

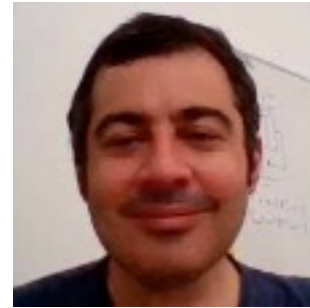
Techniques micro-onde pour l'ingénierie quantique

*Jérôme Estève, Laboratoire de Physique des Solides
ENS Associate Professor*

**Journée thématique : Quelle formation en électronique pour les
technologies quantiques et l'IA ?**

ENS Paris-Saclay 18/06/2026

Manipuler un Qubit Supraconducteur

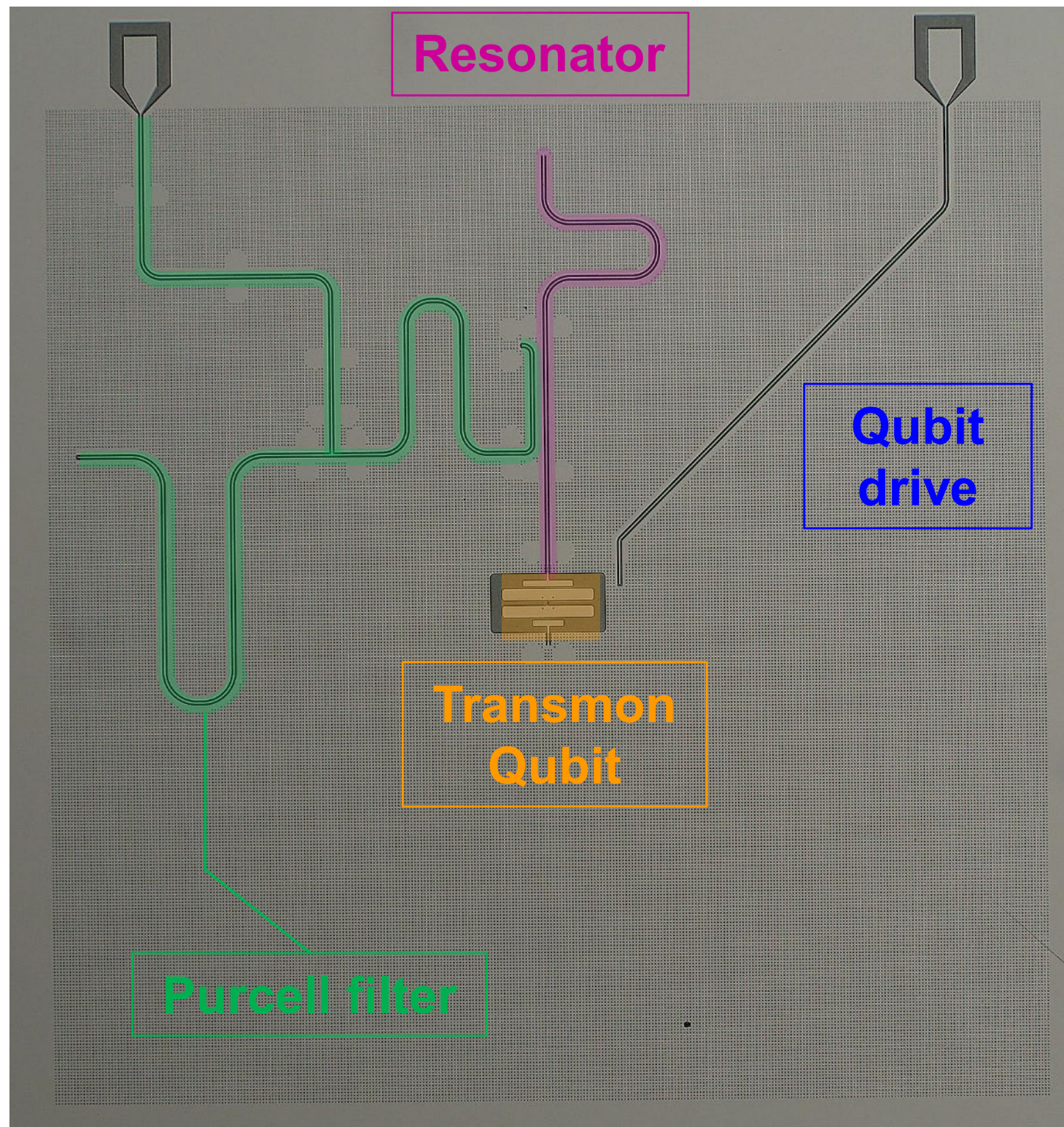


LPS : J. Basset, J. Estève, M. Ferrier, J. Gabelli

SPEC : M. Goffman

- Formation continue pour ingénieurs arrivant dans le quantique
- Formation initiale: ARTEQ, Quarmen, ...
- Jour 1 : Comprendre un circuit supraconducteur et sa conception
- Jour 2 : Génération et mesure de signaux micro-ondes
- Jour 3 : Manipulation du qubit

Circuit Supraconducteur Micro-Onde

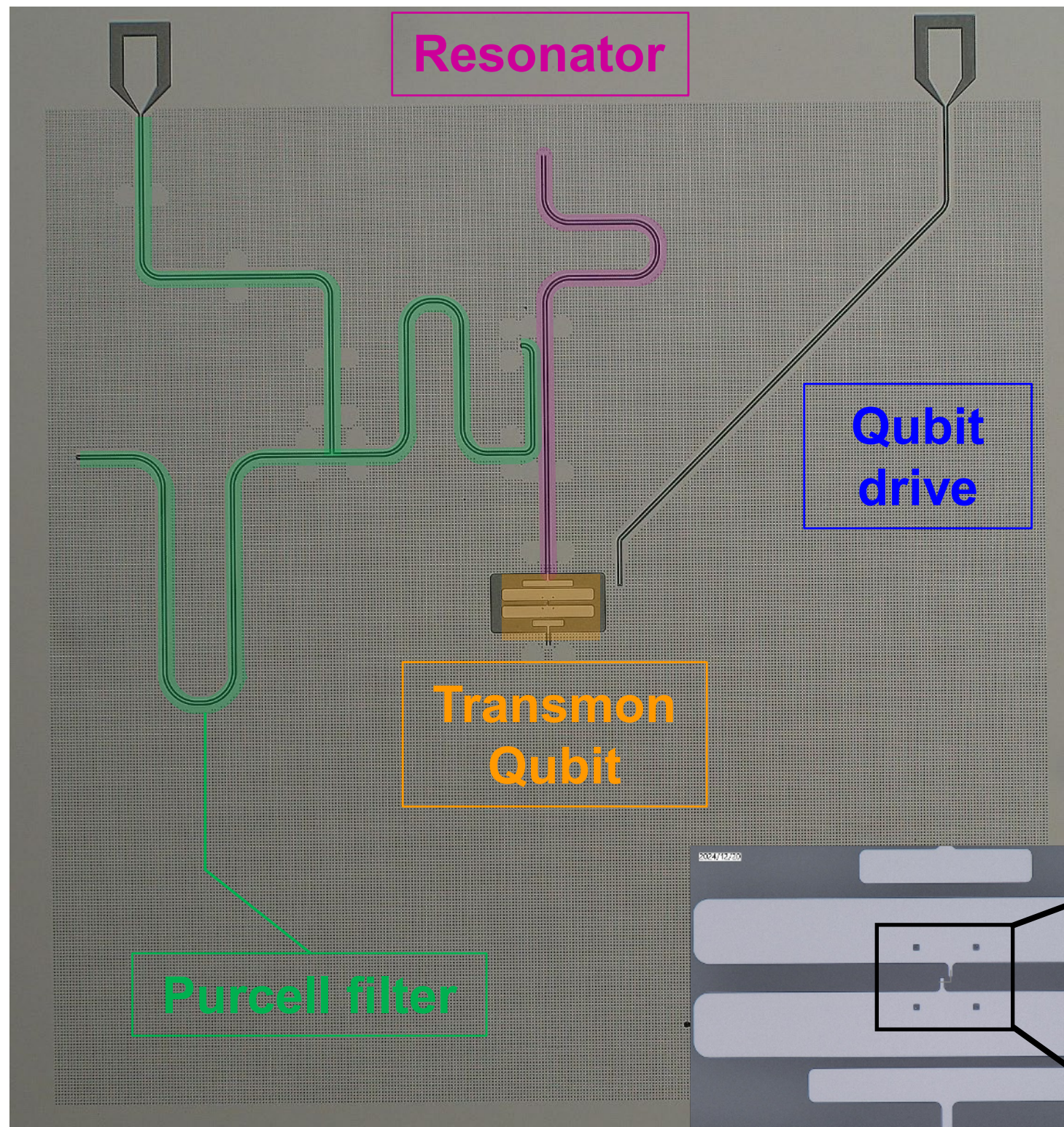


- Guide d'onde coplanaire
- Résonateur $\lambda/2$
- Filtre $\lambda/4$ (Stub)

Modélisation:

- Sonnet
- Python (Scikit RF)

