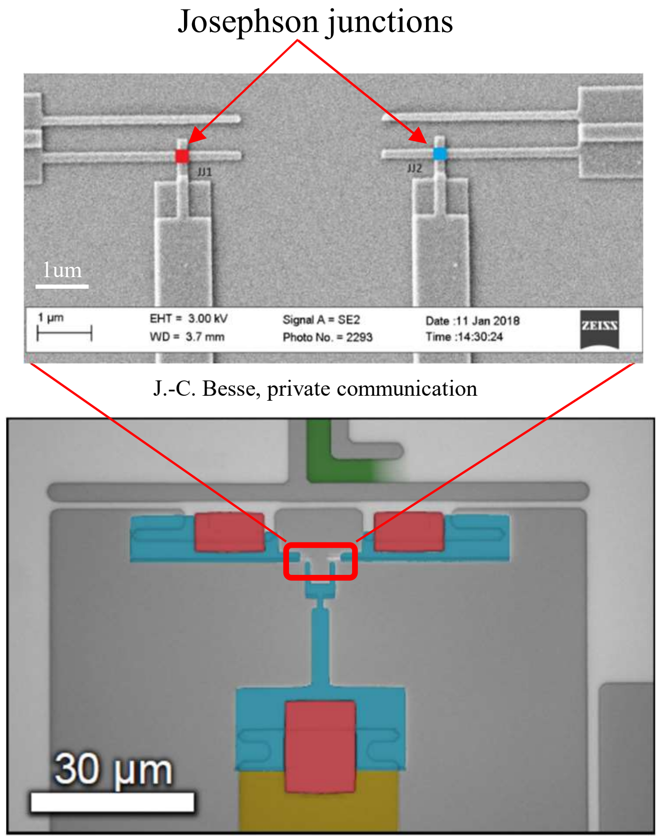


Exemples de transmons









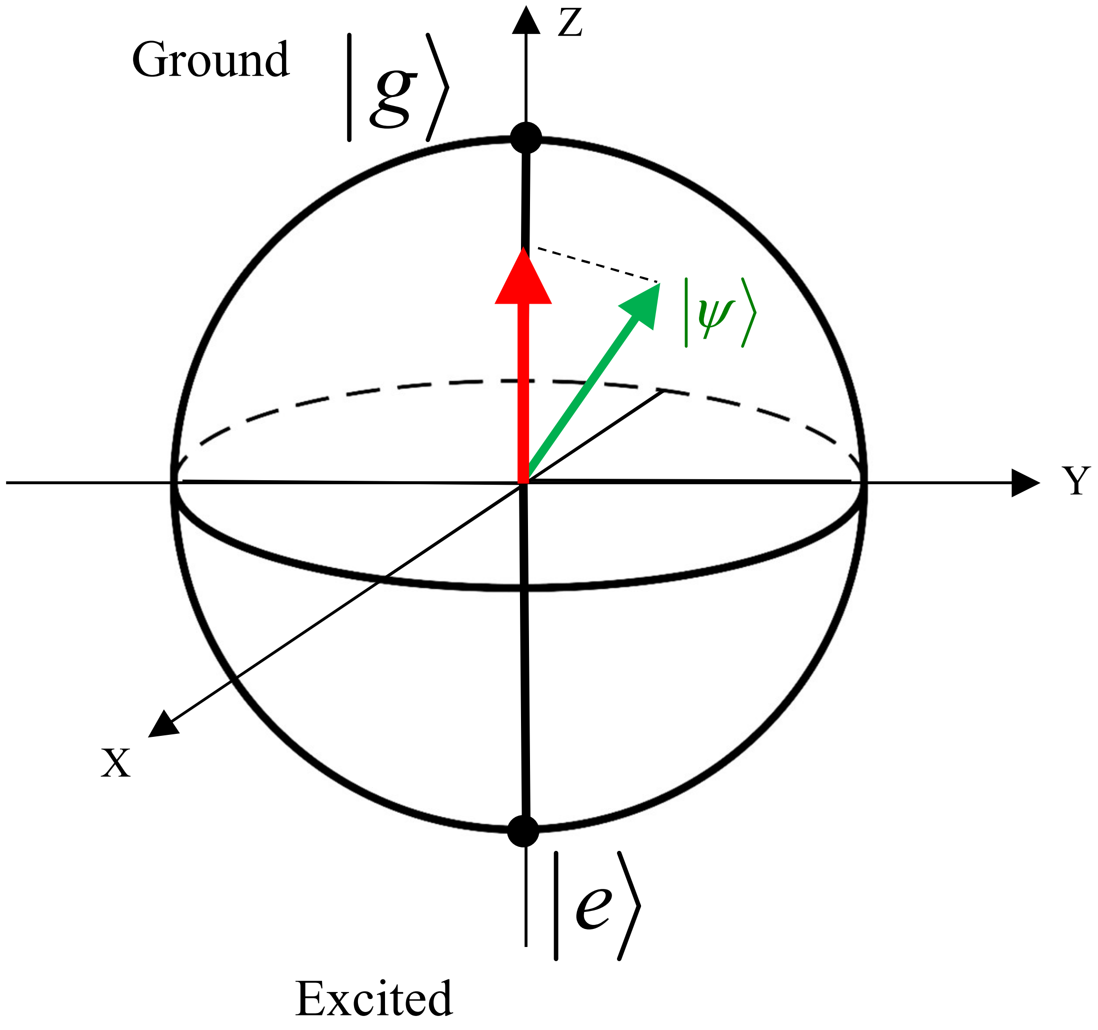
https://www.nature.com/articles/s41534-019-0185-4

Couplage

avec un résonateur:

Mesures en résonnance

Principe général de mesure



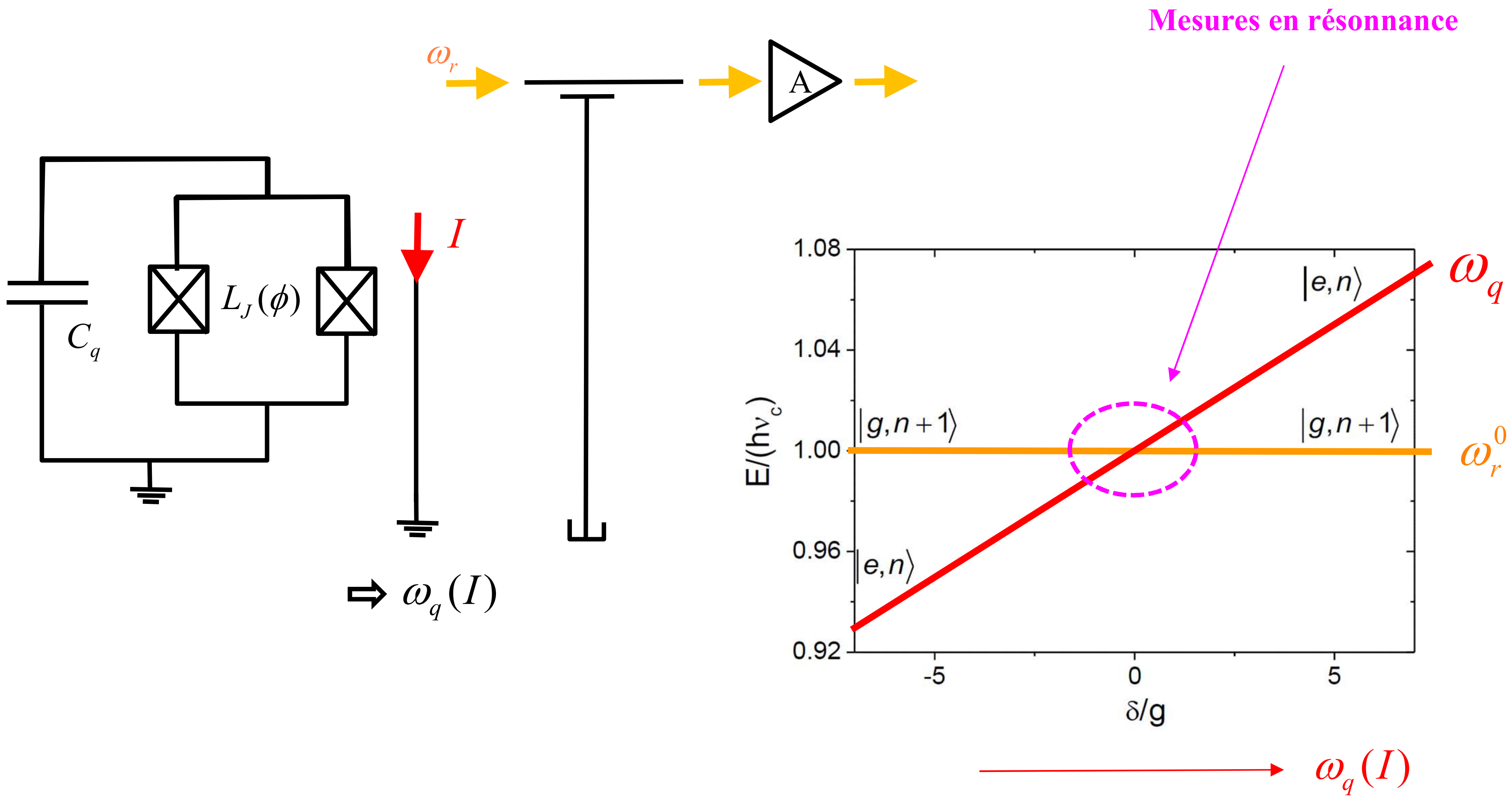
Mesures en Z

$$\langle \sigma_Z \rangle$$

$$P_g \equiv \left| \langle g | | \psi \rangle \right|^2 = \frac{1 + \langle \sigma_Z \rangle}{2}$$

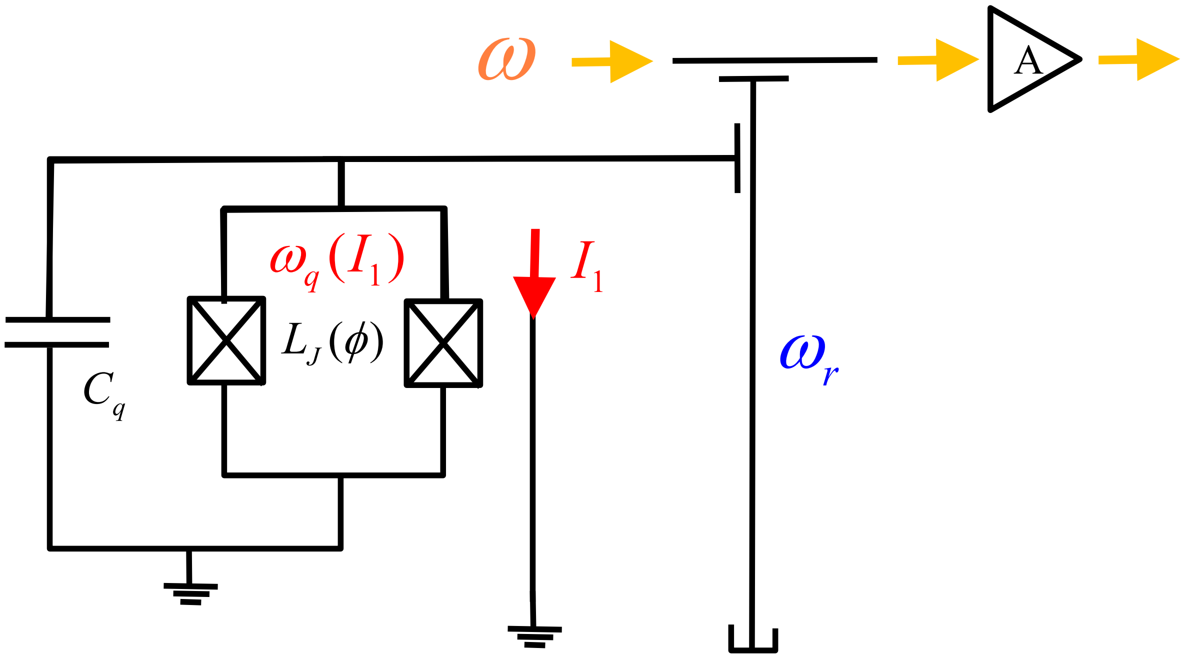
$$P_e \equiv \left| \langle e | | \psi \rangle \right|^2 = \frac{1 - \langle \sigma_Z \rangle}{2}$$

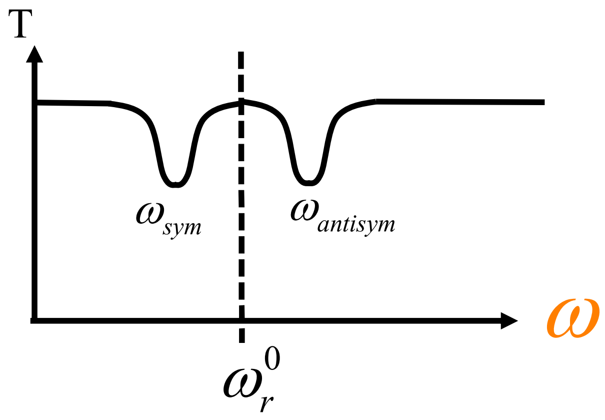
Transmon et résonateur découplés



Transmon et résonateur couplés

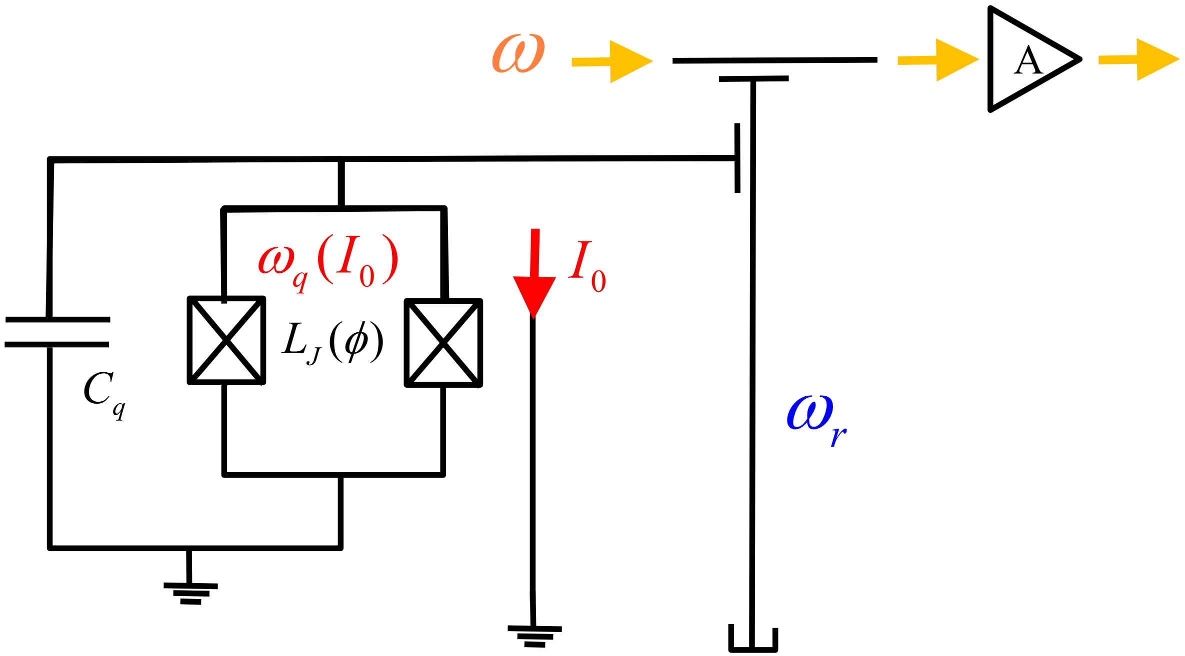
$$\omega_q = \omega_r^0$$

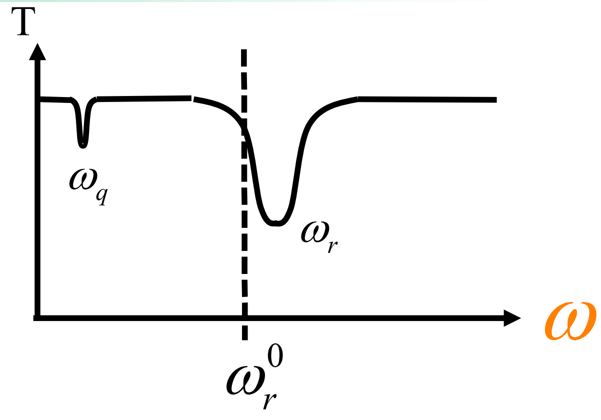




Transmon et résonateur couplés

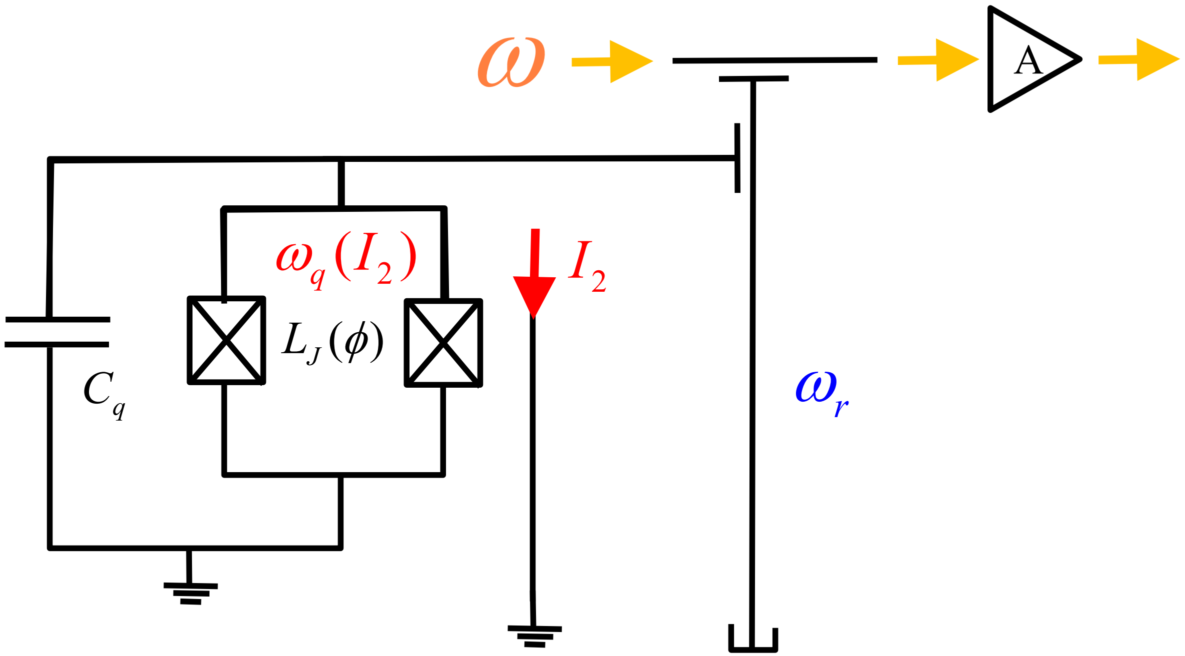
$$\omega_q < \omega_r^0$$

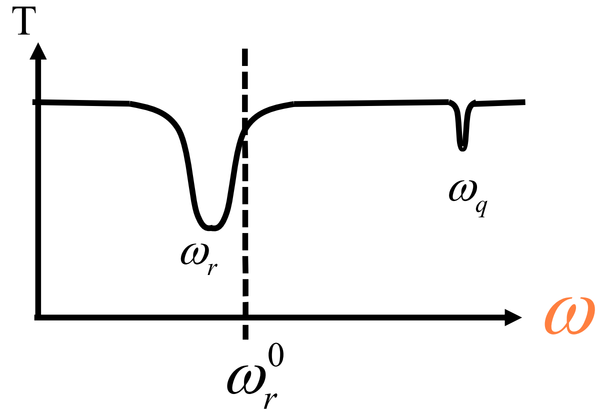




Transmon et résonateur couplés

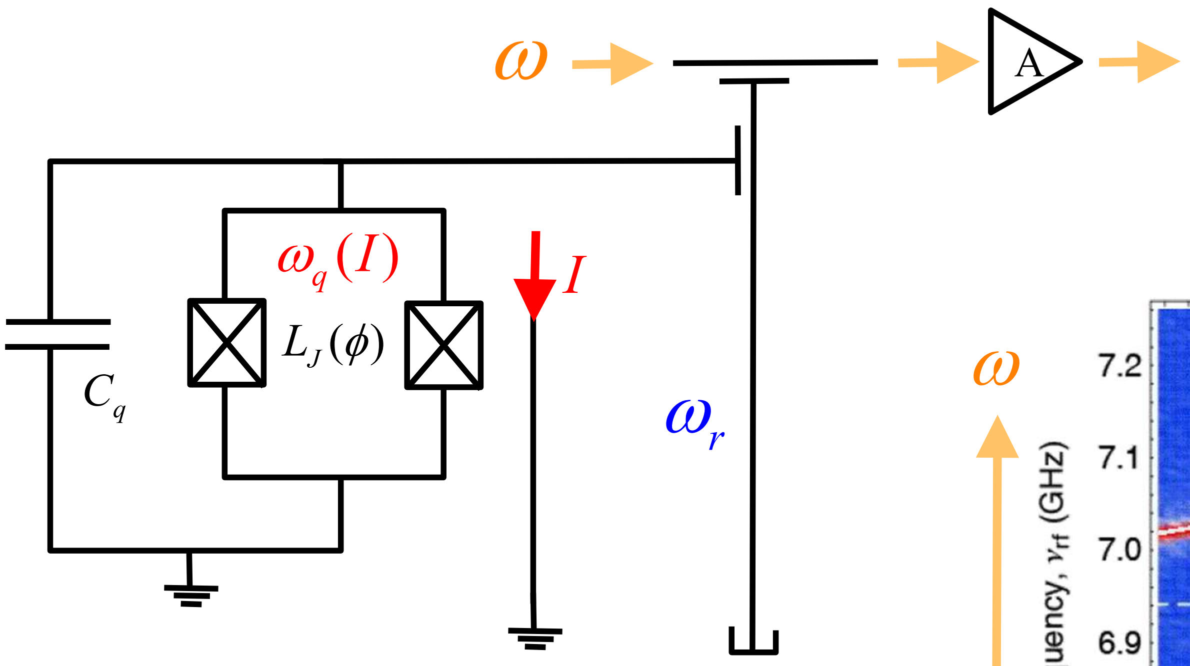
$\omega_q > \omega_r^0$



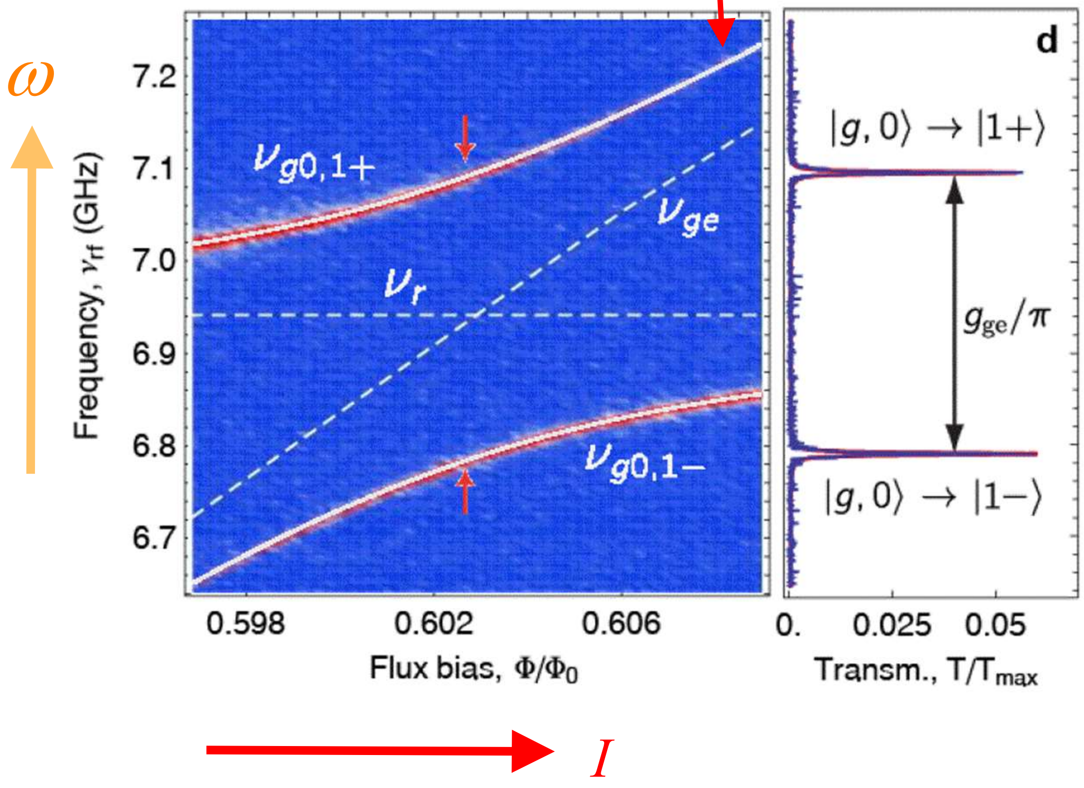


Transmon et résonateur couplés: Mesures en résonnance

J. Fink et al., *Nature (London)* **454**, 315 (2008)

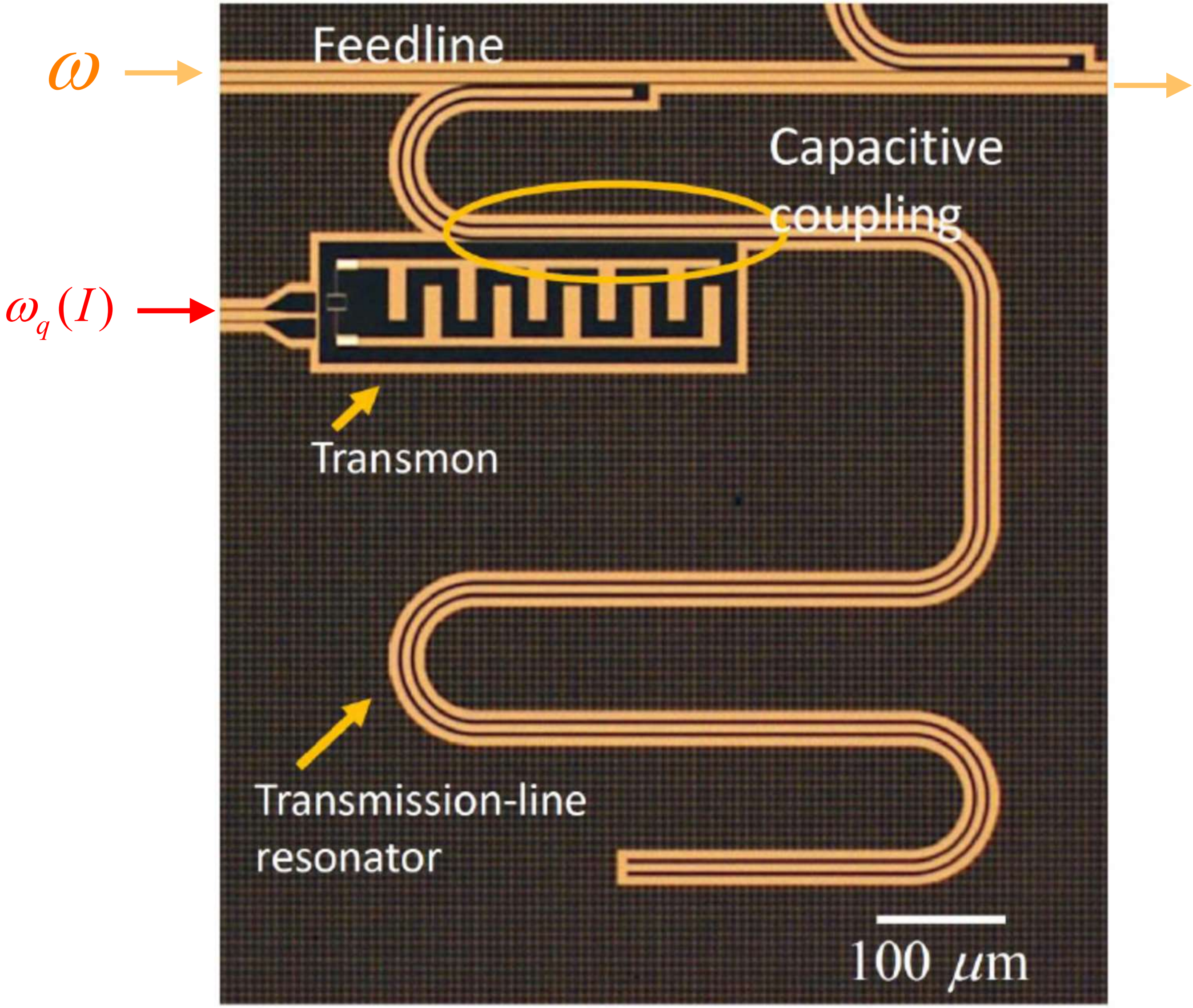


Très faible signal !!