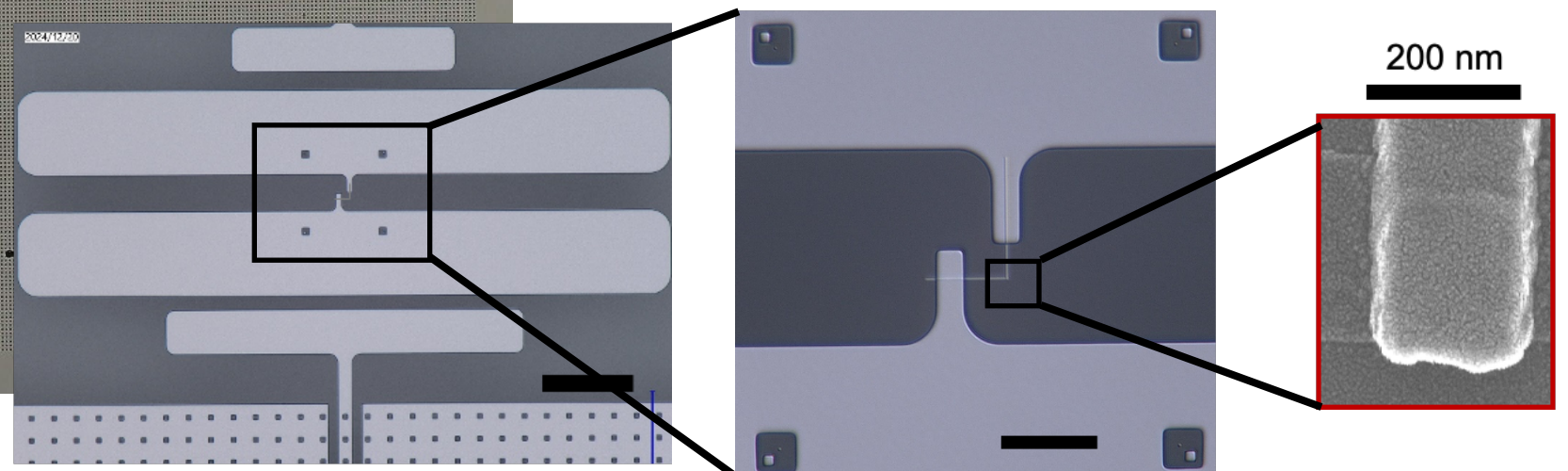
Circuit Supraconducteur Micro-Onde



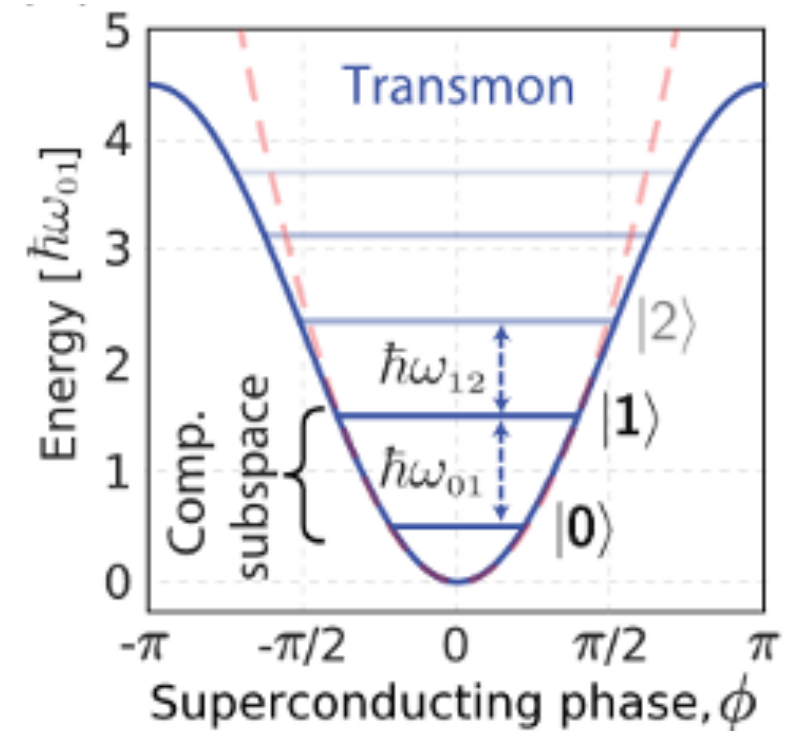
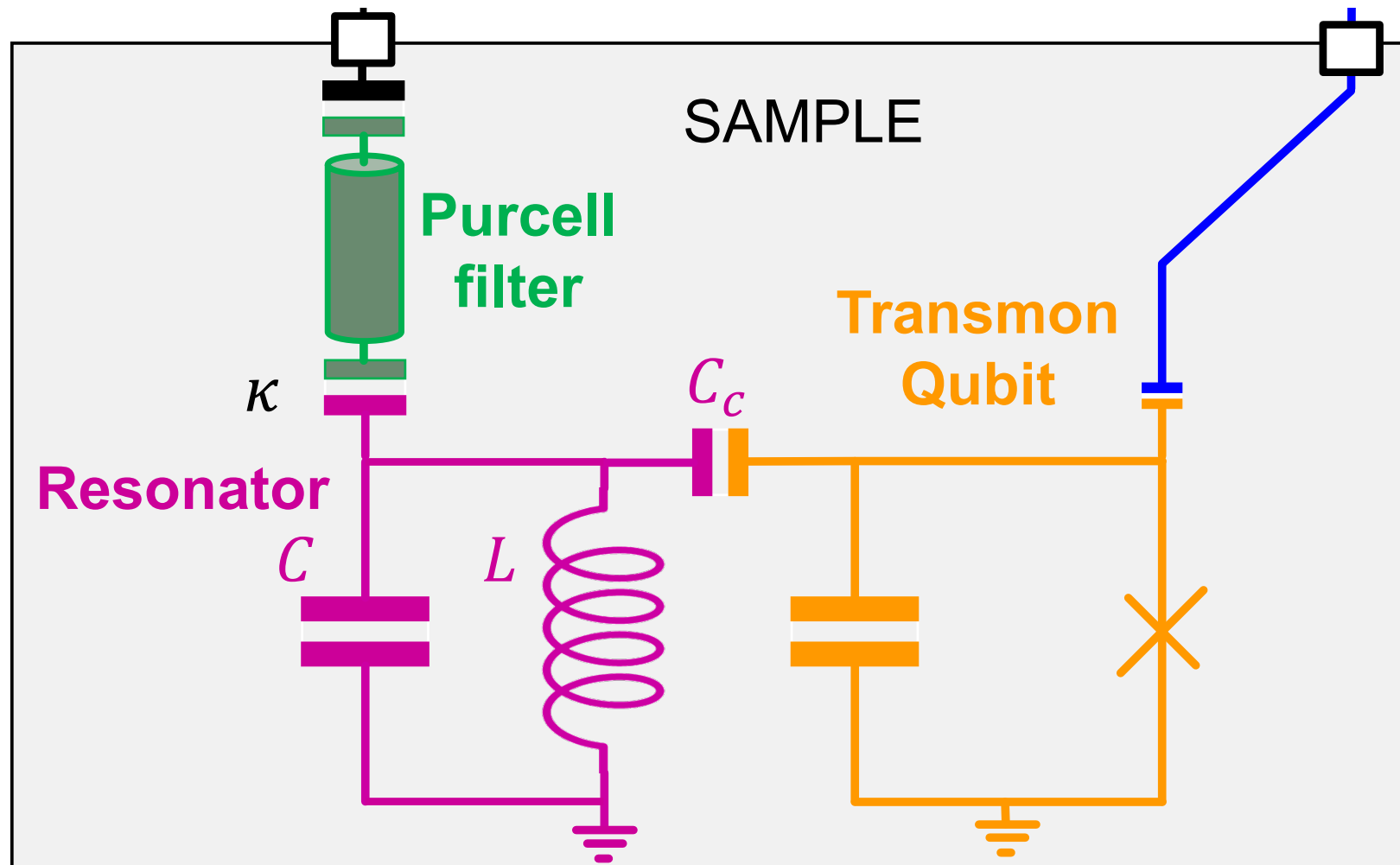
- Guide d'onde coplanaire
- Résonateur $\lambda/2$
- Filtre $\lambda/4$ (Stub)

Modélisation:

- Sonnet
- Python (Scikit RF)



Modélisation



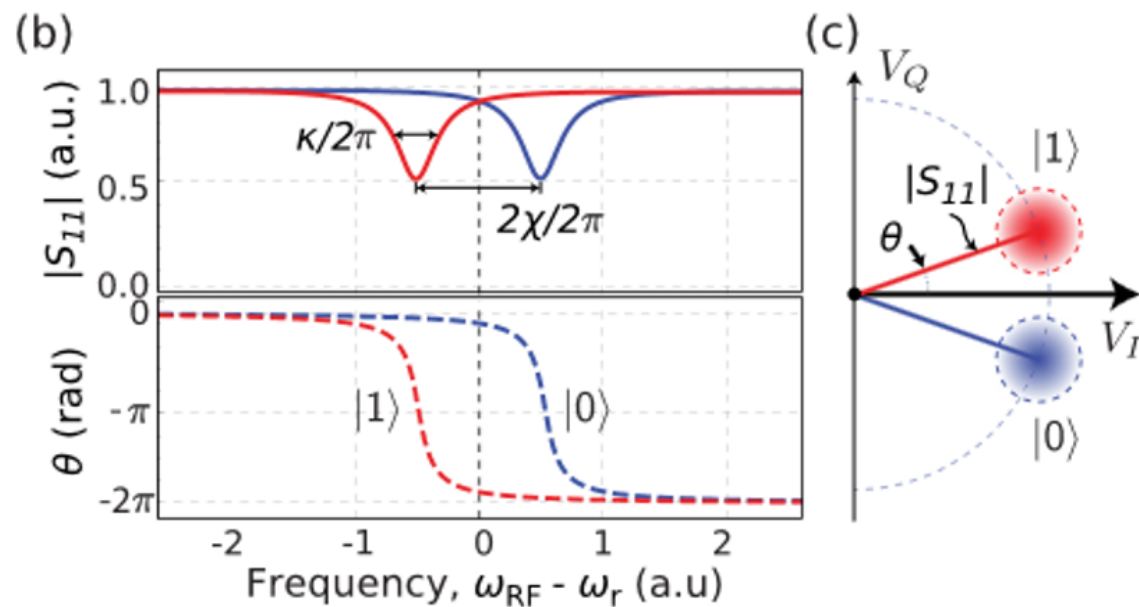
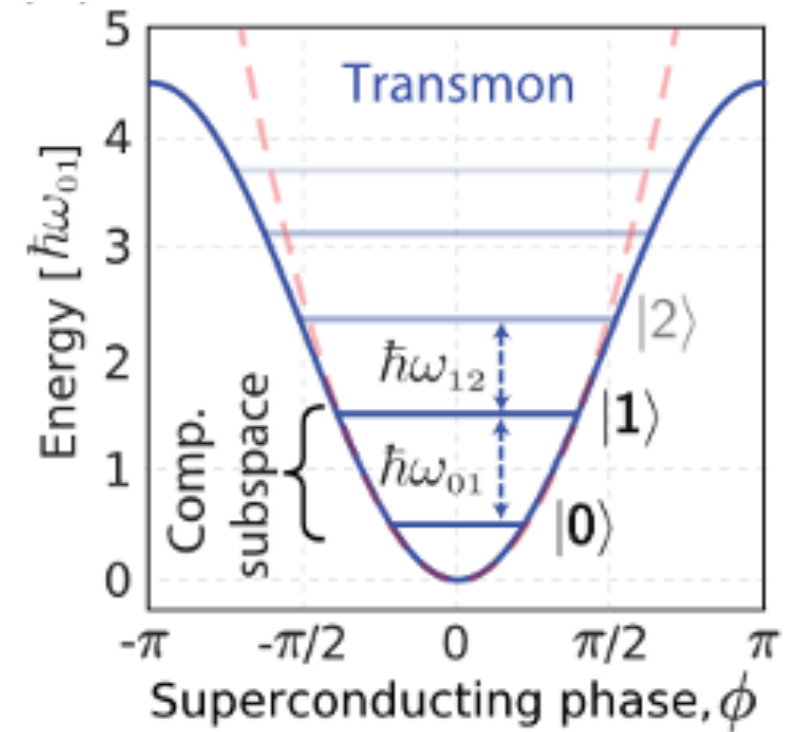
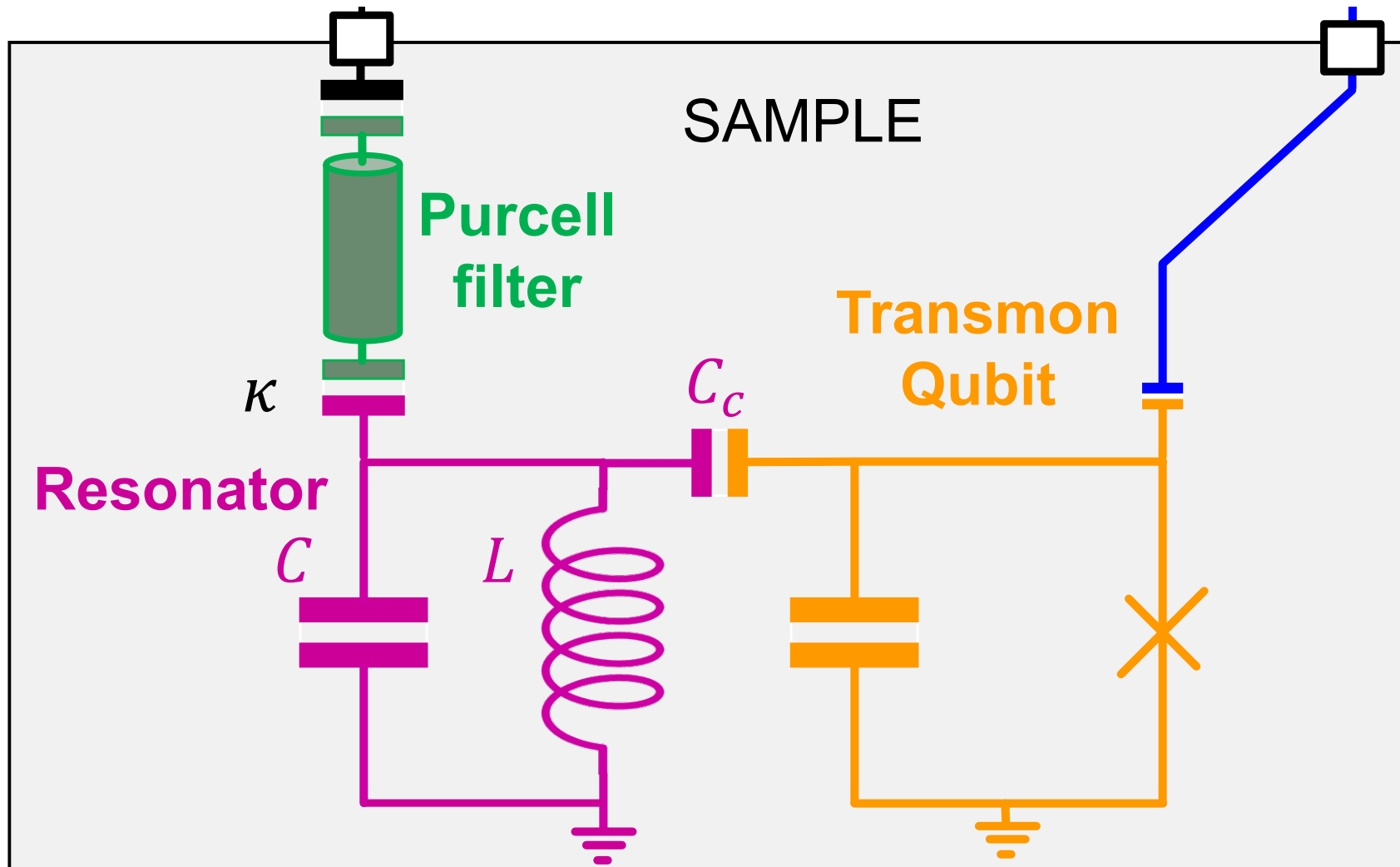
Modèle:

- Deux oscillateurs couplés, dont un non-linéaire
- Deux ports connectés vers l'extérieur, dont un filtré