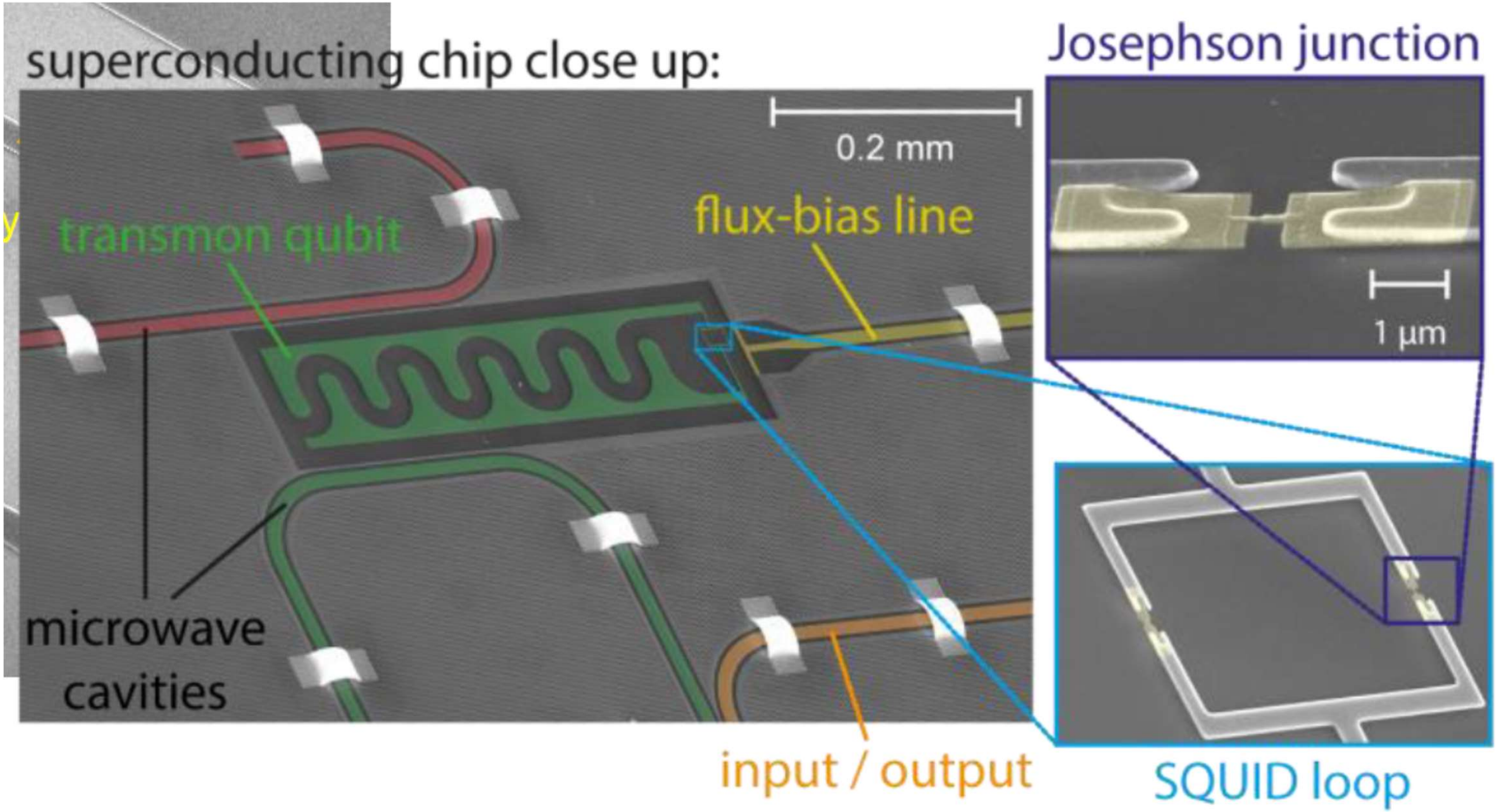


Chaque point de la figure correspond à une moyenne sur env. 10'000 mesures

Transmons et résonateur couplés: exemples



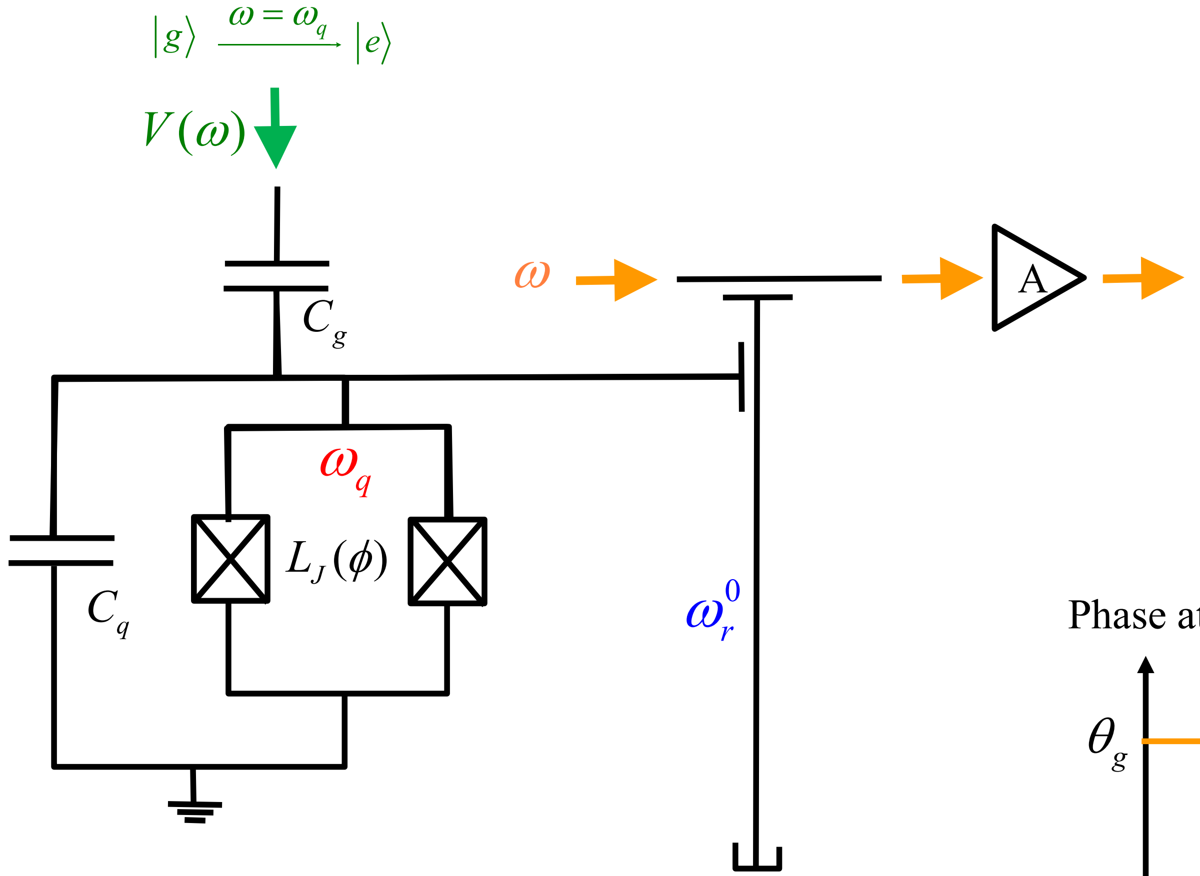
Transmon et résonateur couplés: exemples

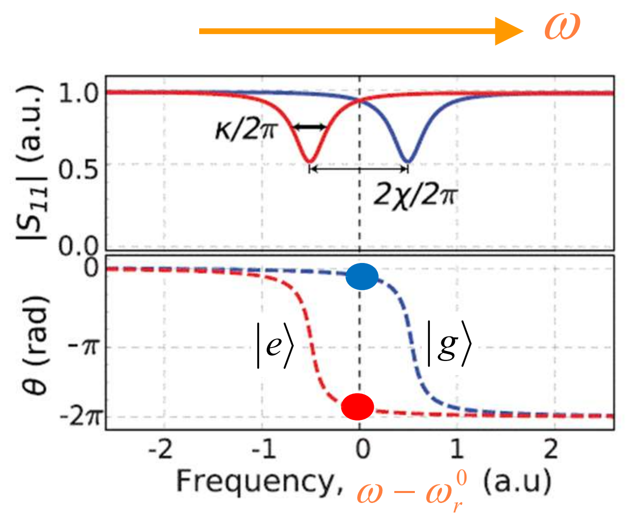


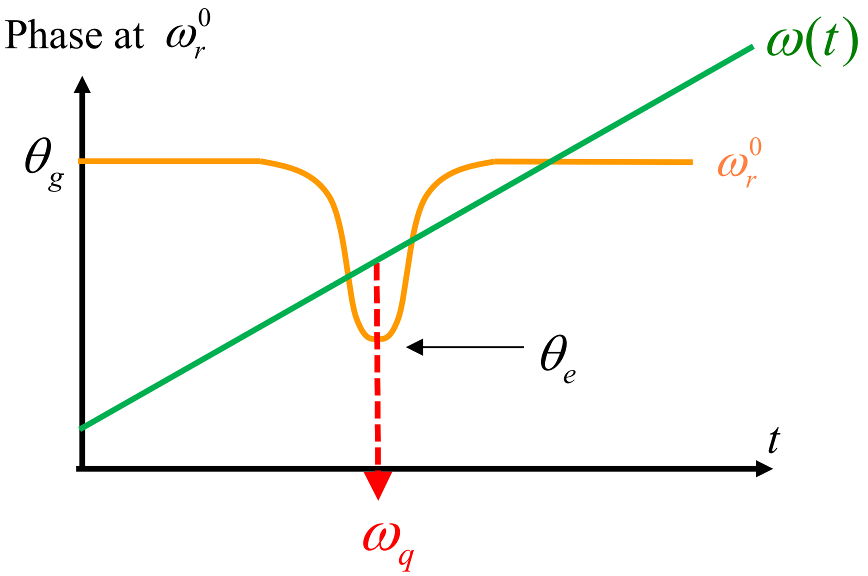
https://blog.qutech.nl/2017/08/13/how-to-make-artificial-atoms-out-of-electrical-circuits-part-ii-circuit-quantum-electrodynamics-and-the-transmon/

Qubit supraconducteur:
Régime dispersif et
Mesures en quantum non-demolition

Transmon et résonateur en régime dispersif
déterminer la fréquence de résonnance du qubit

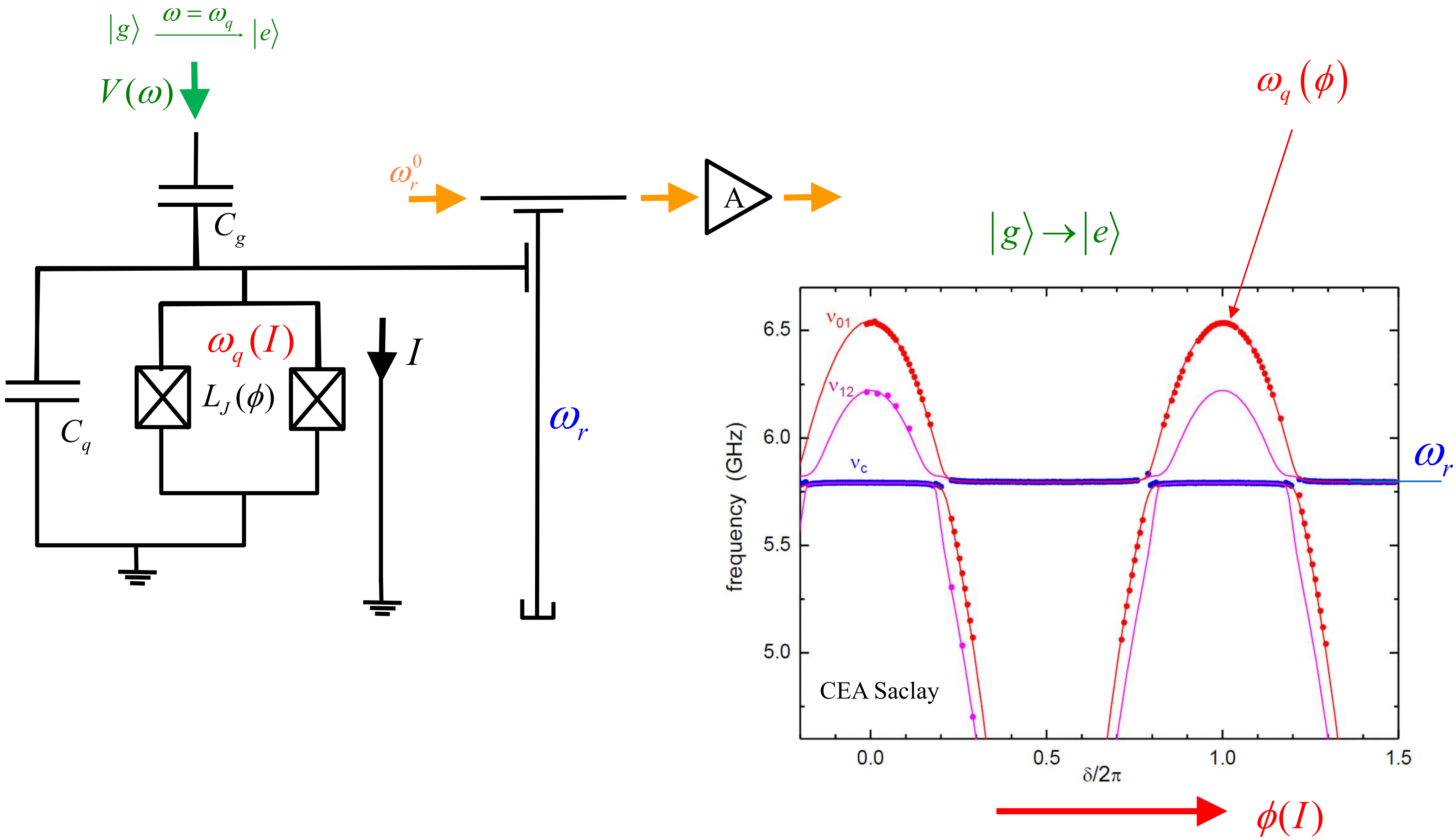






Transmon et résonateur en régime dispersif

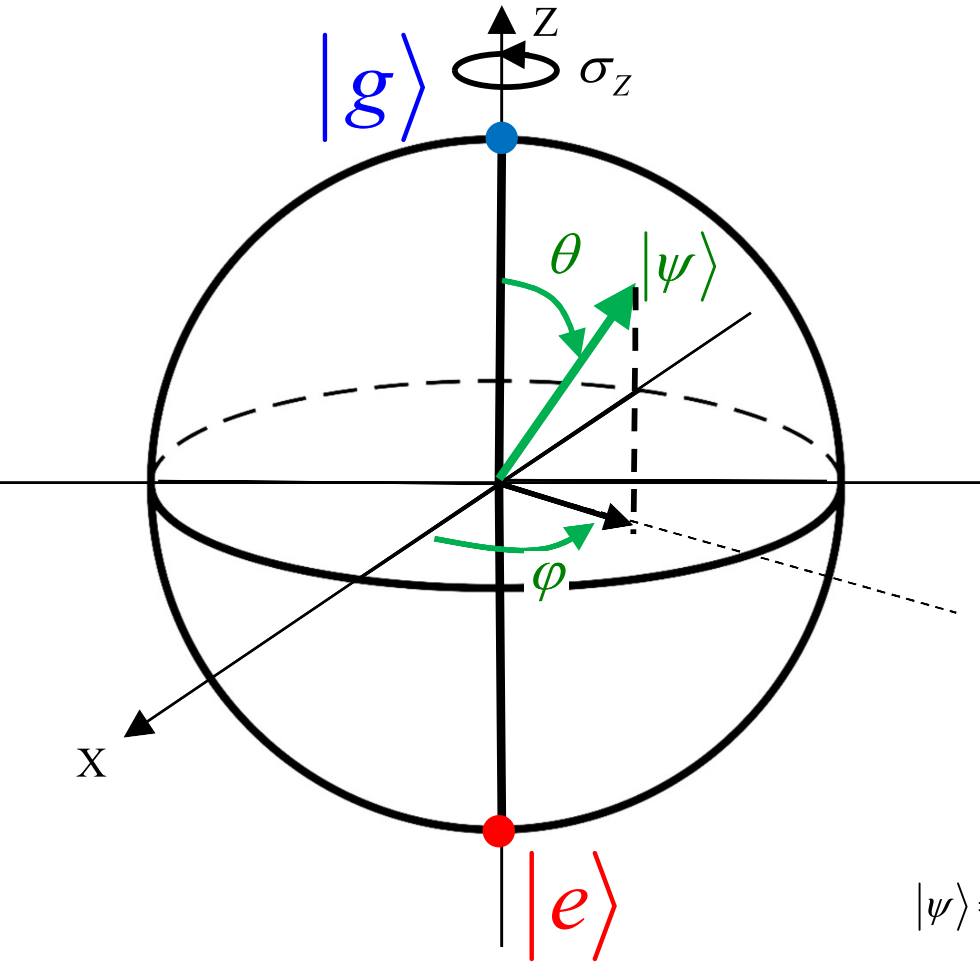
déterminer la fréquence de résonnance du qubit



Qubit supraconducteur:

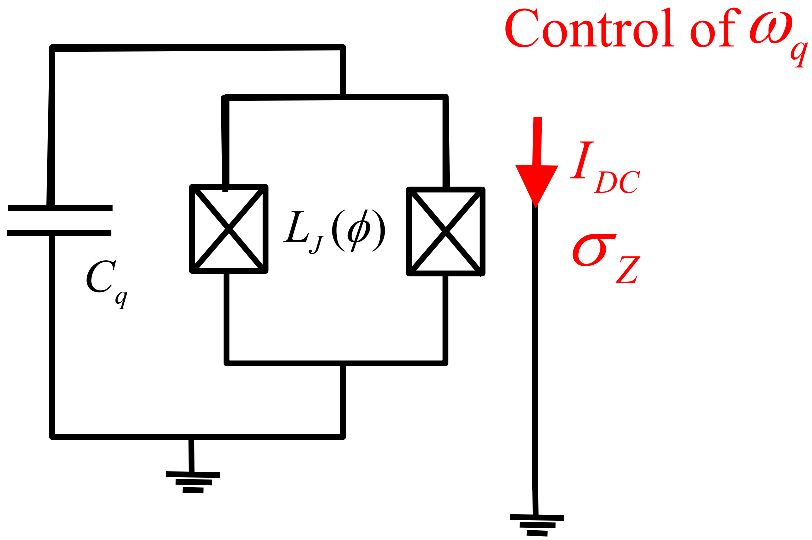
Rotation σ_Z

Rotation en Z



$$|\psi\rangle = \begin{pmatrix} \cos\left(\frac{\theta}{2}\right) \\ e^{i\varphi}\cdot\sin\left(\frac{\theta}{2}\right) \end{pmatrix}$$