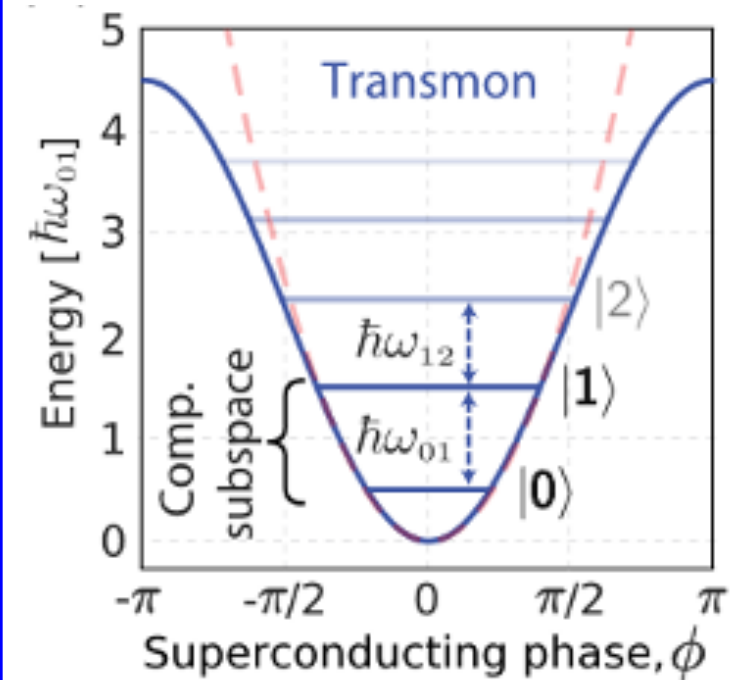
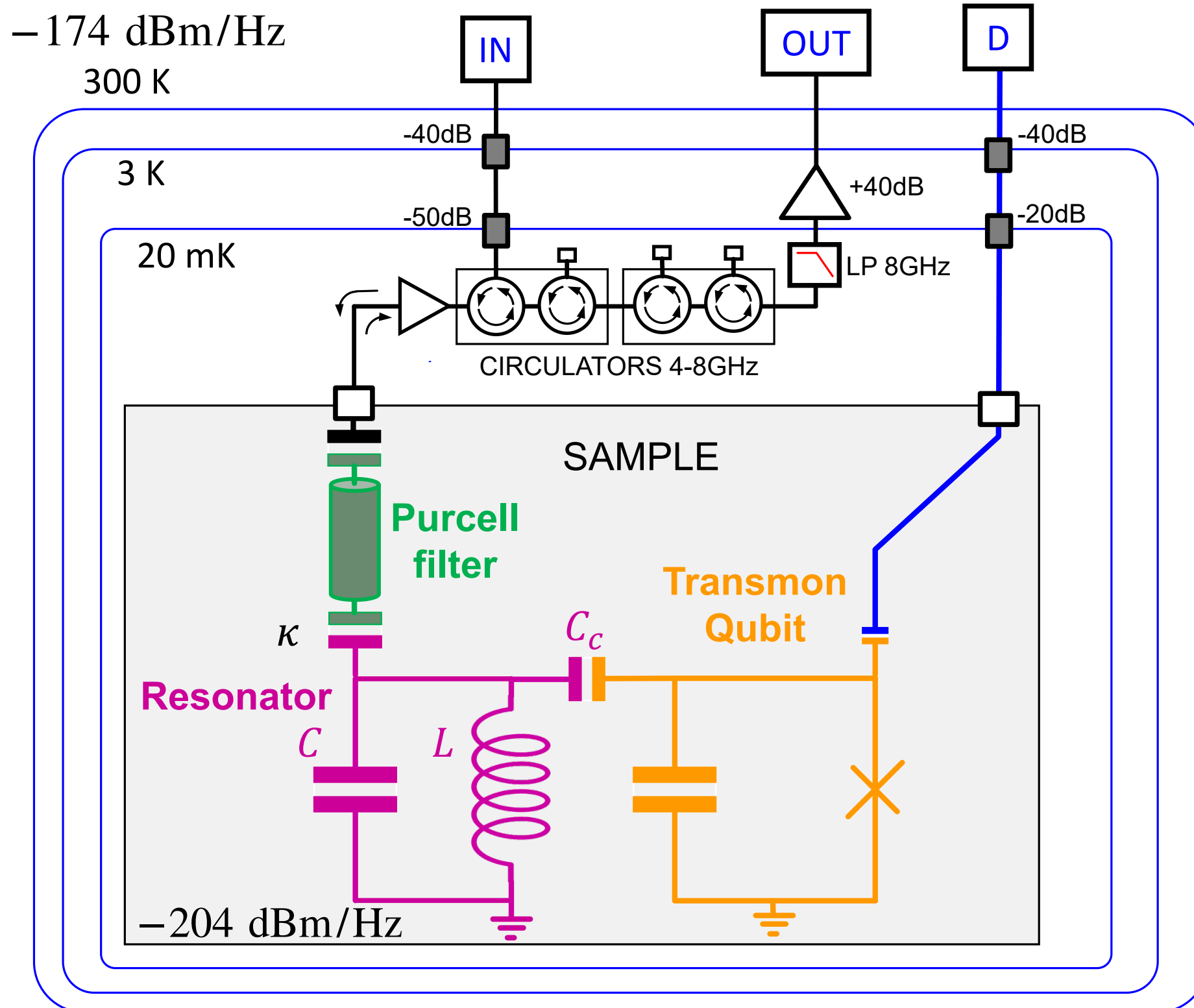
Modélisation