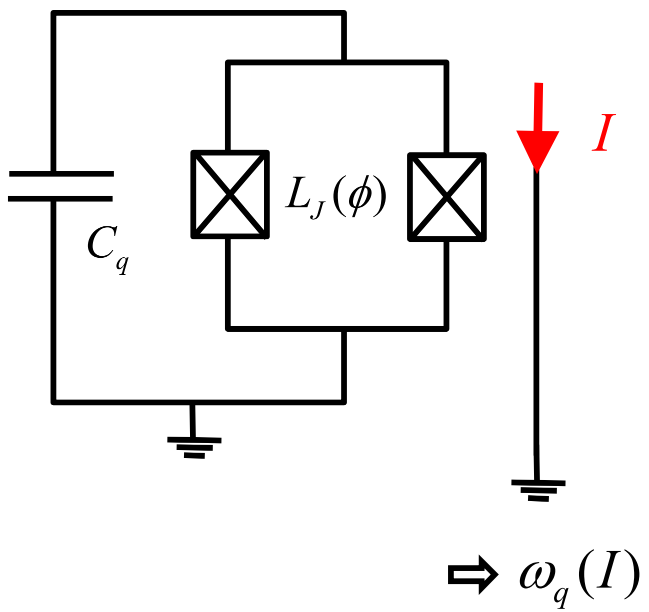
$$\omega_q(\phi) \equiv \frac{1}{\sqrt{L_J(\phi)\,C_q}}$$

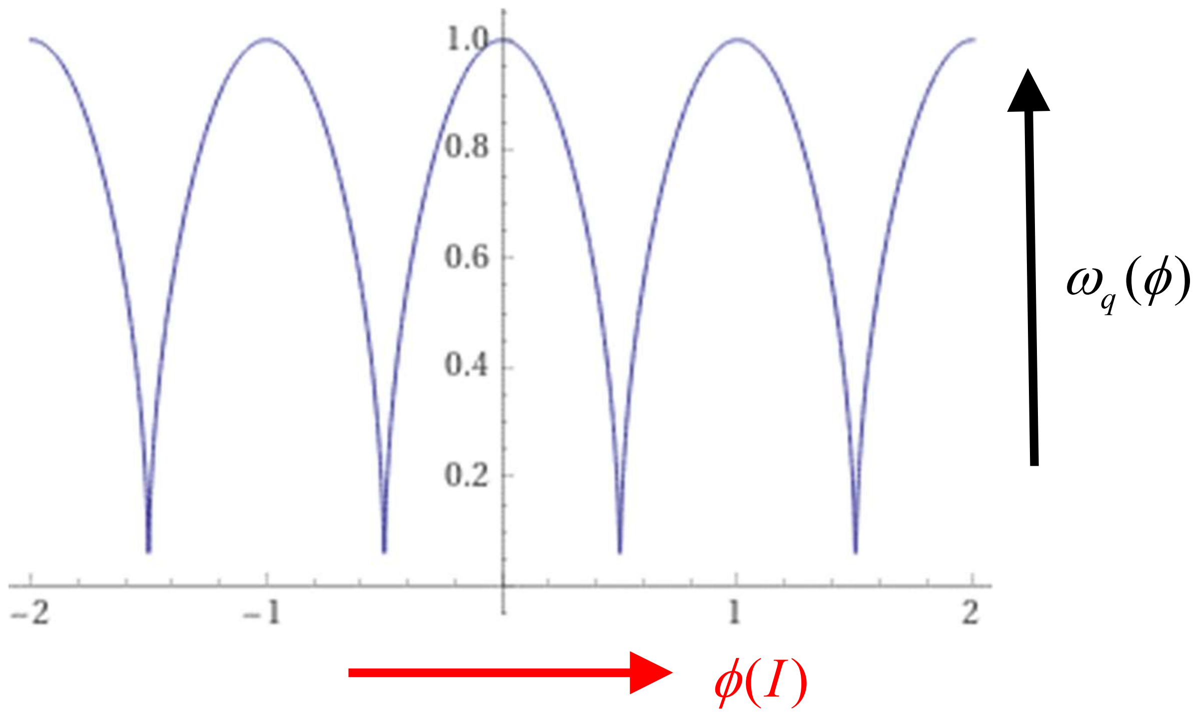


$\Rightarrow \omega_q(I)$

Contrôle de la fréquence

$$\omega_q(\phi) \equiv \frac{1}{\sqrt{L_J(\phi)C_q}} \approx \sqrt{\left|\cos\left(\frac{1}{\pi}\cdot\frac{\phi}{\phi_0}\right)\right|}$$





Qubit supraconducteur:

Rotation σ_X et σ_Y

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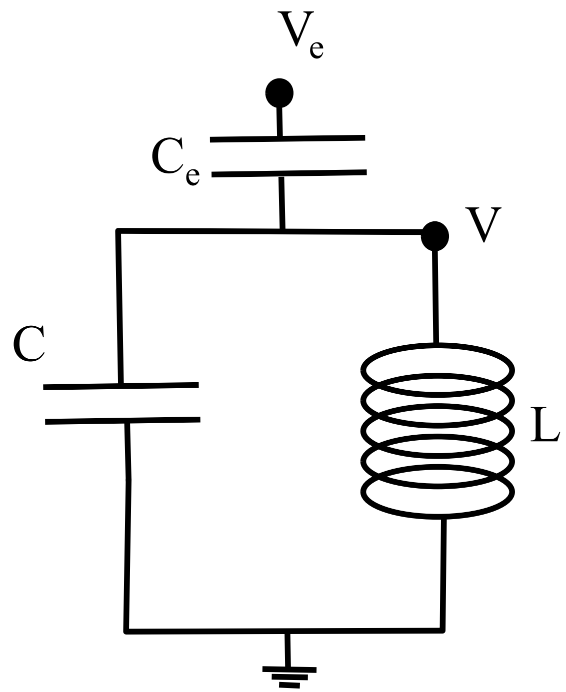
Rappel:
Exercice 9.2: Hamiltonien d'excitation

$$H_e \approx -C_e \cdot V_e \cdot V = -C_e \cdot V_e \cdot \frac{\mathbb{Q}}{(C+C_e)}$$

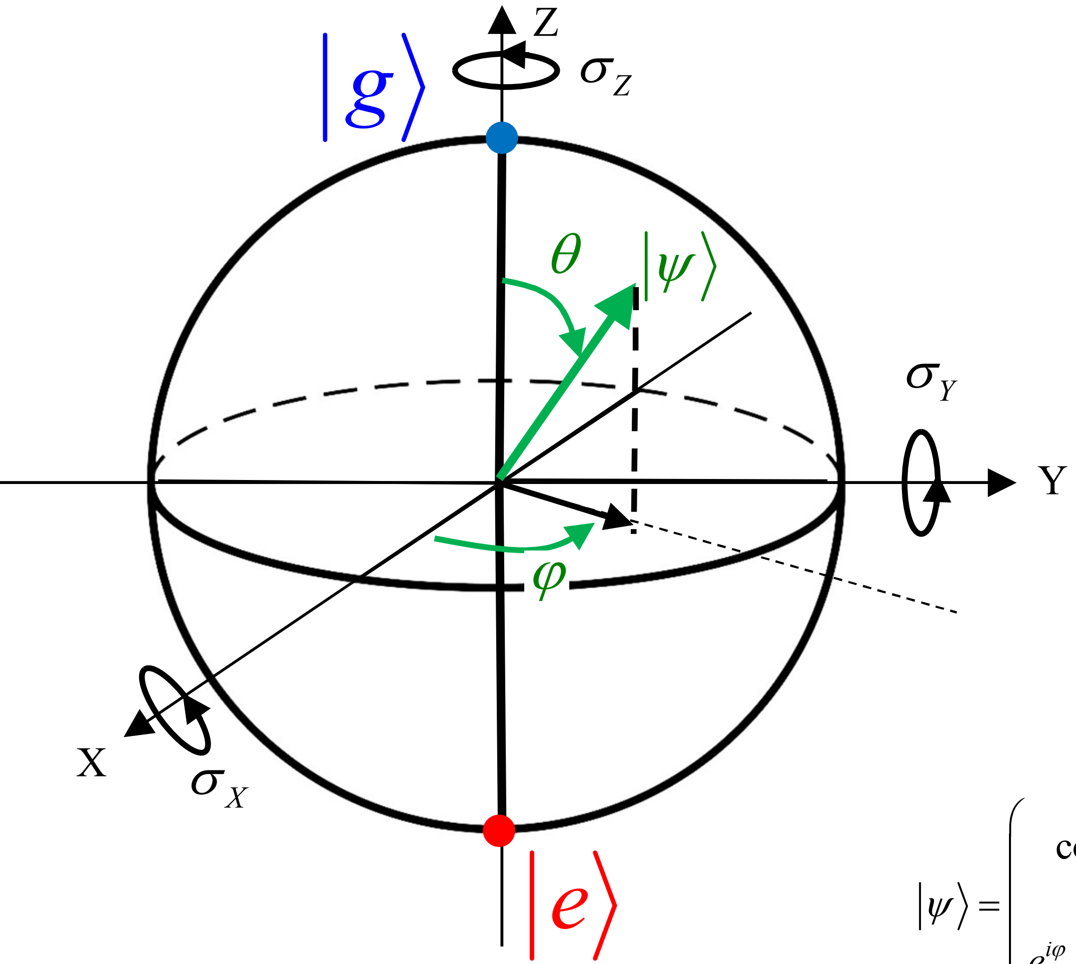
$$H_e \approx \frac{C_e}{C+C_e} \cdot V_e \cdot \left(\frac{\hbar^2 \cdot (C+C_e)}{4 \cdot L} \right)^{1/4} \cdot i \cdot (a_+ - a_-)$$

$$H_e = g \cdot V_e \cdot \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} = g \cdot V_e \cdot \sigma_Y$$

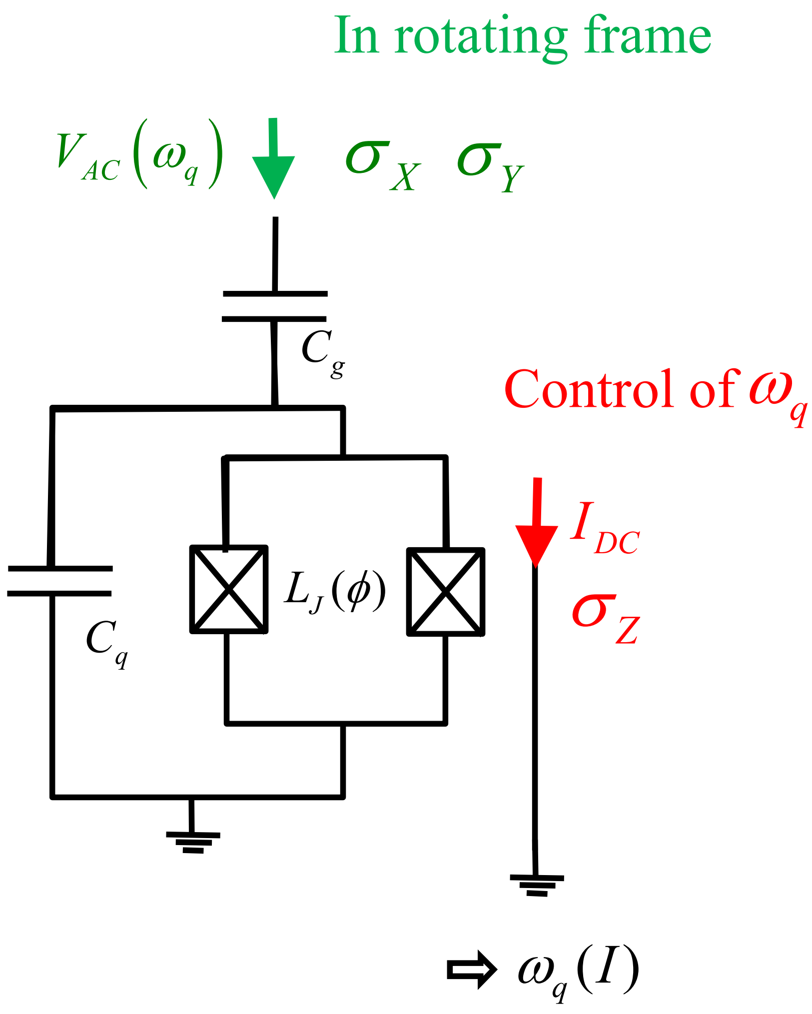
Oscillateur Harmonique LC



Contrôle par couplage capacitif AC dans le référentiel tournant



$$|\psi\rangle = \begin{pmatrix} \cos\left(\frac{\theta}{2}\right) \\ e^{i\varphi} \cdot \sin\left(\frac{\theta}{2}\right) \end{pmatrix}$$

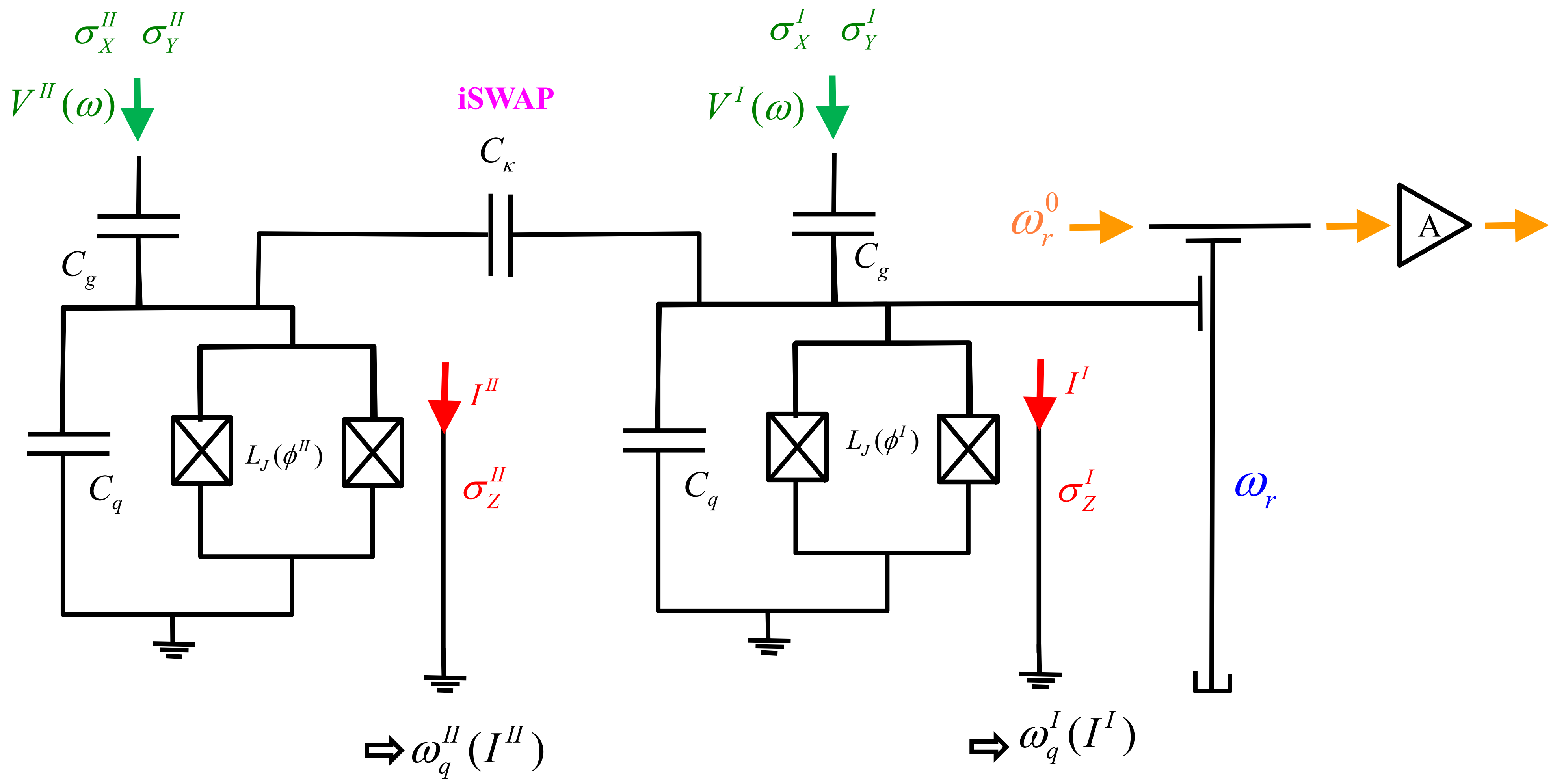


Qubit supraconducteur:

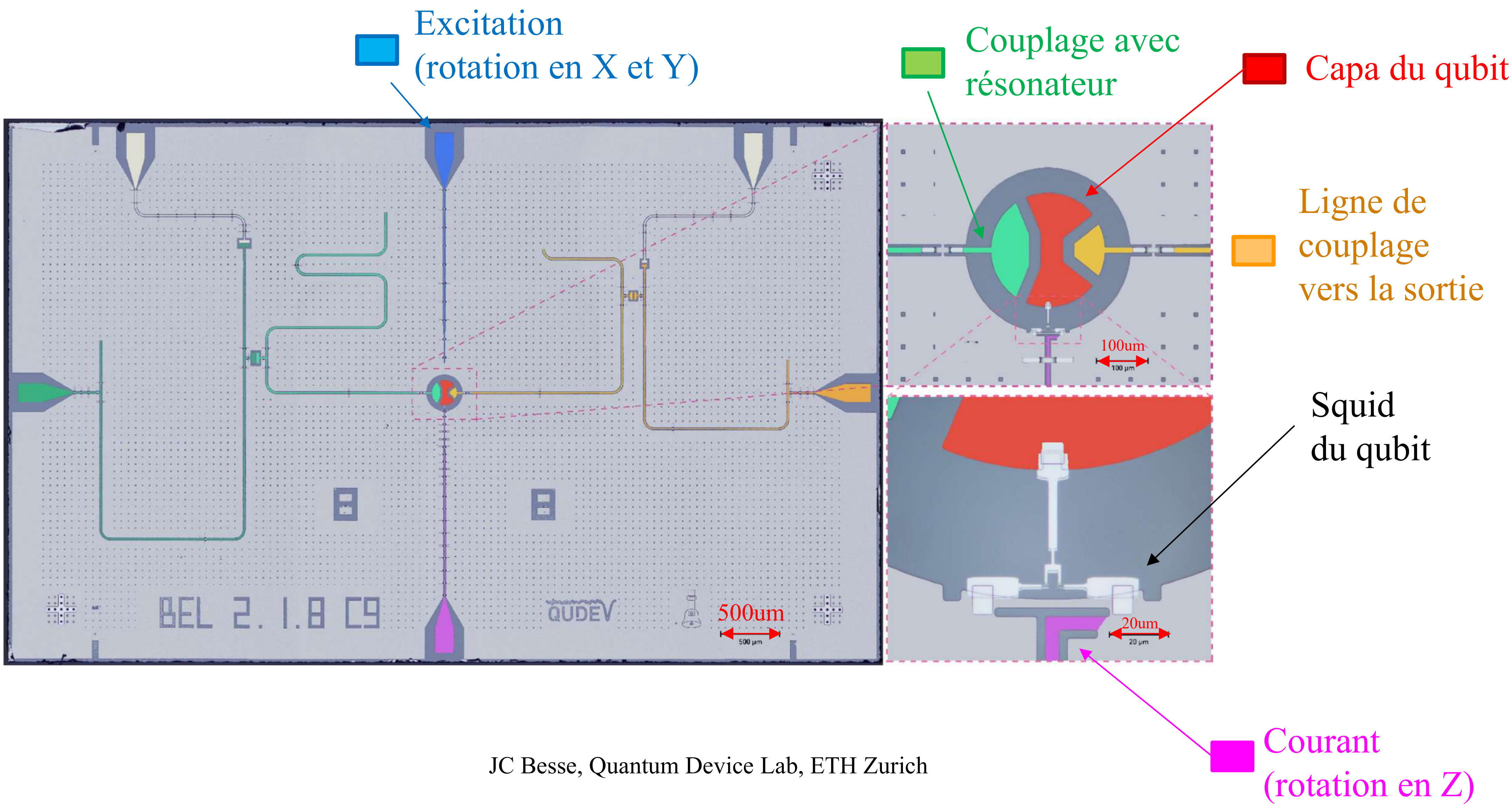
Paire de qubits couplés

(iSWAP)

Paire de Qubits couplés



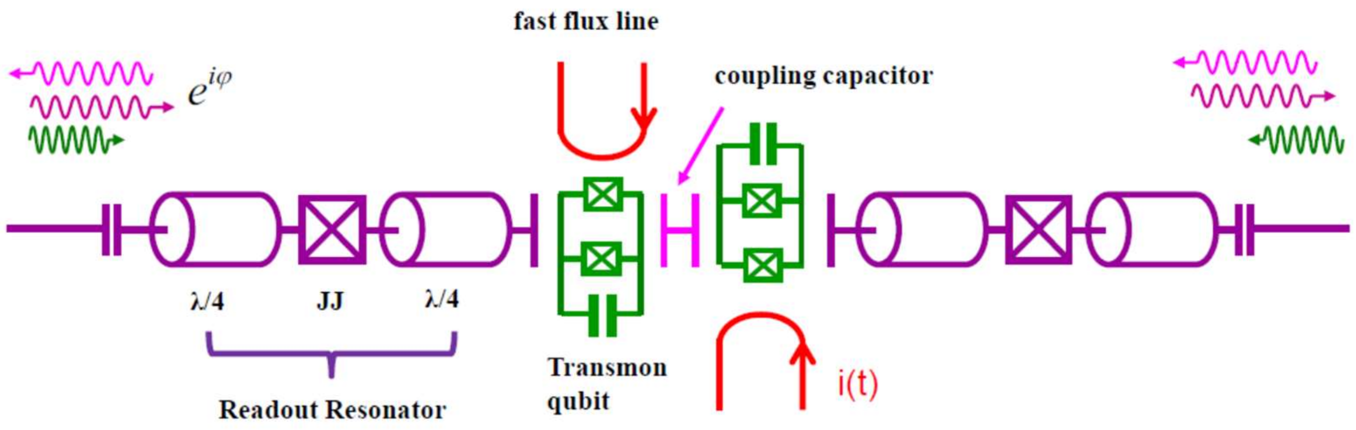
Devices et setup de mesure: exemples

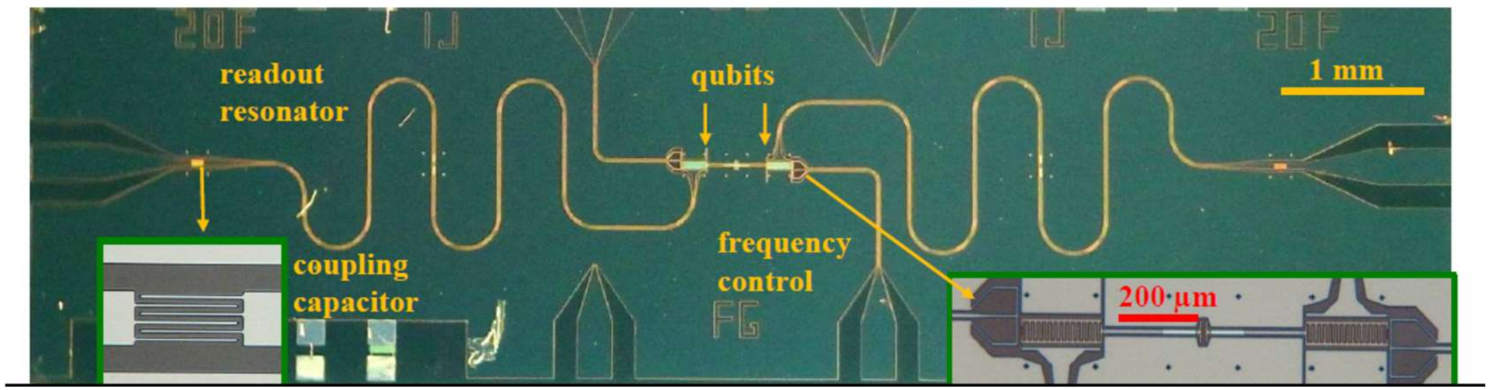


JC Besse, Quantum Device Lab, ETH Zurich

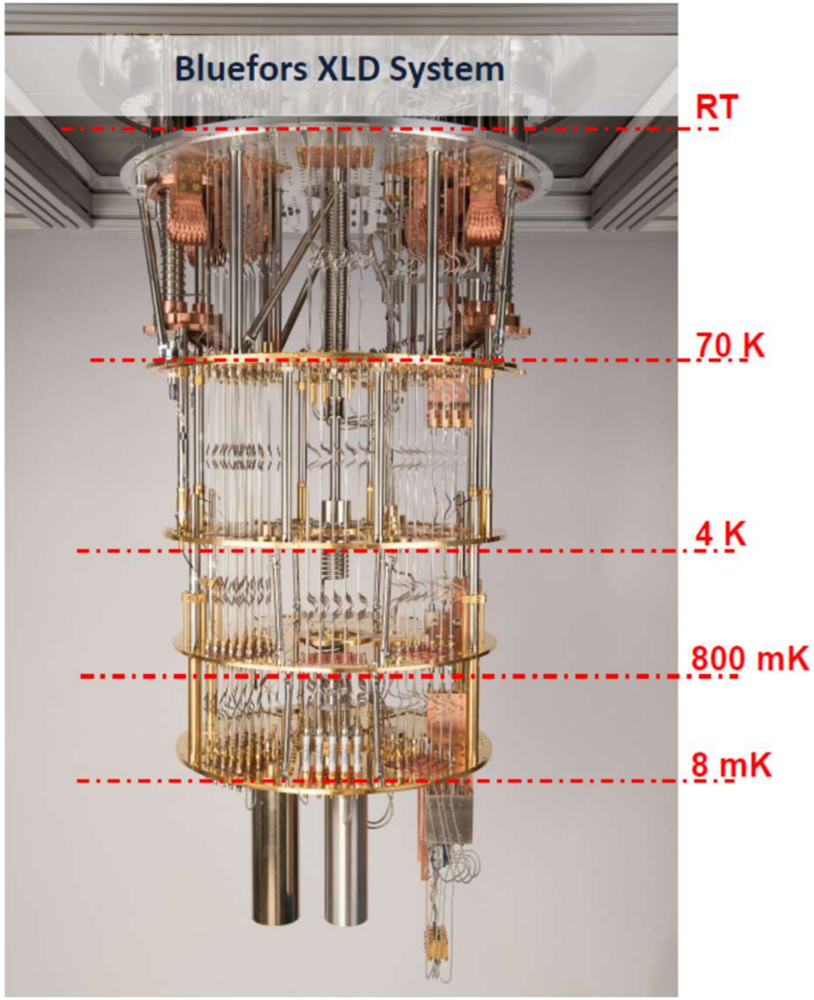
Example : capacitively coupled transmons with individual readout

(Saclay, 2011)





Mesures en cryogénie

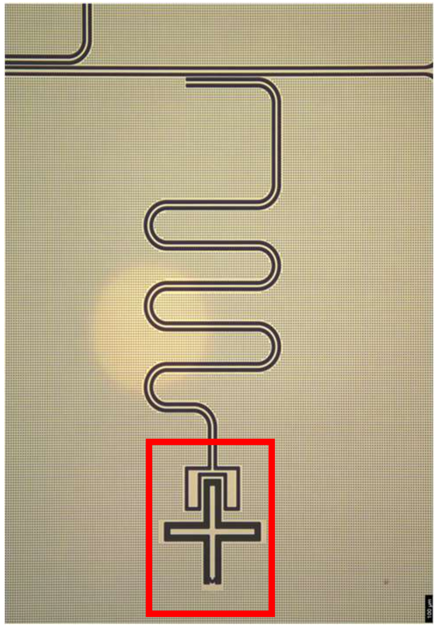


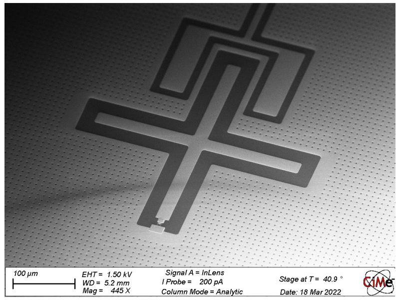
PAB

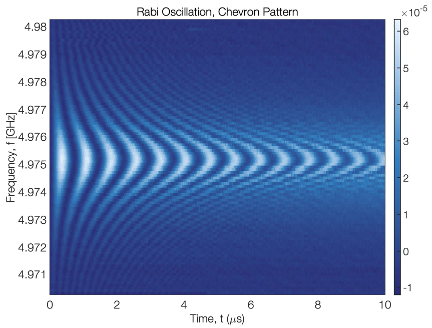
Ordinateur Quantique: EPFL

HQC
Hybrid Quantum Circuits

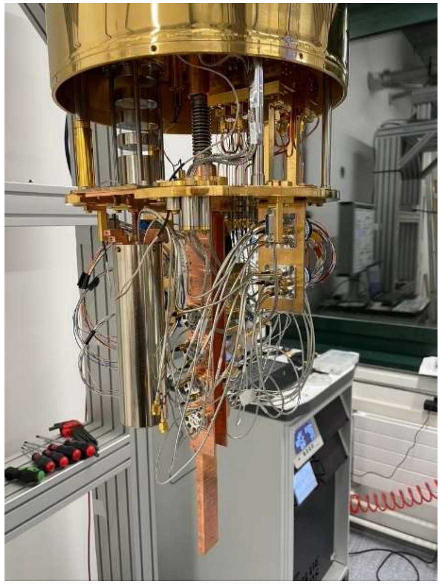
Aluminium Transmon Qubits

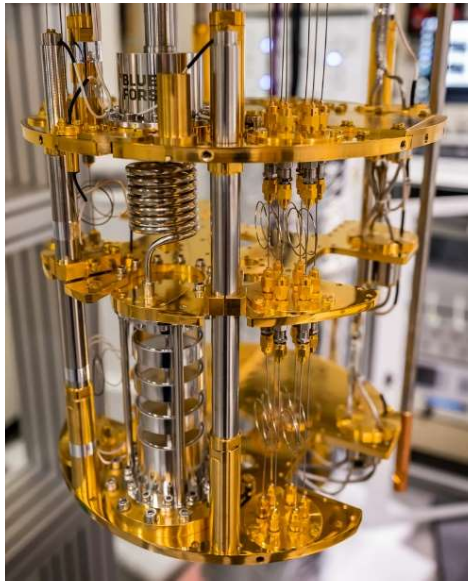




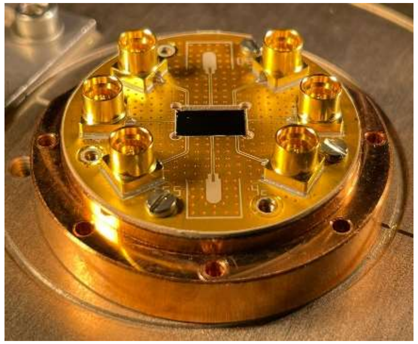


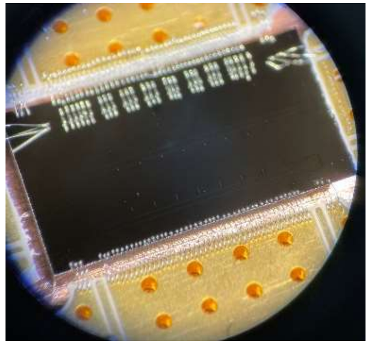
10 mK Dilution Refrigerator in HQC



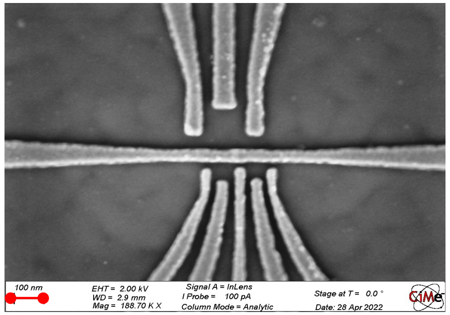


5-10 GHz Printed Circuit Board hosting the device

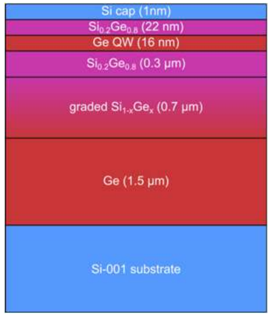




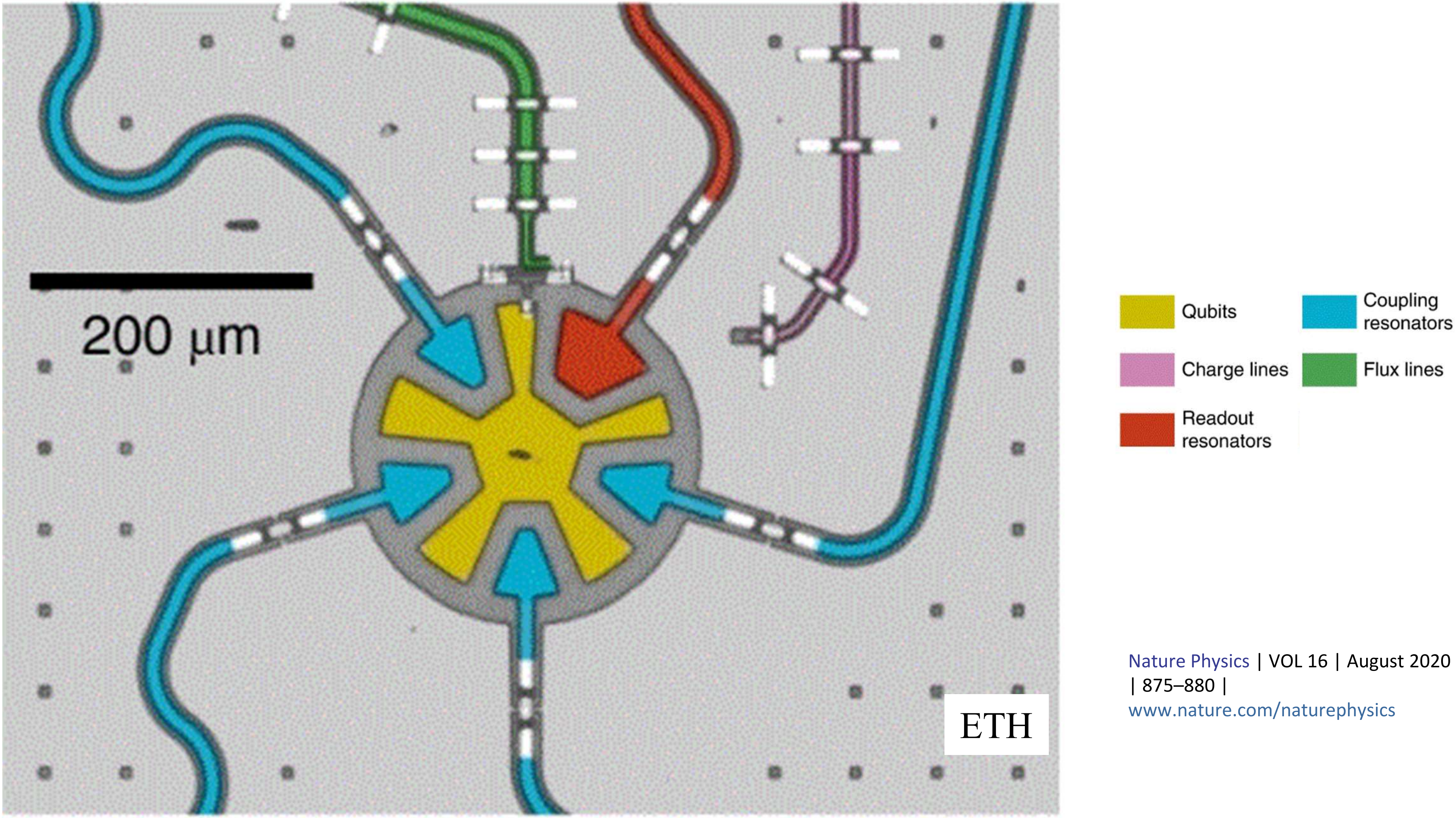
Quantum Dots in Germanium Heterostructures



100 nm

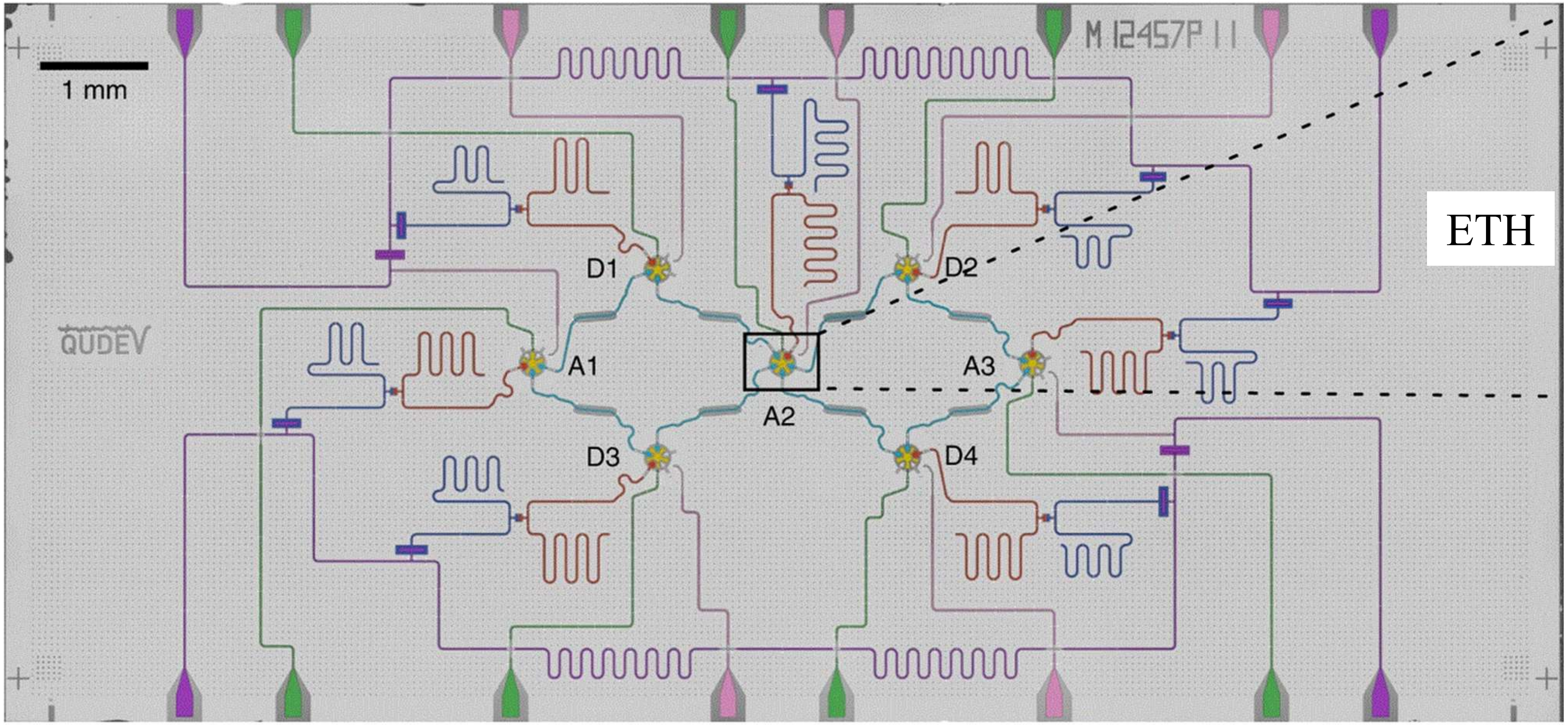


Qubit et lignes de couplage



Nature Physics | VOL 16 | August 2020 | 875–880 |
www.nature.com/naturephysics

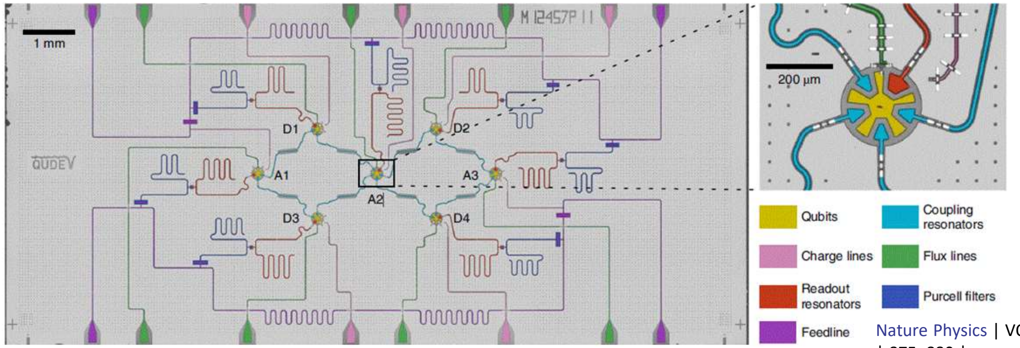
Puce avec 7 qubits



Nature Physics | VOL 16 | August 2020
| 875–880 | www.nature.com/naturephysics

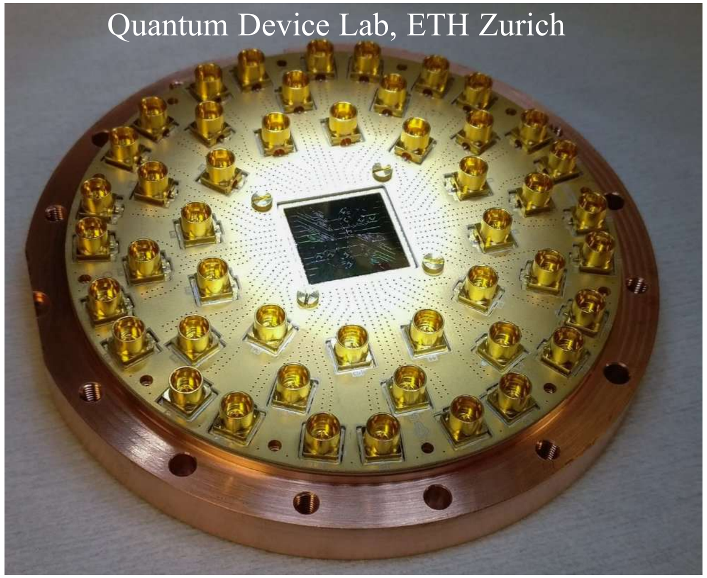
PAB

Ordinateur Quantique: ETH



Nature Physics | VOL 16 | August 2020 | 875–880 | www.nature.com/naturephysics

5-10 GHz
10 mK



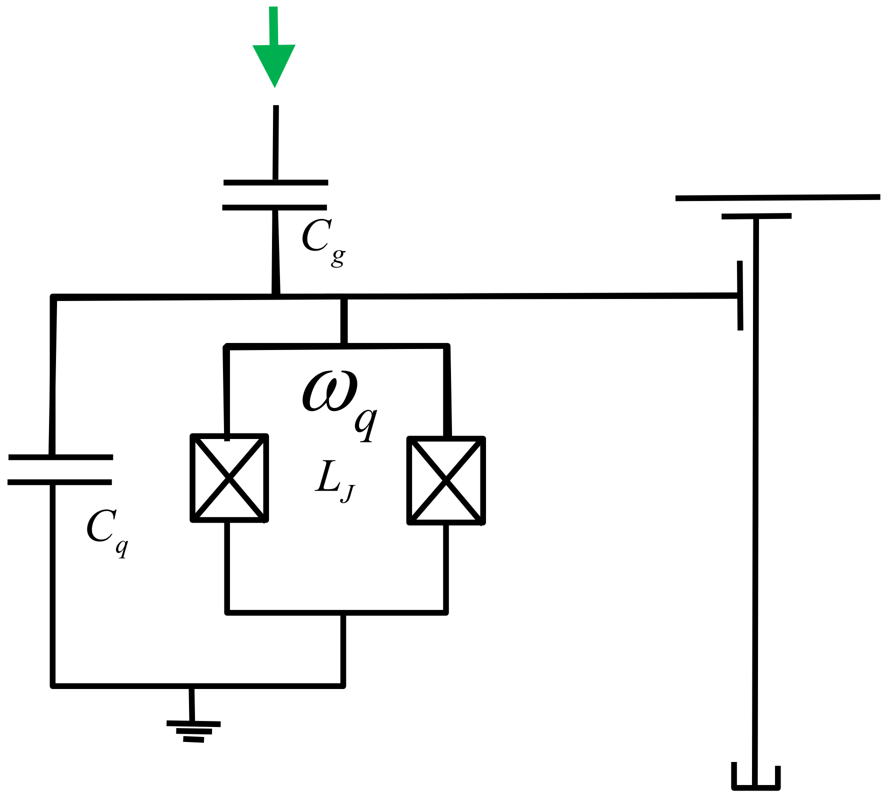
Mesures de Qubits:

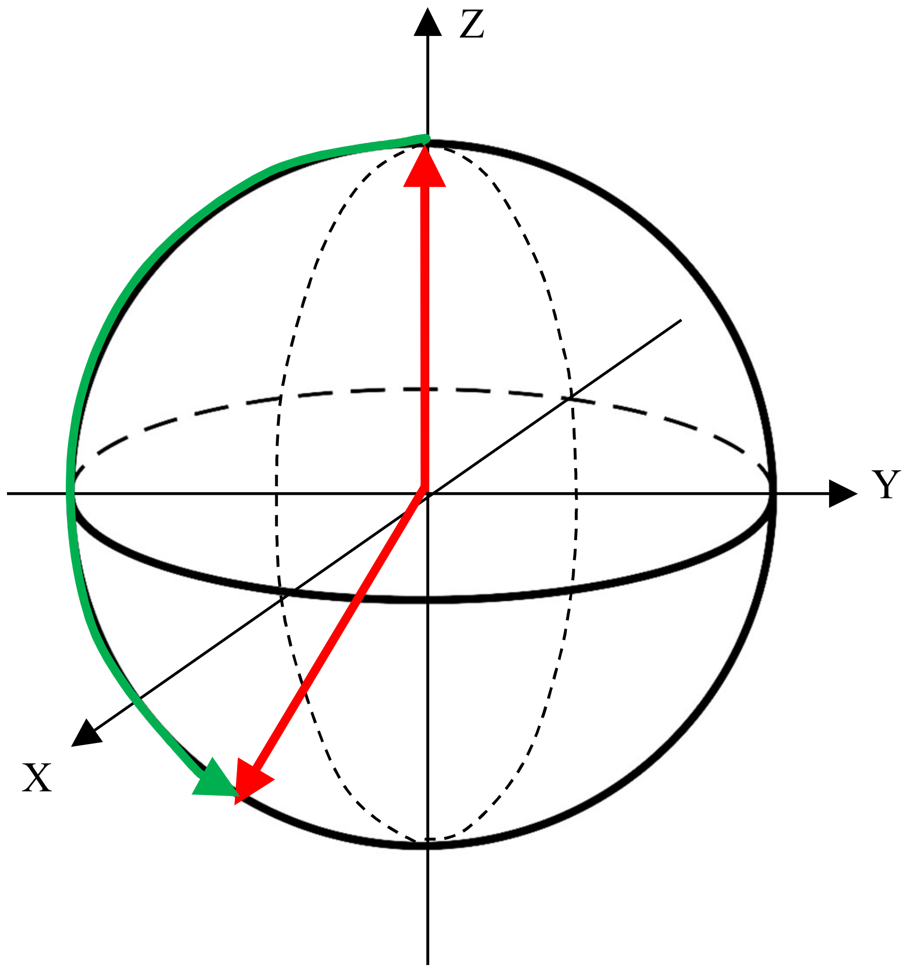
- Fréquence de Rabi
- Relaxation, mesures de T_1
- Décohérence