Lecture

Drive



Amplitude des signaux



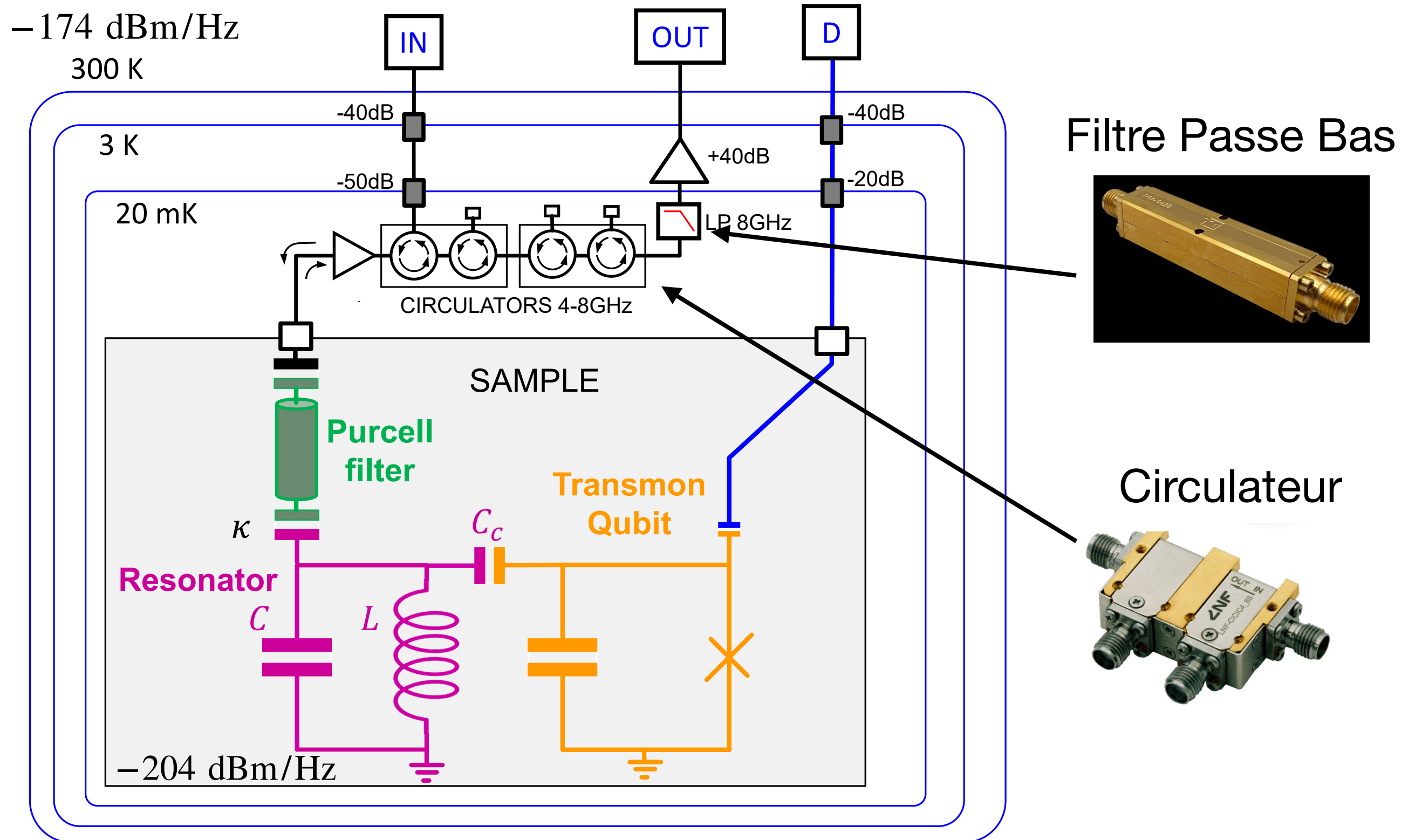
$$k_B T \ll \hbar\omega_{01}$$

$$\text{Noise} \ll \hbar\omega_{01}$$

$$\text{Signal} \approx \hbar\omega_{01}$$

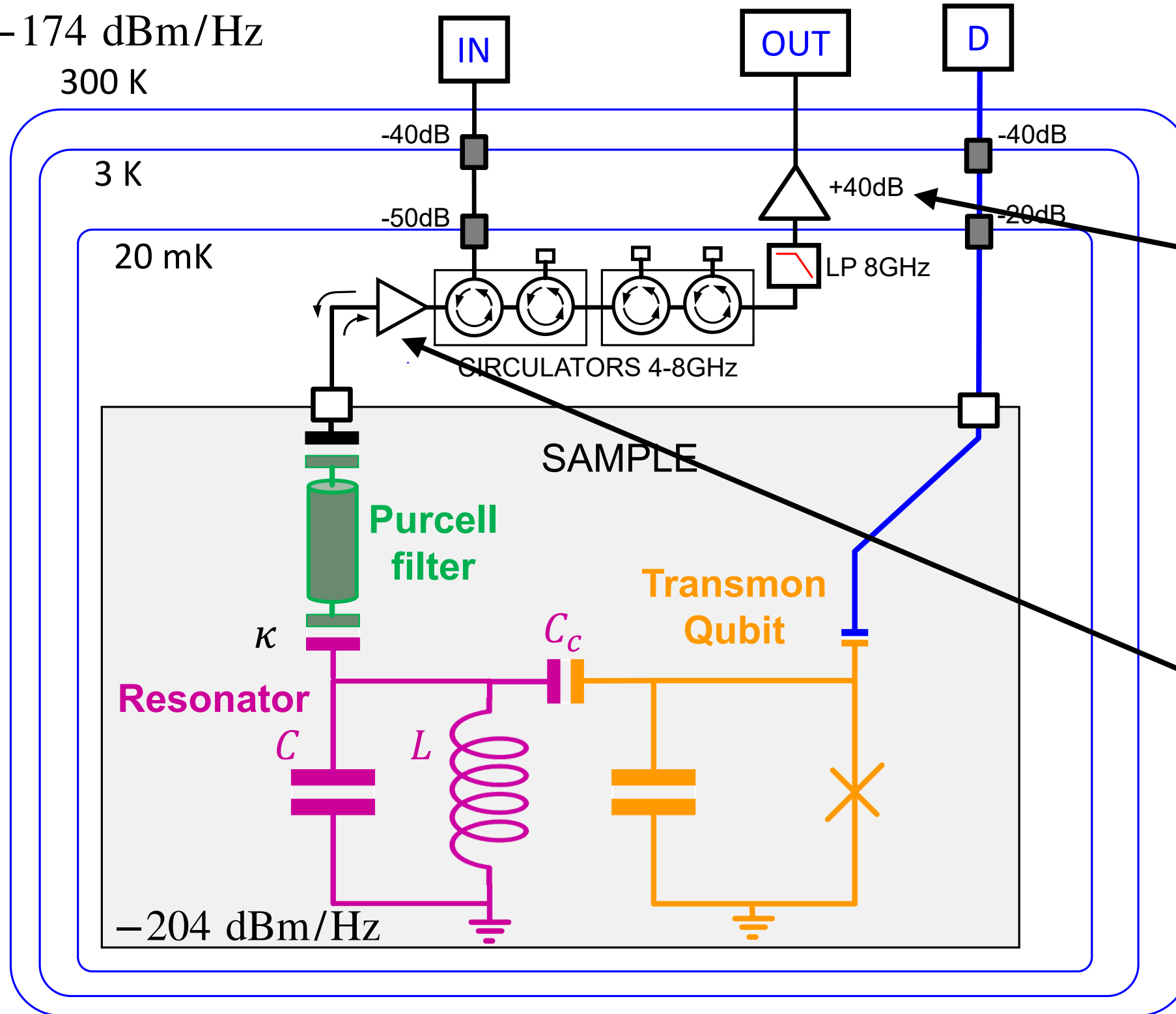
Cryostat à dilution

Filtres et isolateurs cryogéniques



Amplificateurs cryogéniques

-174 dBm/Hz
300 K



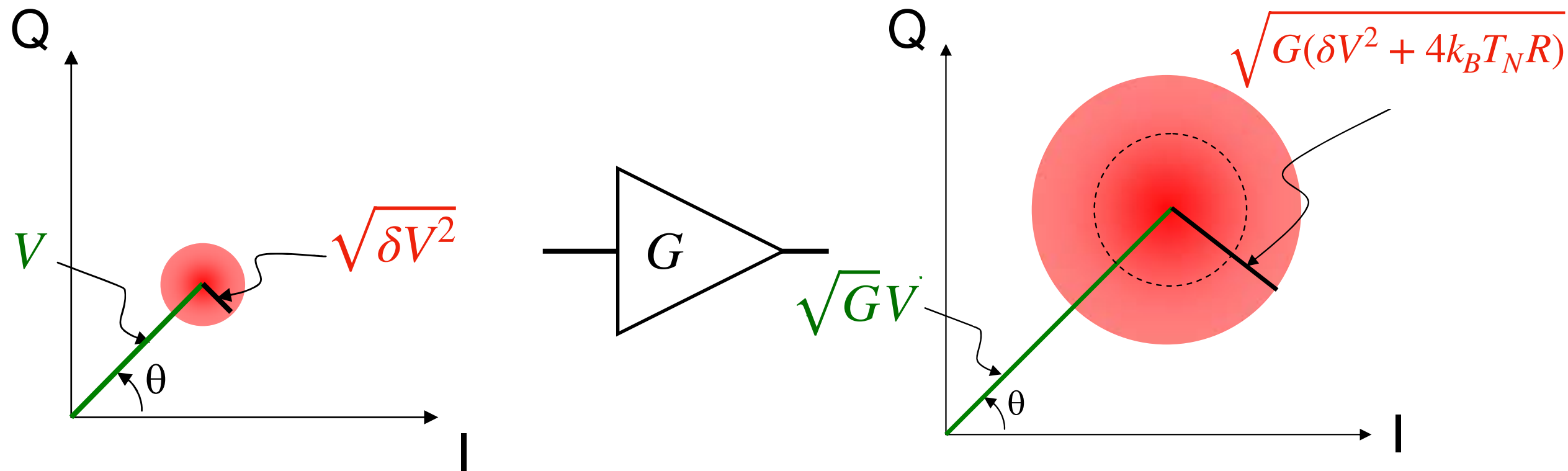
HEMT Amplifier



Ampli Paramétrique

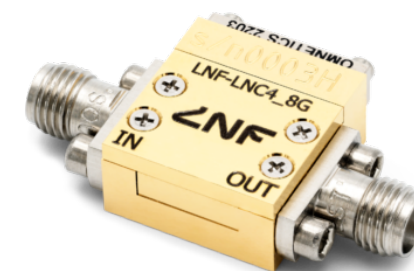


Bruit d'un amplificateur



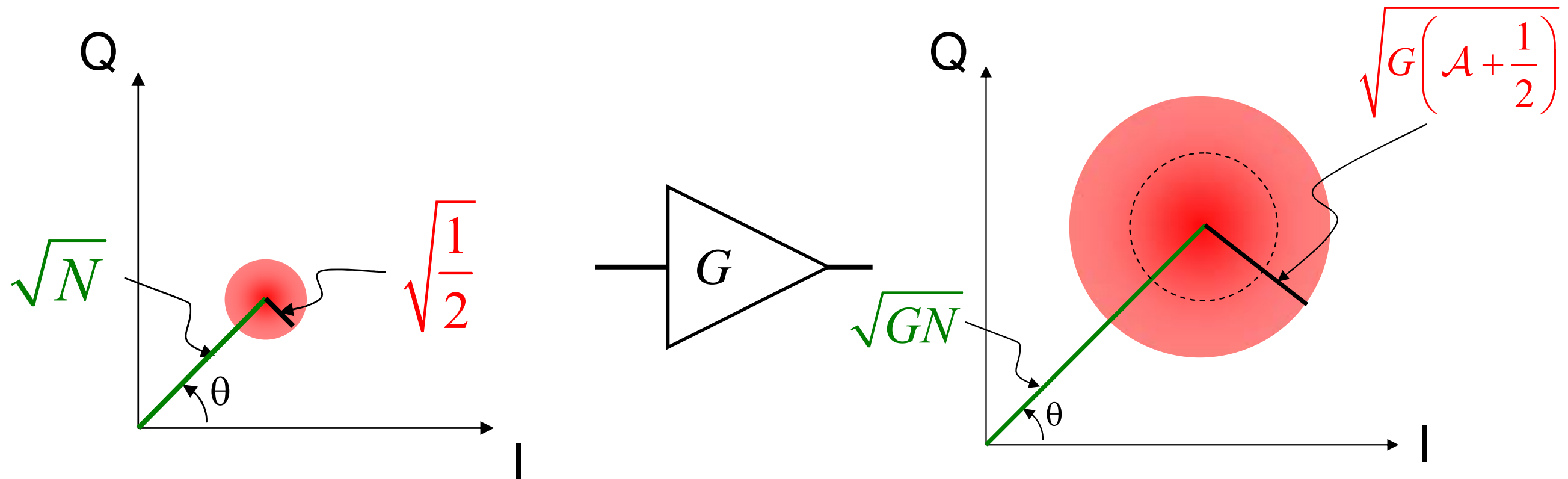
Bruit ajouté : $k_B T_N$

HEMT cryogénique



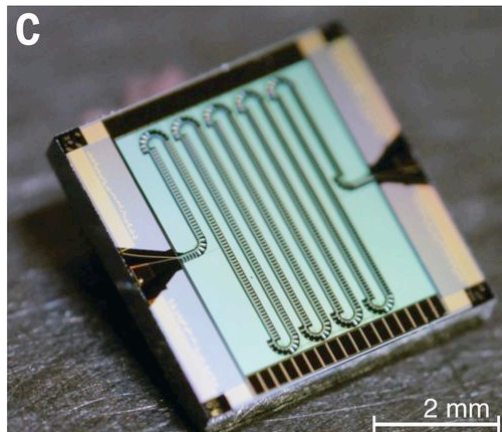
$$T_N = 1.5 \text{ K}$$

Bruit d'un amplificateur



Bruit ajouté : $\mathcal{A} = \frac{k_B T_N}{\hbar \omega} > \frac{1}{2}$ (Limite Quantique)

TWPA



$$\mathcal{A} \approx 1 - 1.5$$

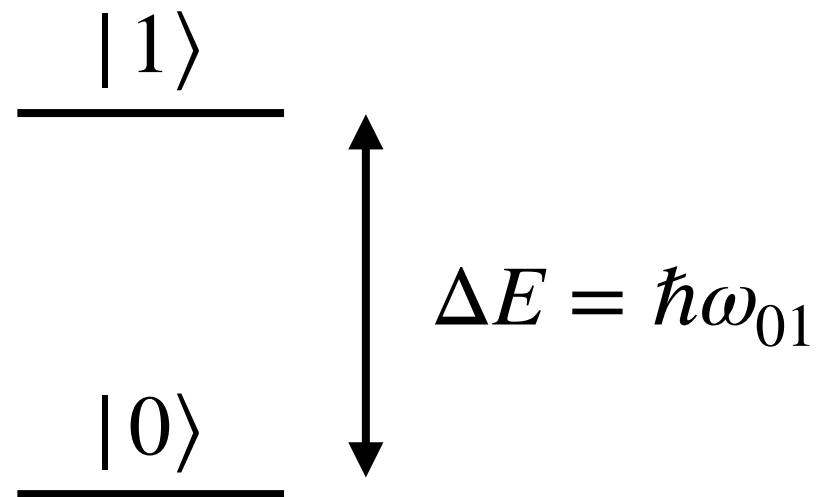
HEMT



$$T_N = 1.5 \text{ K}$$

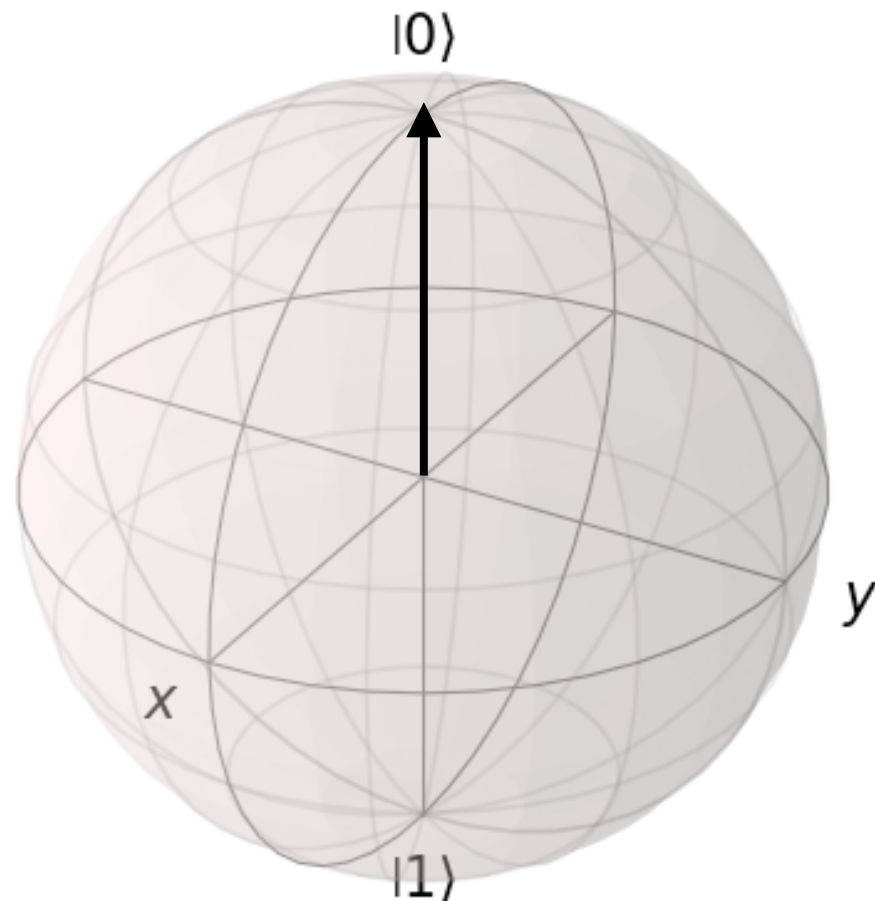
$$\mathcal{A} = 5.2$$

Manipulation du qubit

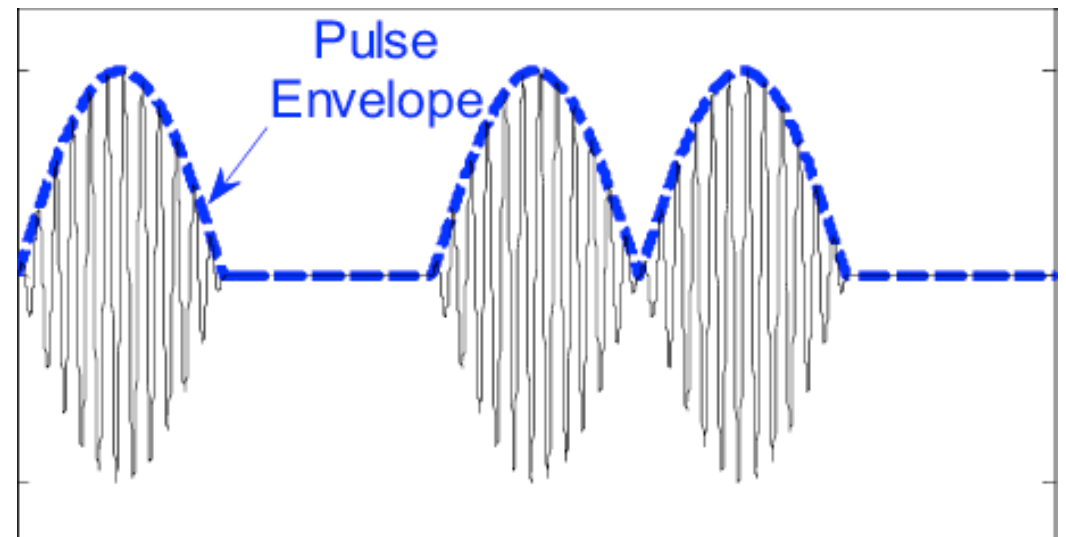


Fréquence du qubit