PAB

1) Fréquence de Rabi: Excitation

$$V(\omega) = T \cdot \cos(\omega \cdot t)$$

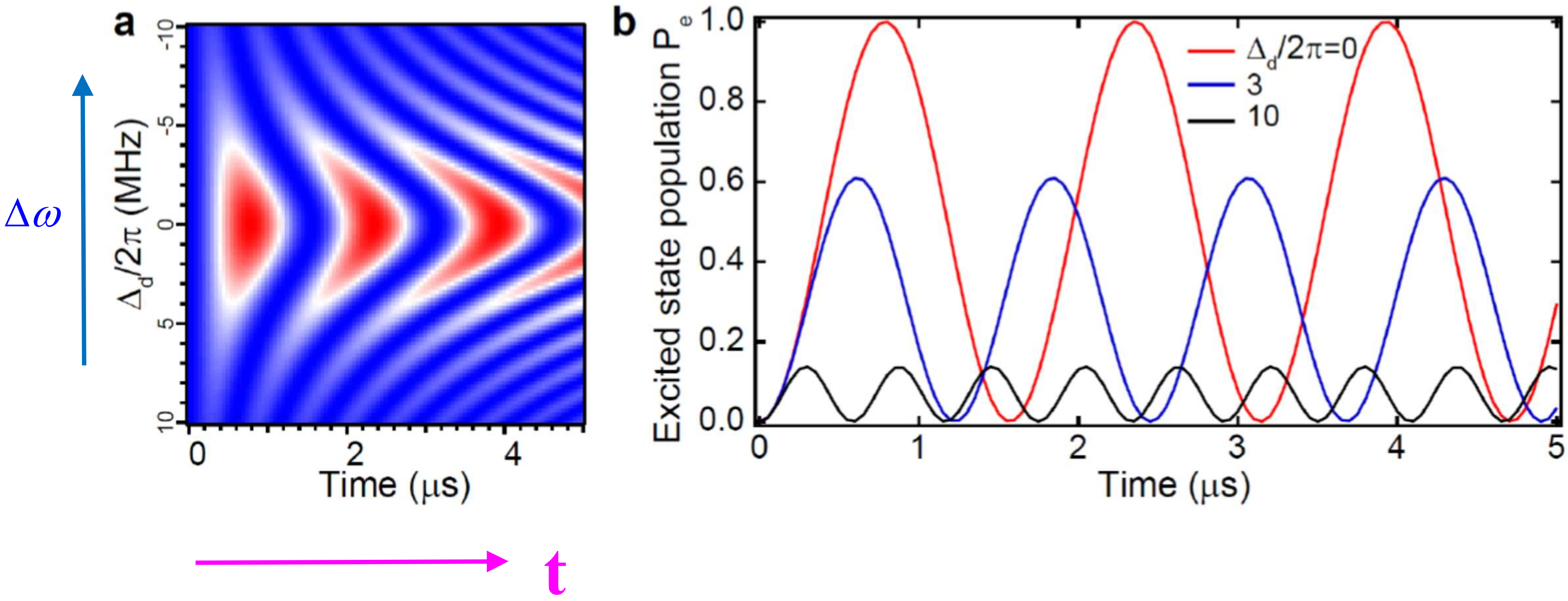




1) Fréquence de Rabi: Résultats

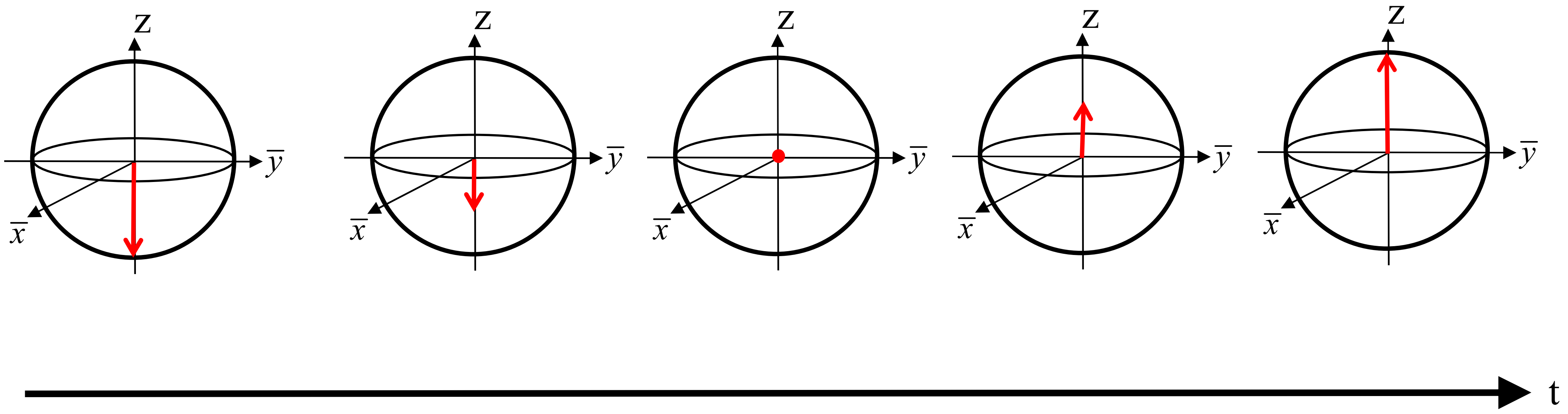
$$\Delta\omega \equiv \omega - \omega_q$$

Chaque point de la figure correspond à une moyenne sur env. 10’000 mesures

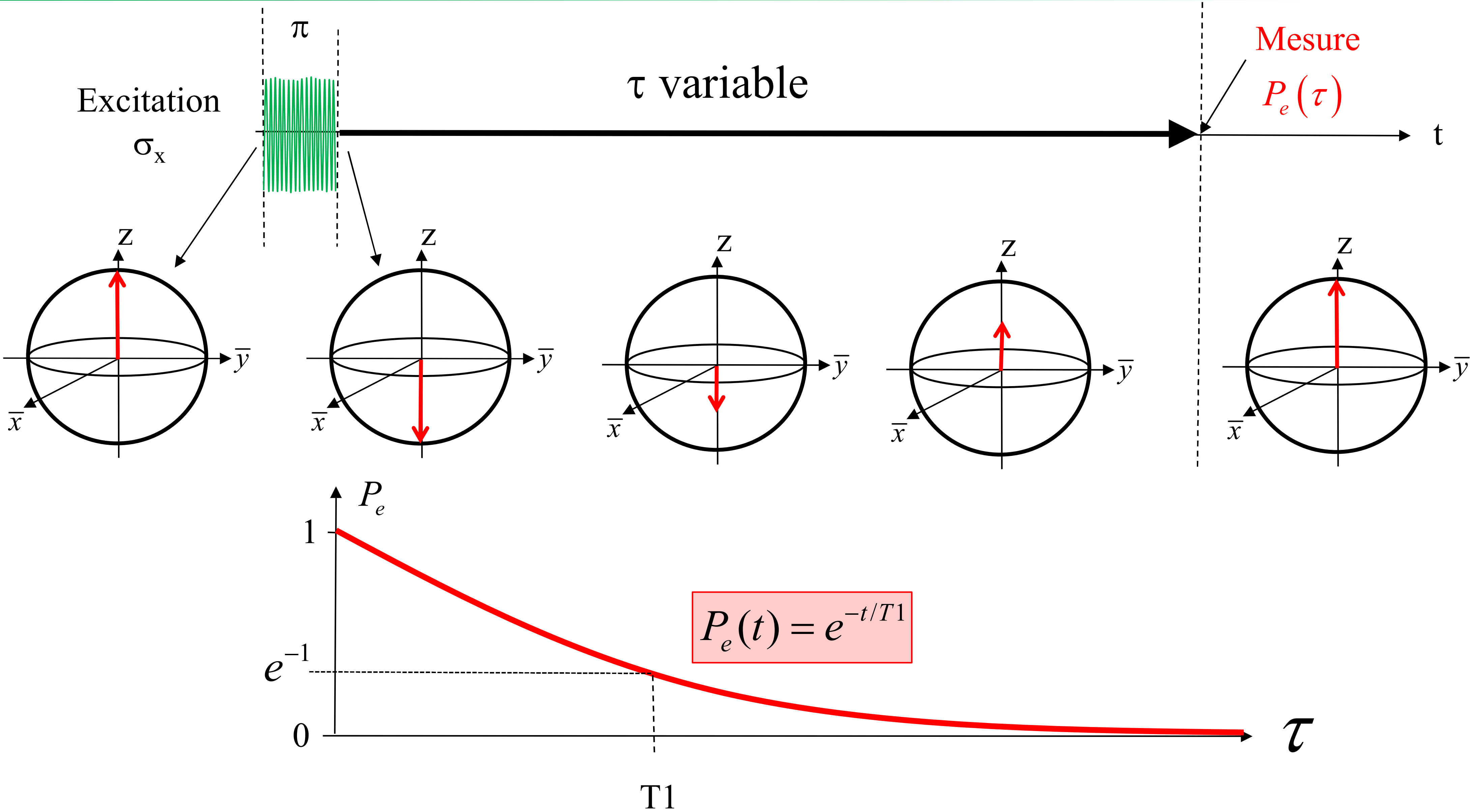


2) Relaxation

Relaxation: Temps T1

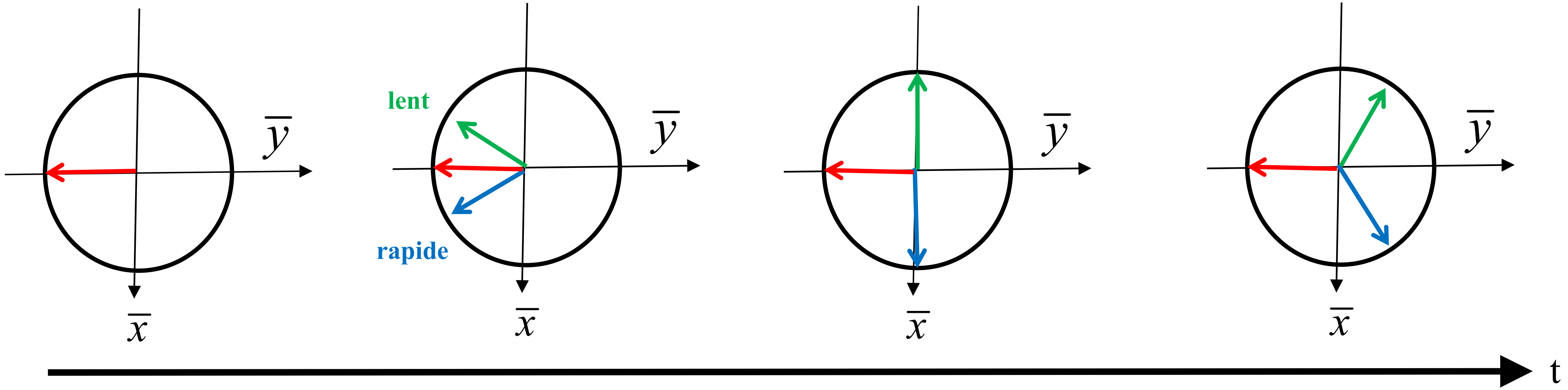


2) Mesure du temps de relaxation T1

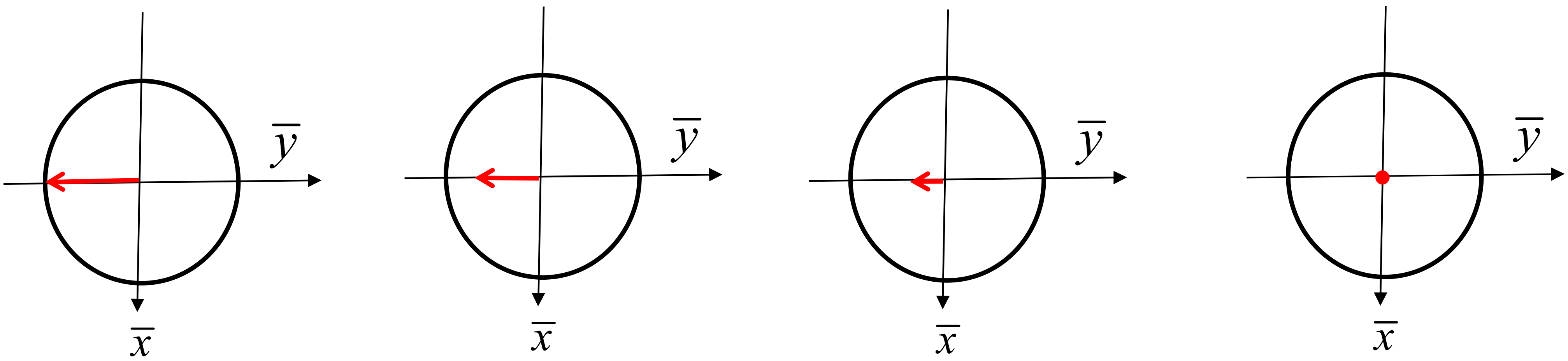


3) Décohérence dans le plan X,Y

Décohérence: Temps T2* (T2)

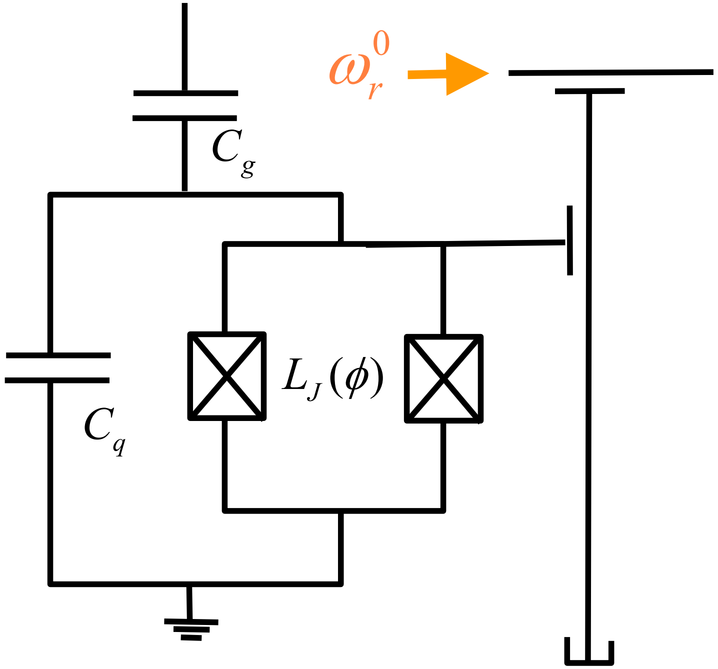


Qubit moyen



Exercices

Exercice 13.1: mesure par quantum non-demolition



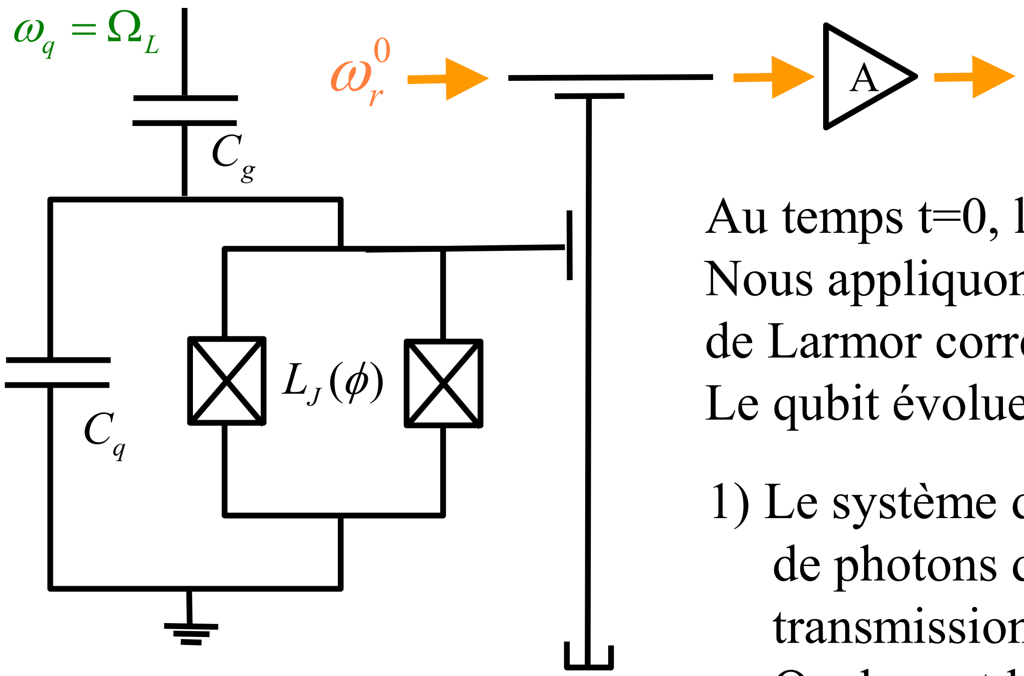
Le qubit est dans l'état de base,

- Nous appliquons une impulsion en X de π/2

- Nous faisons directement (en négligeant la relaxation et la décohérence) une mesure par quantum non-demolition.