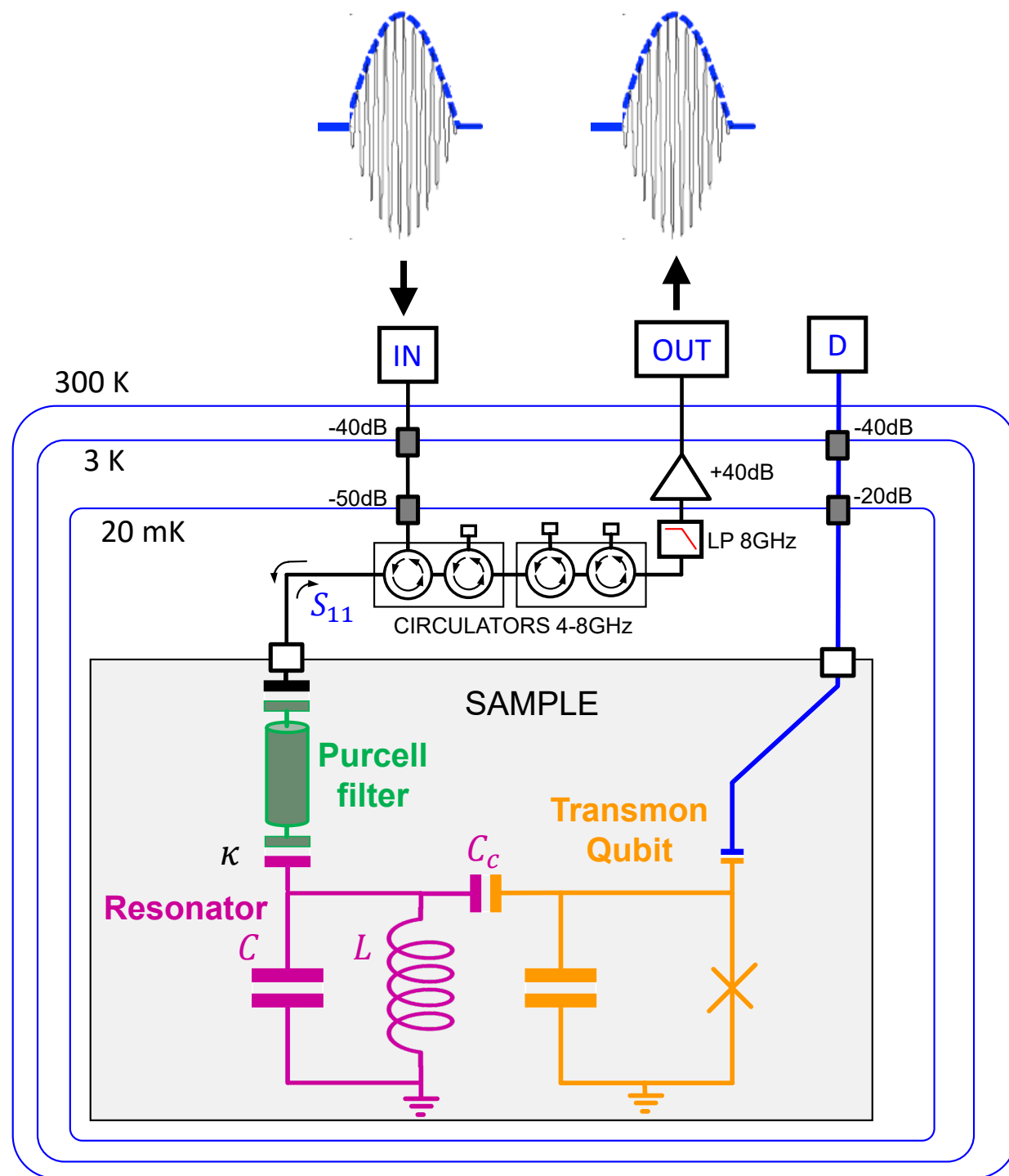
Typiquement entre 4 et 8 GHz



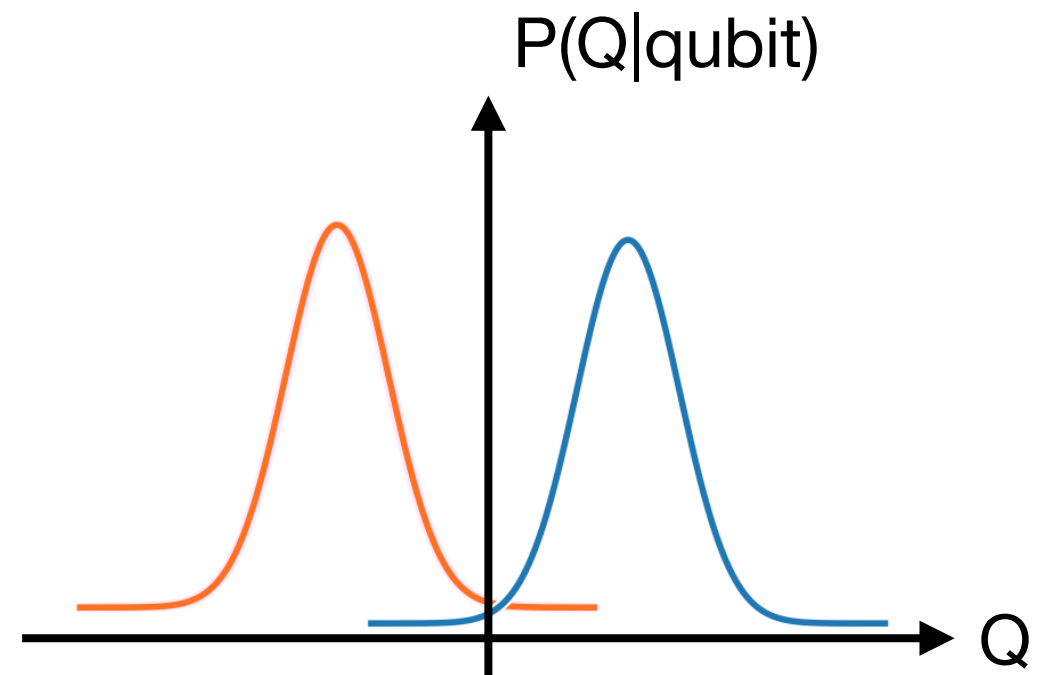
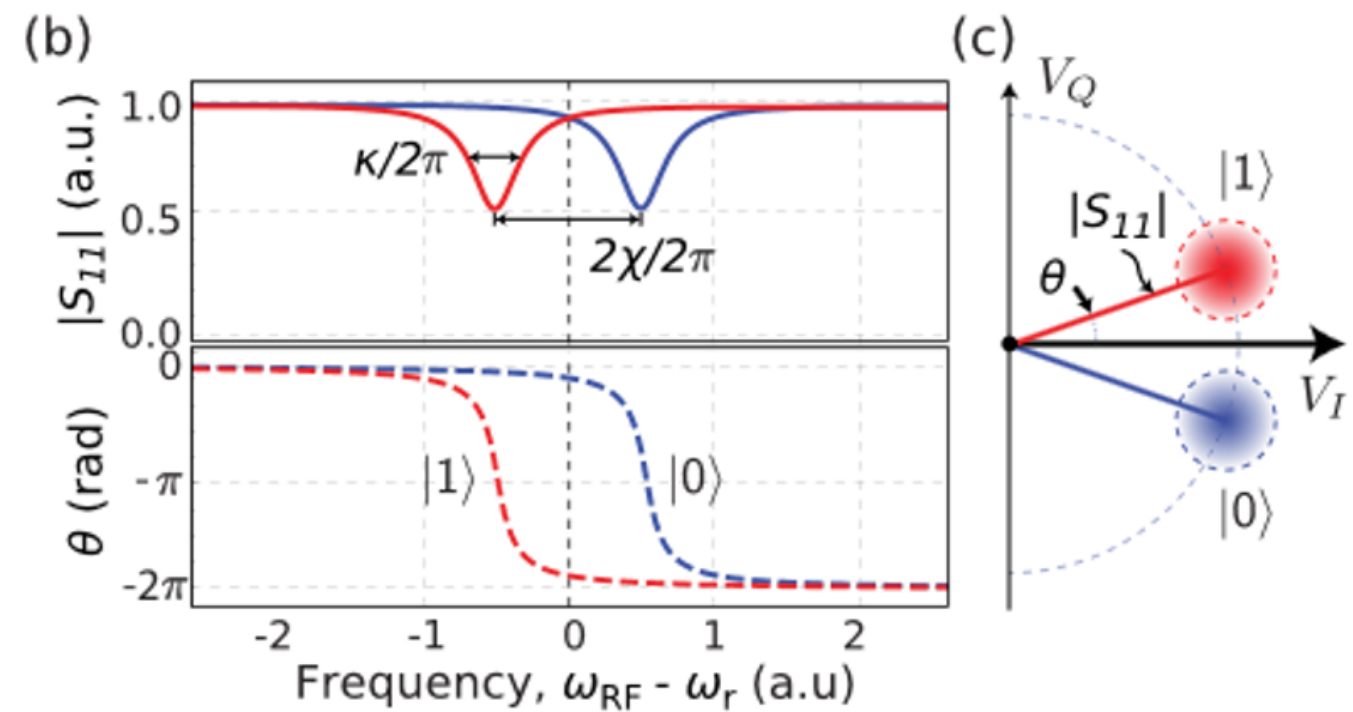
Impulsions contrôlées en phase et en amplitude

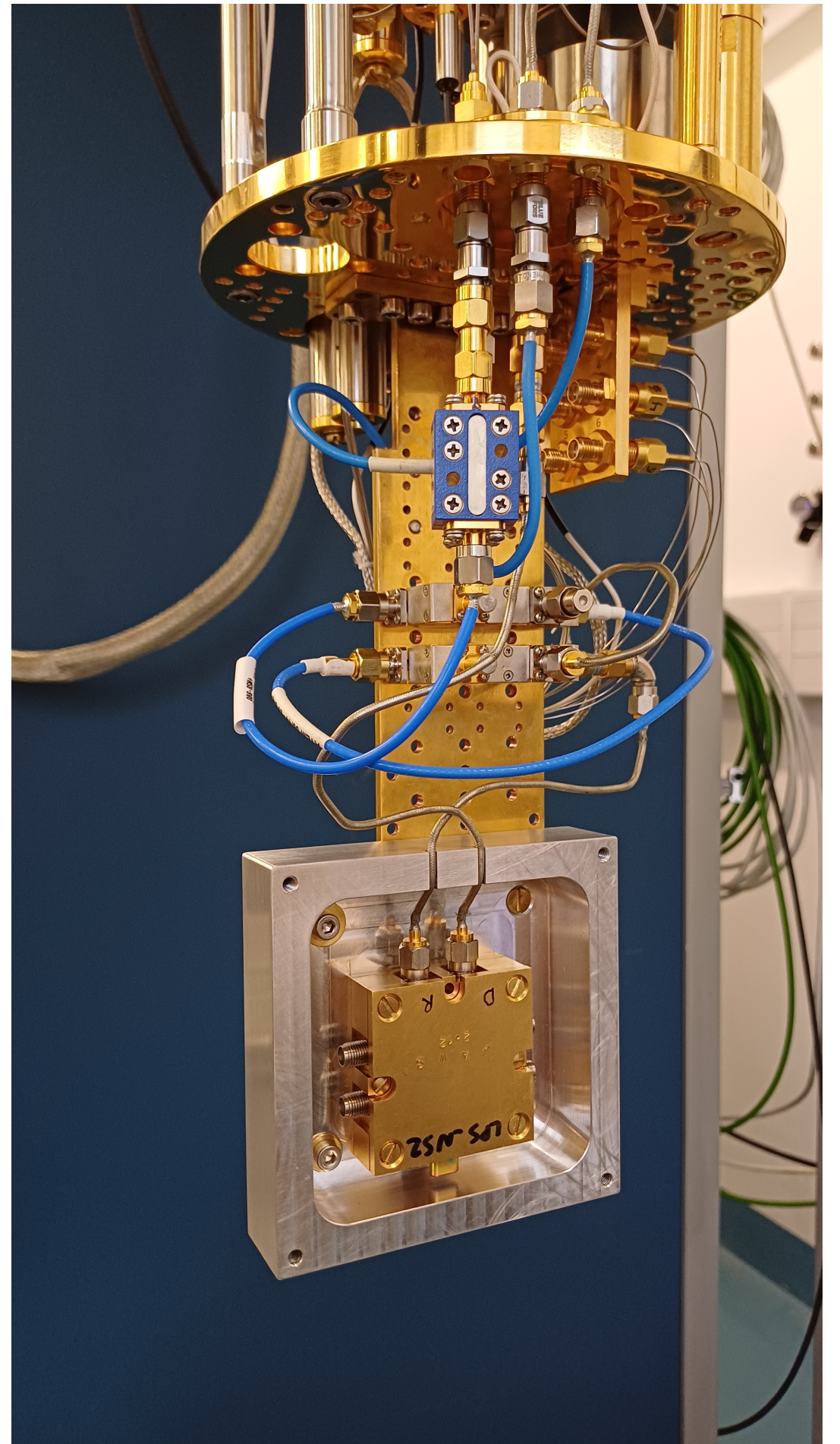
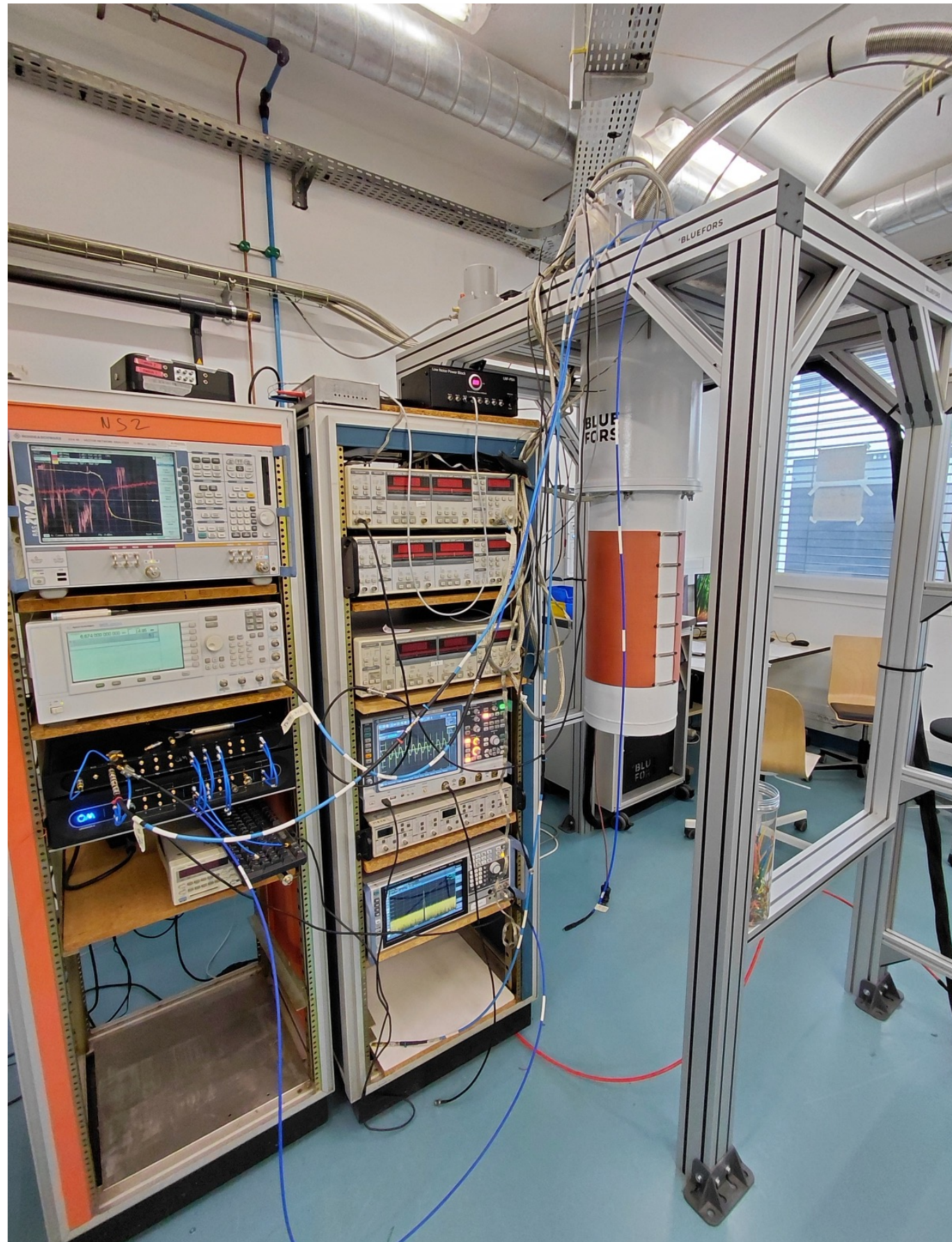


Lecture du qubit

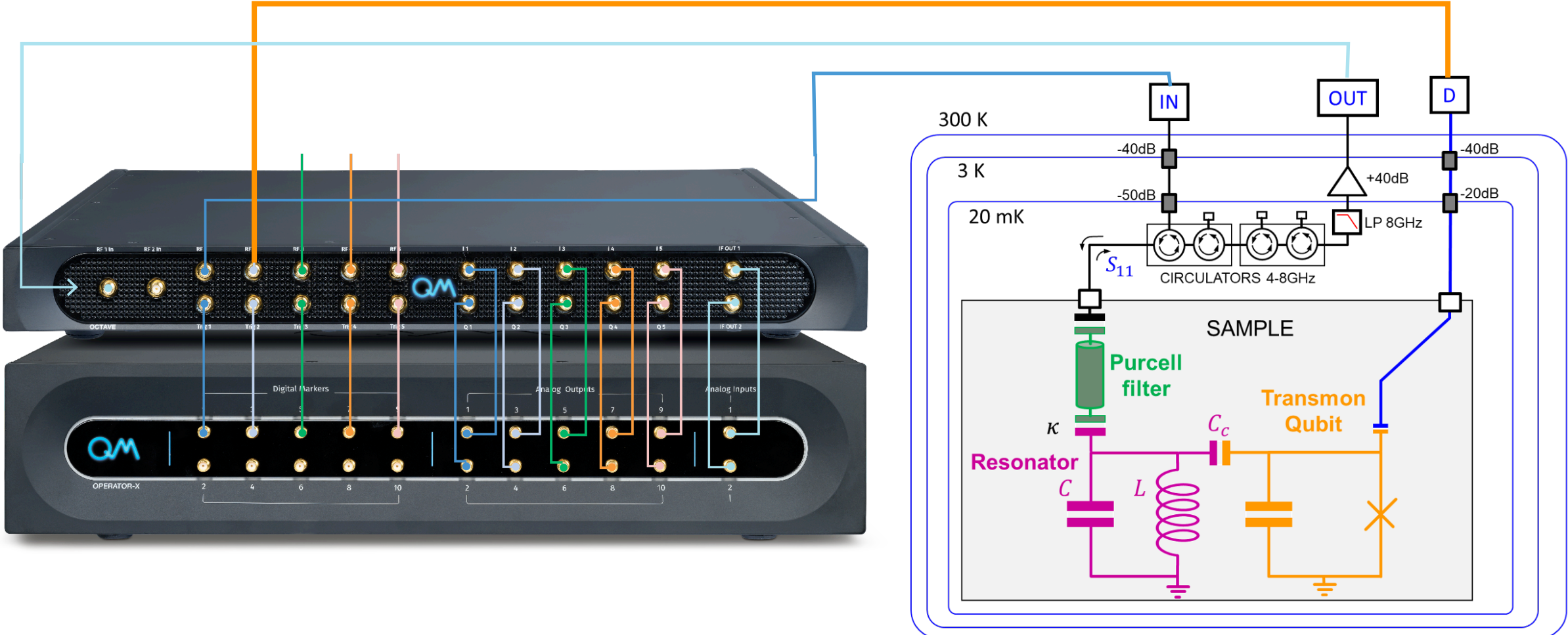


Mesurer I et Q
après réflexion

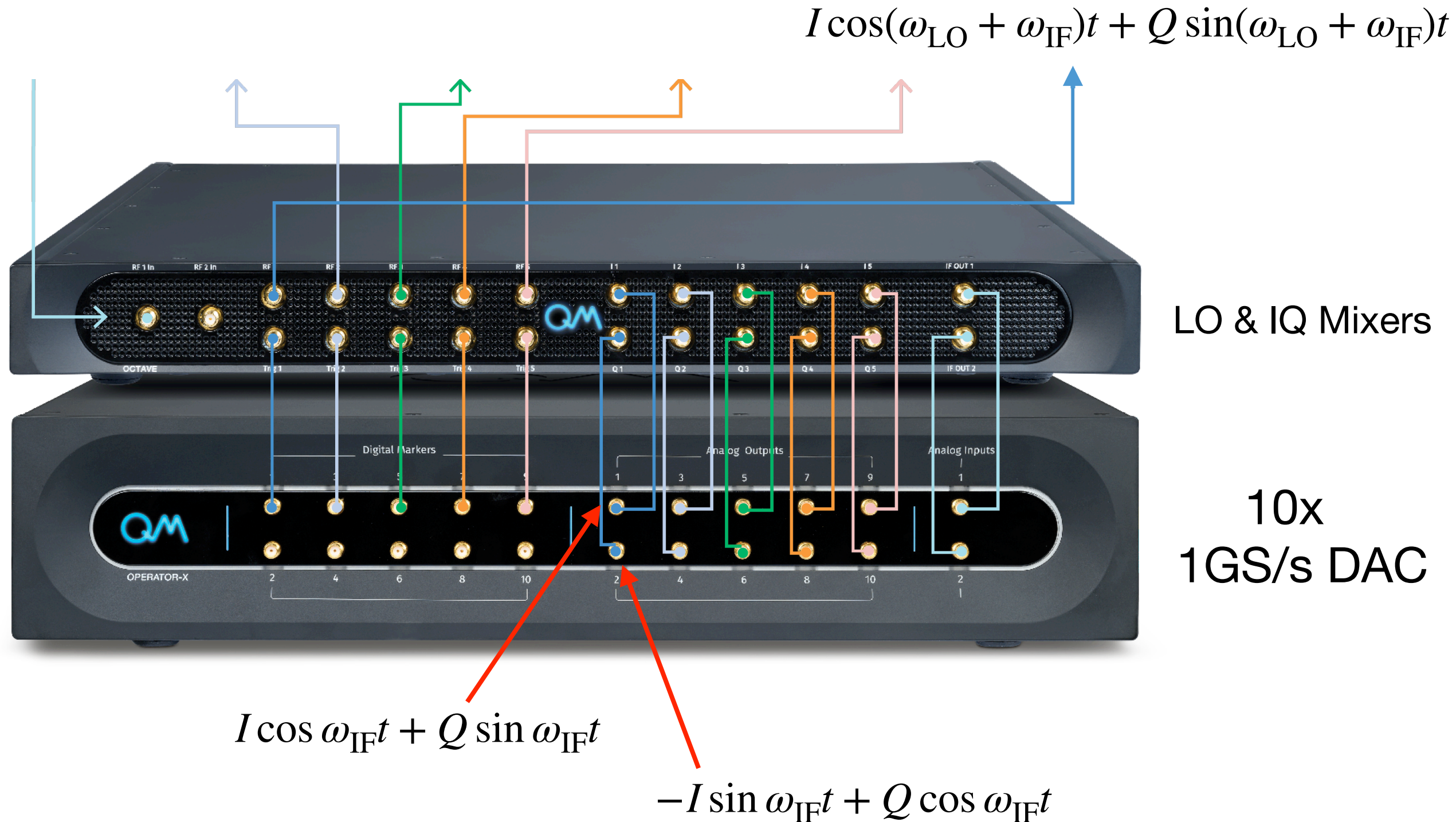




Quantum Machine



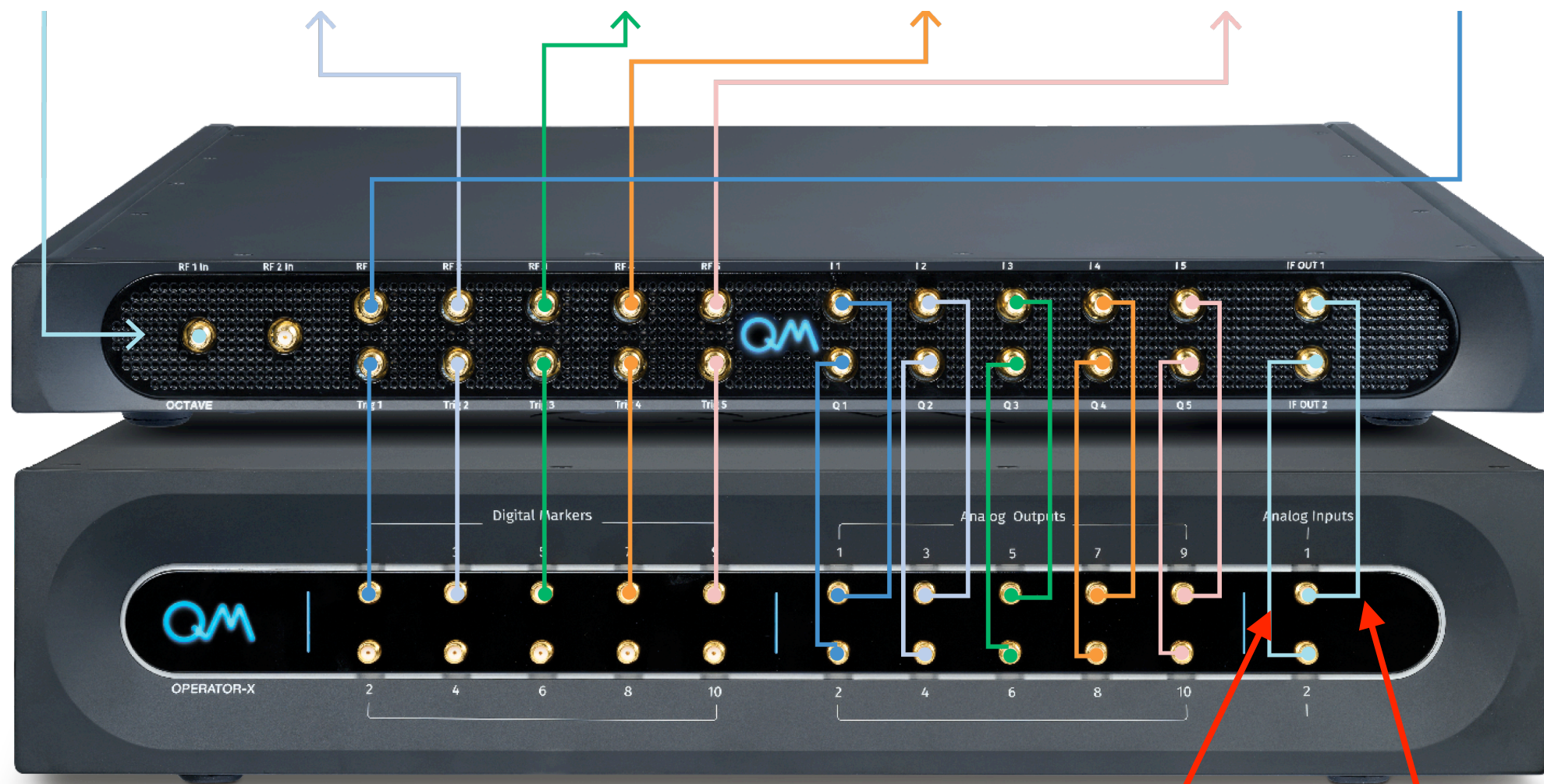
Modulation IQ avec la Quantum Machine



LO frequency : 2 to 18 GHz
IF frequency : -350 to 350 MHz

Démodulation IQ avec la Quantum Machine

$$I \cos(\omega_{LO} + \omega_{IF})t + Q \sin(\omega_{LO} + \omega_{IF})t$$



2x
1GS/s ADC

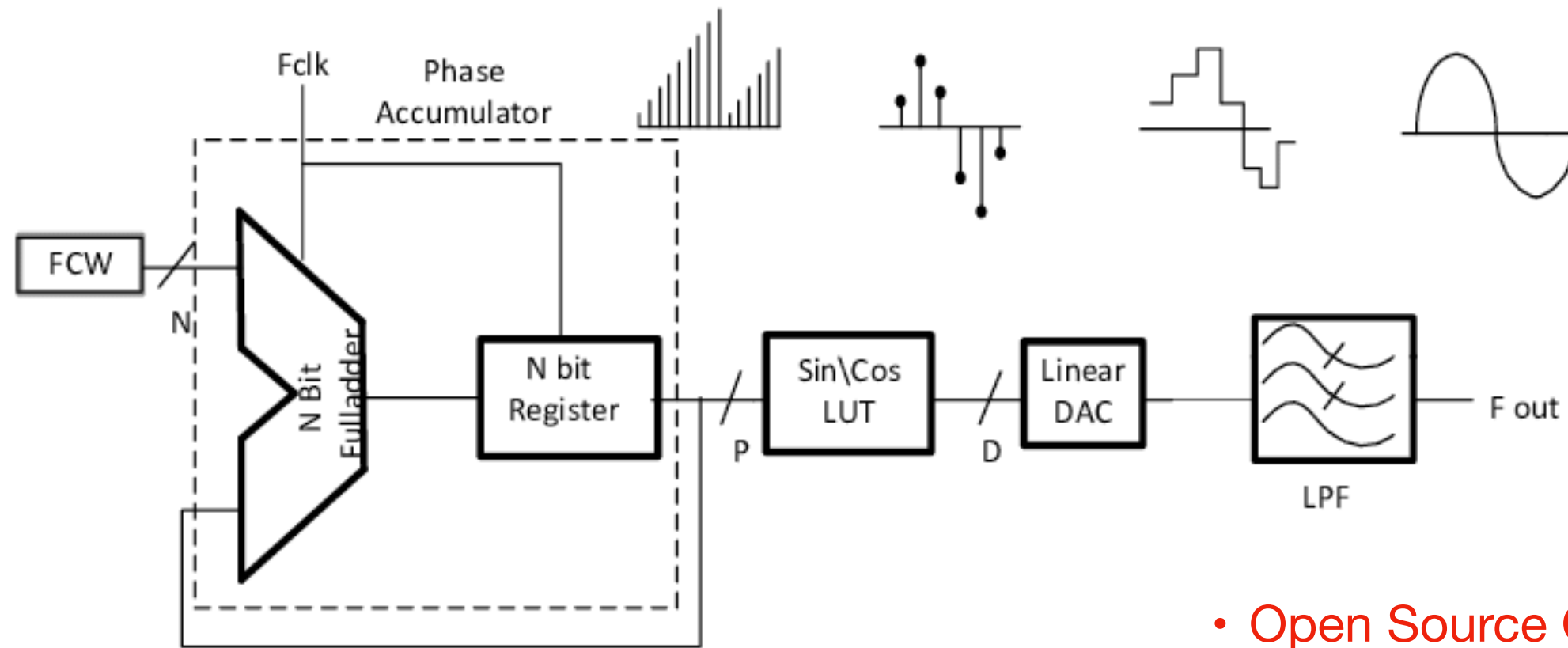
$$-I \sin \omega_{IF}t + Q \cos \omega_{IF}t$$

$$I \cos \omega_{IF}t + Q \sin \omega_{IF}t$$

FPGA to demodulate to I and Q

Approche par synthèse digitale directe

Direct Digital Synthesis (DDS)



- Open Source Qick (Fermilab)
- Quantum Machine OPX1000
- Qblox, Zurich Instruments, ...

Zynq™ UltraScale+™ RFSoc



Fréquence de fonctionnement jusqu'à 4 GHz

- 8 ou 16 DAC 6,554 GSPS
- 8 ADC 4,096 GSPS ou 16 ADC 2,058 GSPS



Fréquence de fonctionnement jusqu'à 5 GHz

- 16 DAC 6,554 GSPS
- 16 ADC 2,220 GSPS



Fréquence de fonctionnement jusqu'à 6 GHz

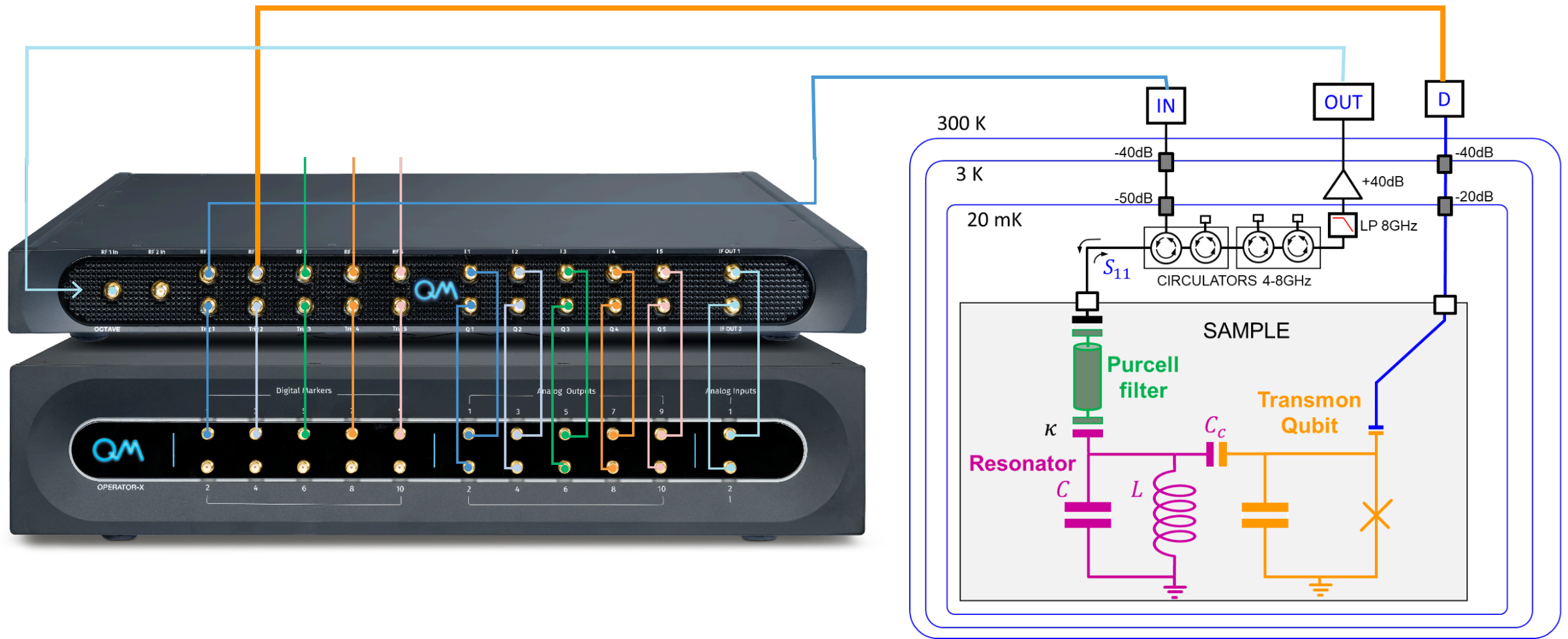
- 8 ou 16 DAC 9,85 GSPS (2 PLC)
- Jusqu'à 8 ADC 5,0 GSPS ou 16 ADC 2,5 GSPS



Fréquence de fonctionnement jusqu'à 7,125 GHz

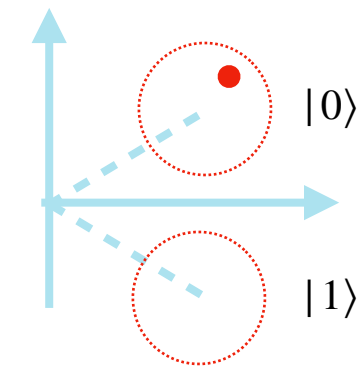
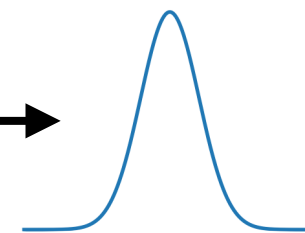
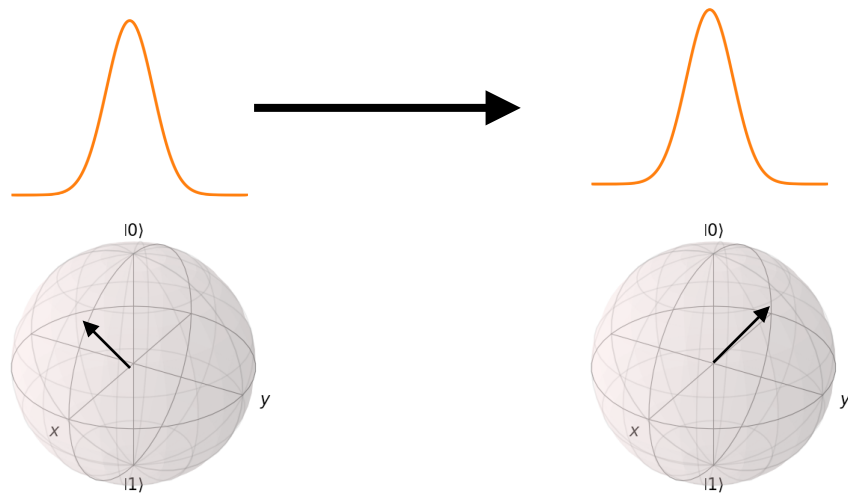
- 8 ou 6 DAC 9,851 GSPS
- 8 ADC 2,95 GSPS et 2 ADC 5,9 GSPS ou 6 ADC 5,9 GSPS