Indiquez, sur la sphère de Bloch, l'évolution du qubit.

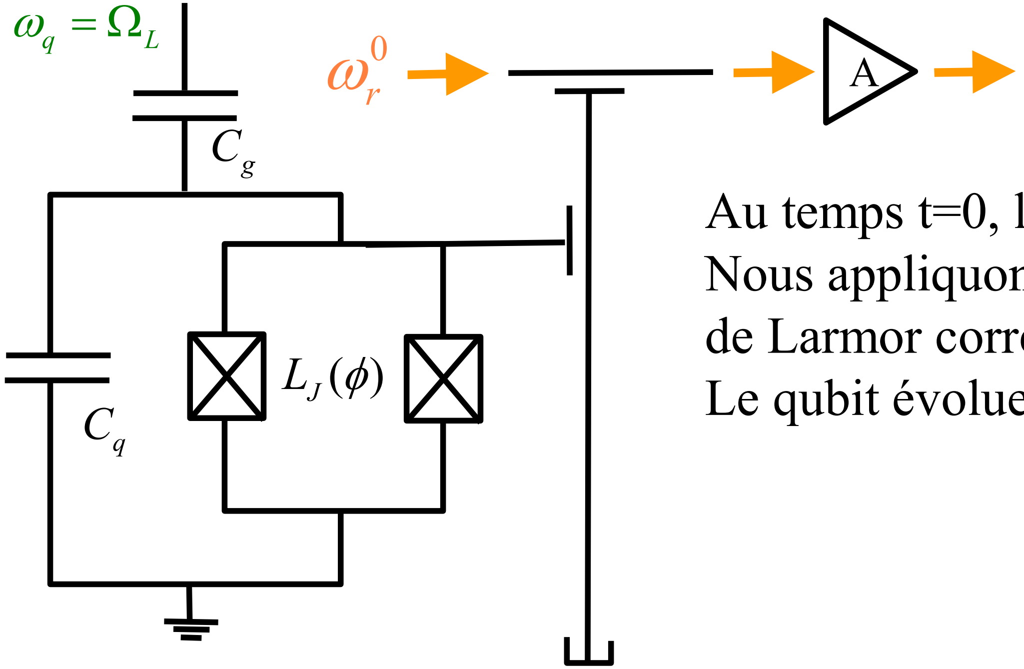
Exercice 13.2: effet Zénon



Au temps t=0, le qubit est dans l'état de base,
Nous appliquons en continu un signal d'excitation à la fréquence de Larmor correspondant à la résonance du qubit ($w_q=\Omega_L$).
Le qubit évolue à la fréquence de Rabi Ω_R.

1) Le système de mesure par non-démolition (excitation par injection de photons dans le résonateur et mesure électronique de la transmission) est enclenché à intervalles $\Omega_R.T=\pi$
Quels sont les signaux détectés ?
«0» = état de base, «1» = état excité

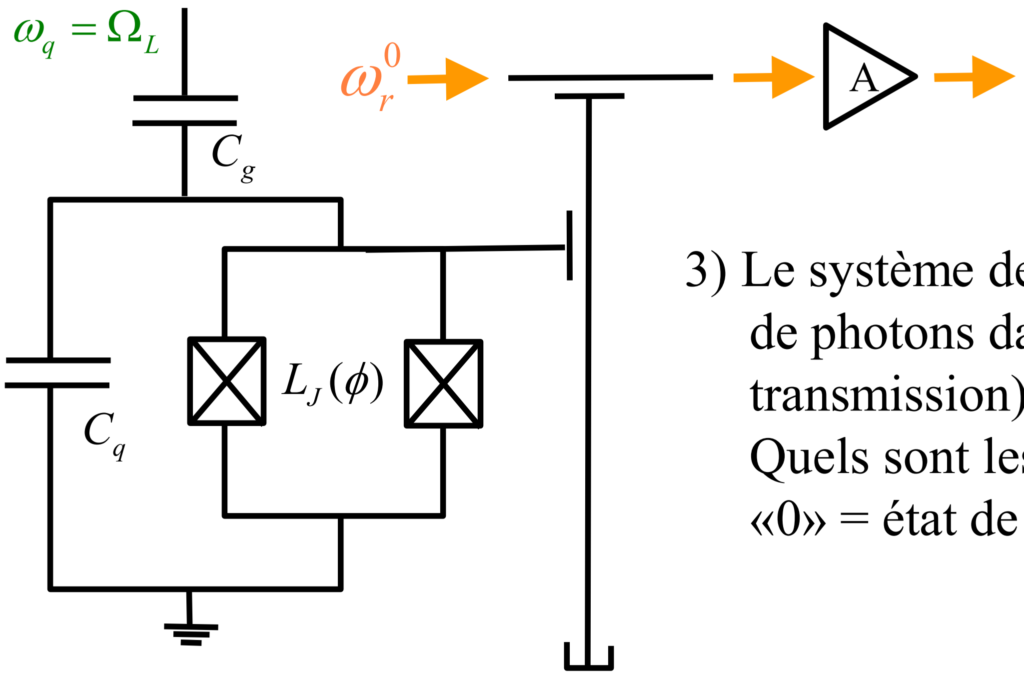
Exercice 13.2: effet Zénon



Au temps t=0, le qubit est dans l'état de base,
Nous appliquons en continu un signal d'excitation à la fréquence de Larmor correspondant à la résonance du qubit ($w_q=\Omega_L$).
Le qubit évolue à la fréquence de Rabi Ω_R.

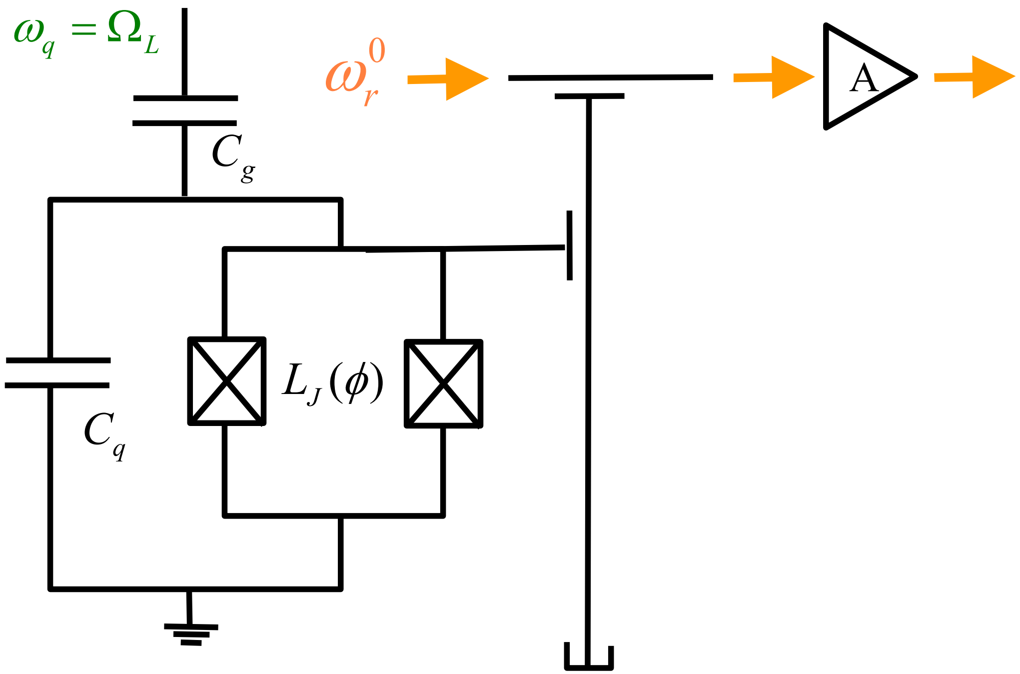
2) Le système de mesure par non-démolition (excitation par injection de photons dans le résonateur et mesure électronique de la transmission) est enclenché à intervalles $\Omega_R.T=\pi/2$.
Quels sont les signaux détectés ?
«0» = état de base, «1» = état excité

Exercice 13.2: effet Zénon



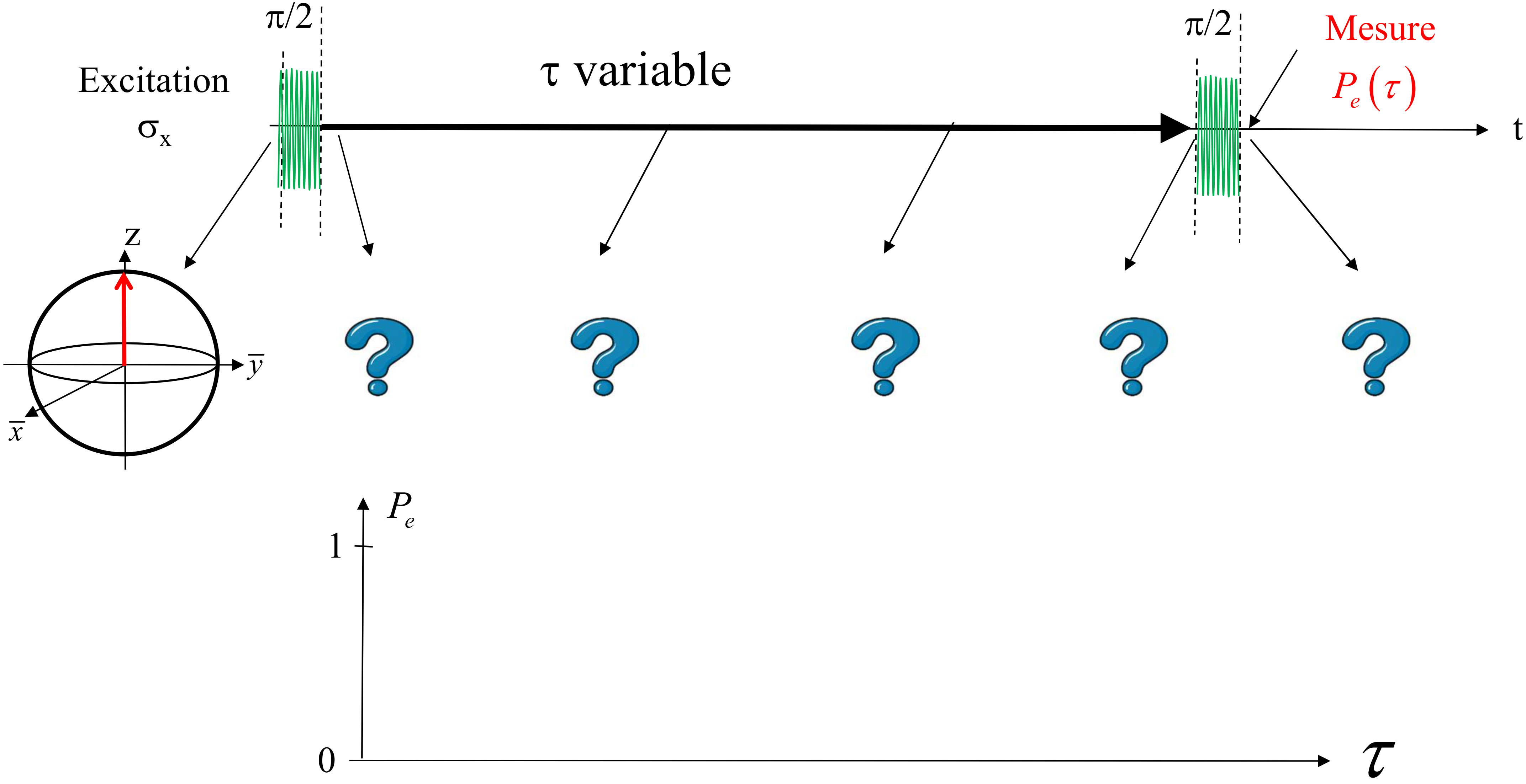
3) Le système de mesure par non-démolition (excitation par injection de photons dans le résonateur et mesure électronique de la transmission) fonctionne en continu.
Quels sont les signaux détectés ?
«0» = état de base, «1» = état excité

Exercice 13.2: effet Zénon



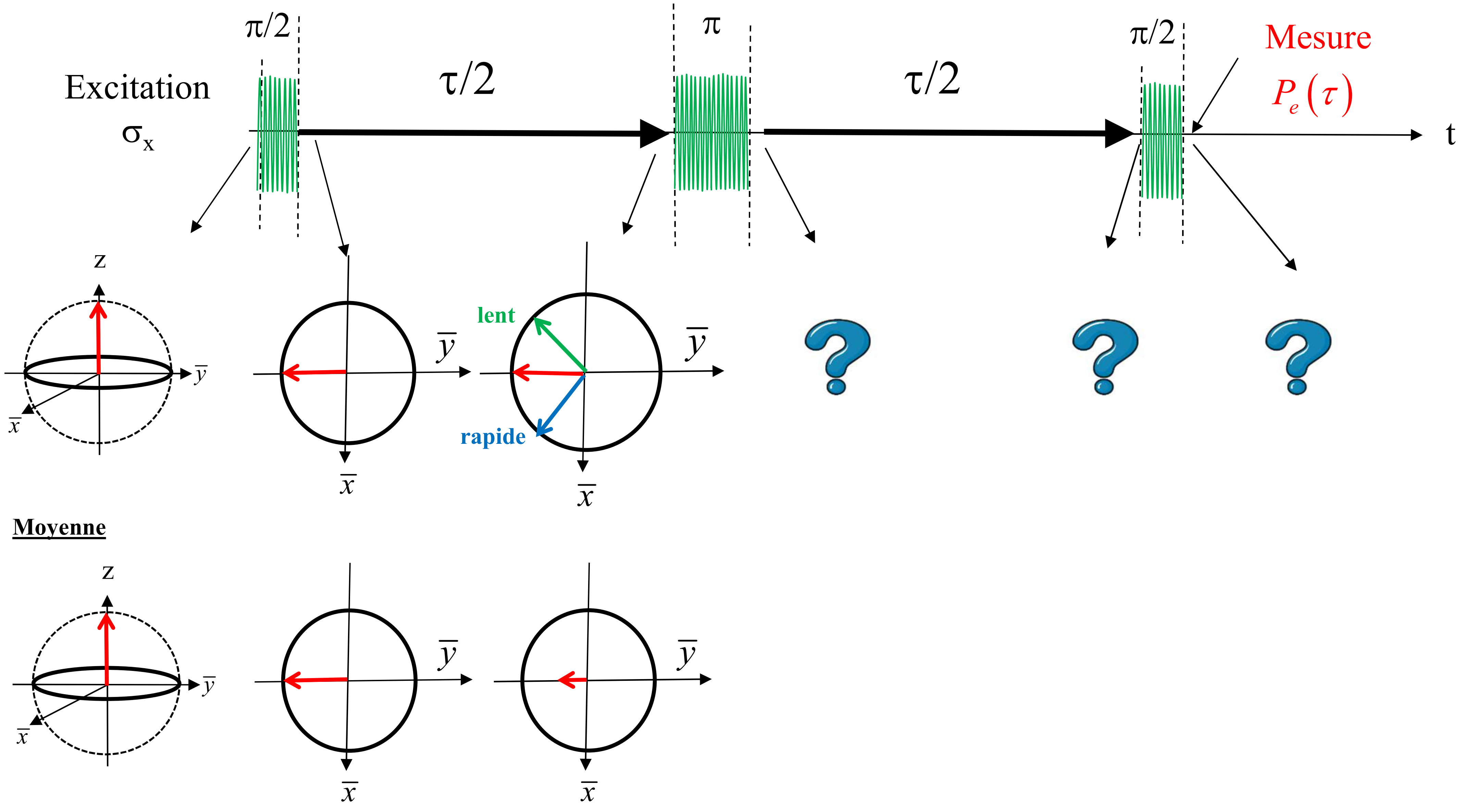
4) Seule l'excitation par injection de photons fonctionne en continu. La mesure électronique de la transmission est elle enclenché à intervalles $\Omega_R.T=\pi$ Quels sont les signaux détectés ?
«0» = état de base, «1» = état excité

Exercice 13.3 Mesures de décohérence: analysez ce cas, mesure de T2*



PAB

Exercice 13.4: Mesures de décohérence: analysez ce cas: mesure de T2



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Exercice 13.4: Mesures de décohérence: analysez ce cas: mesure de T2