Séquence Expérimentale



Qubit Controls

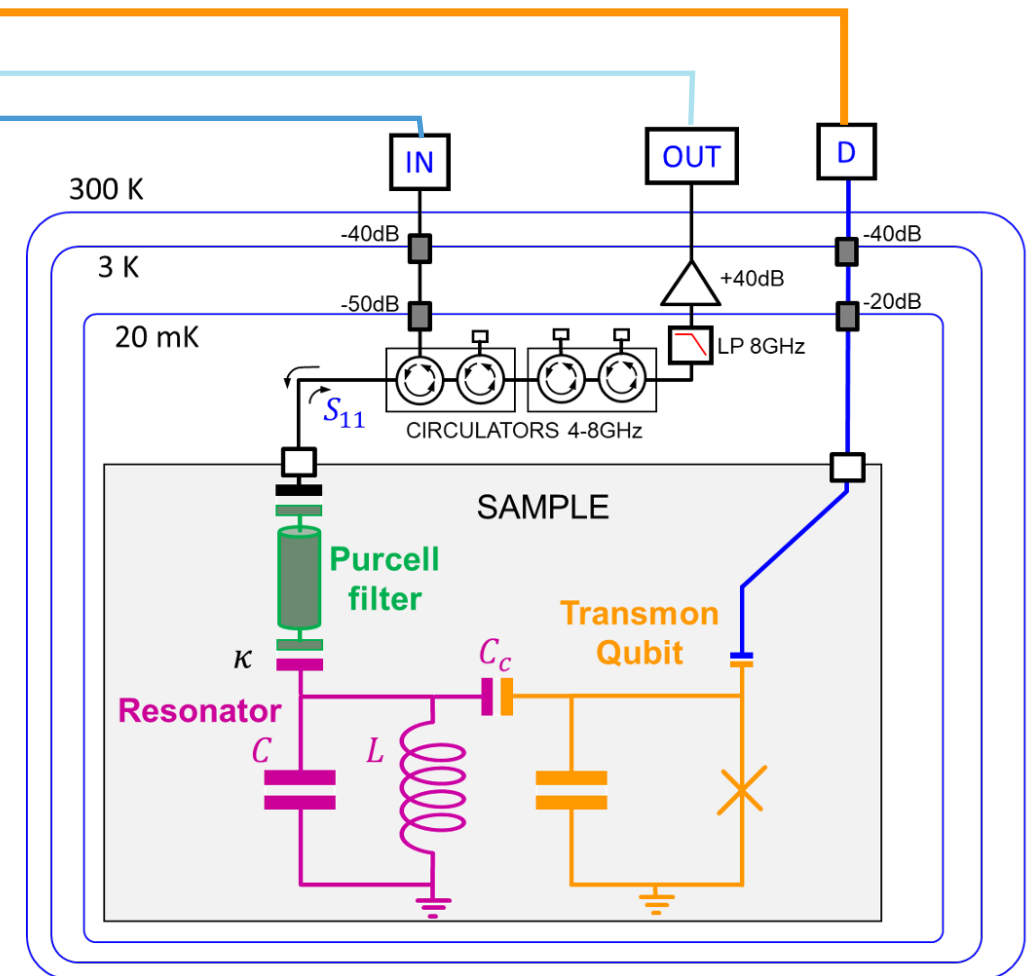
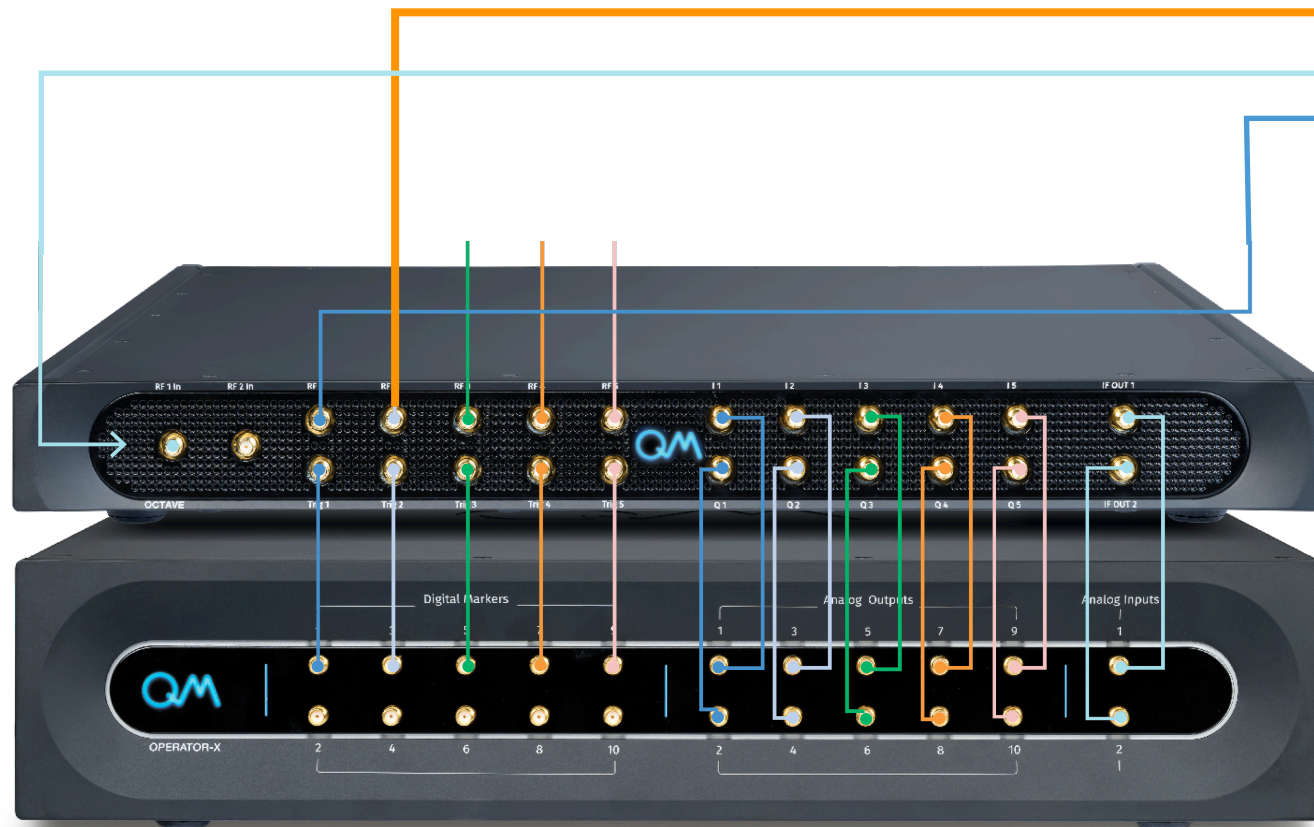
Readout



0, ...

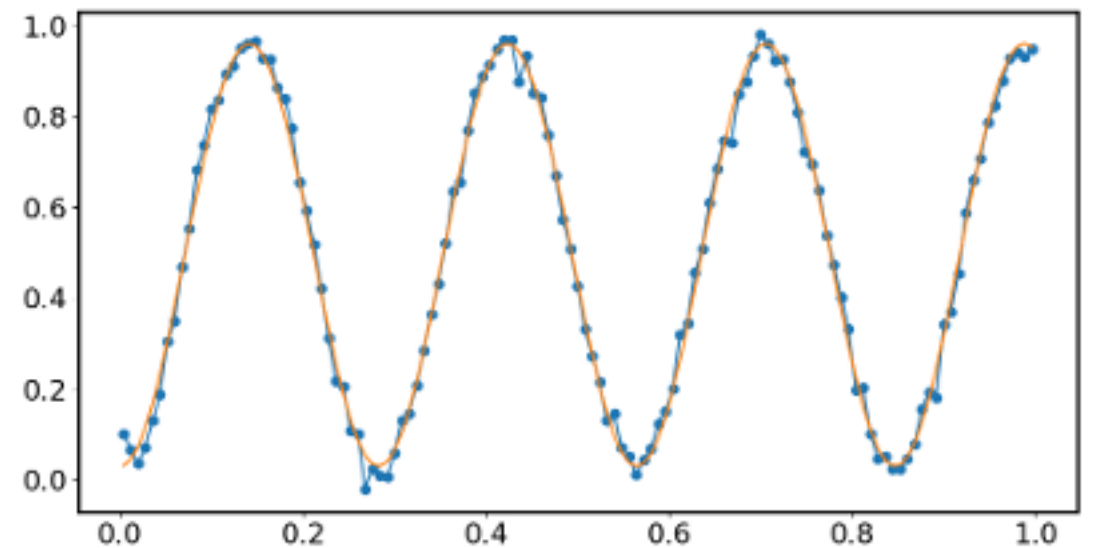
Repeat

Séquence Expérimentale



```
with for_(n, 0, n < n_avg, n + 1):
    with for_(*from_array(t, durations)):
        play("pi", "qubit", duration=t)
        align("qubit", "resonator")
        measure("readout", "resonator", I, Q )
        # Prepare the qubit for next iteration
        with if_(Q<0):
            play("pi", "qubit")
```

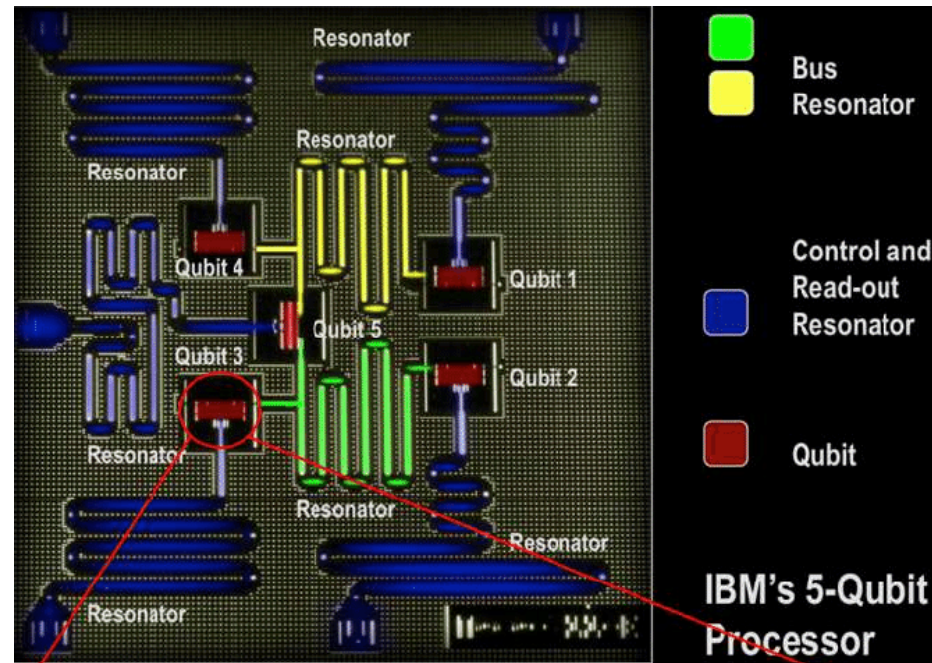
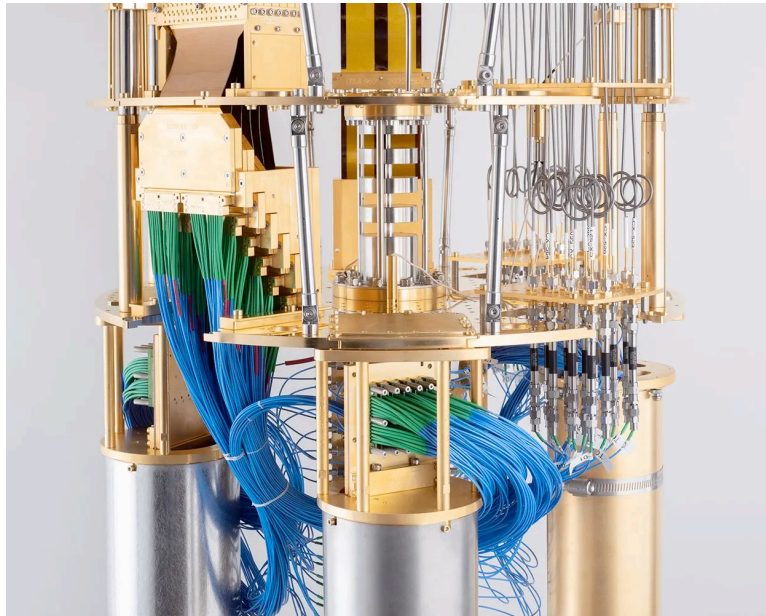
Population dans $|1\rangle$



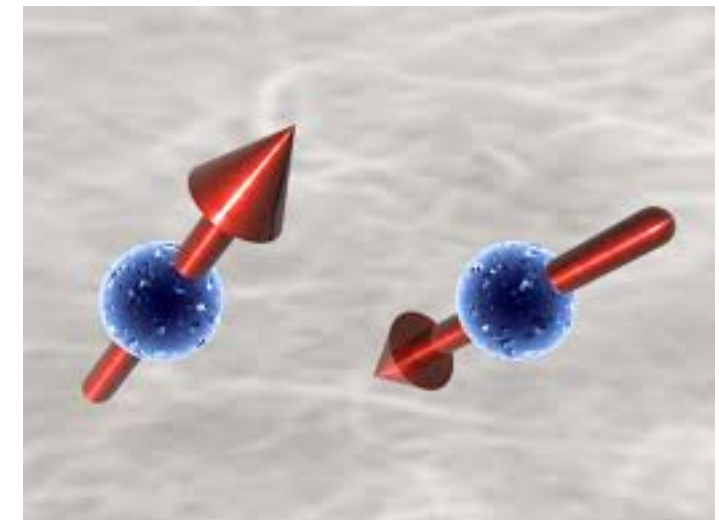
Durée du pulse

Qubits micro-onde

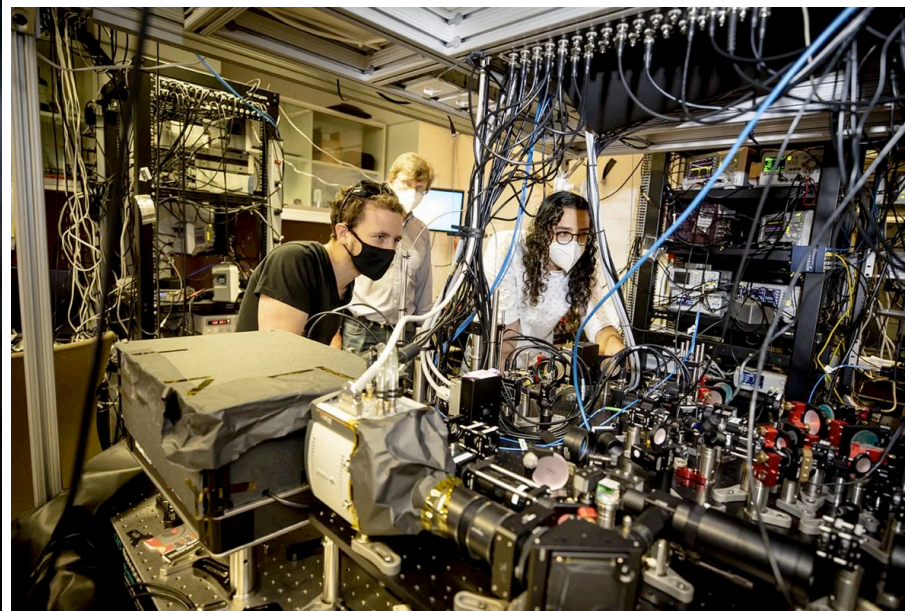
Circuits supraconducteurs



Qubits de spin



Atomes de Rydberg

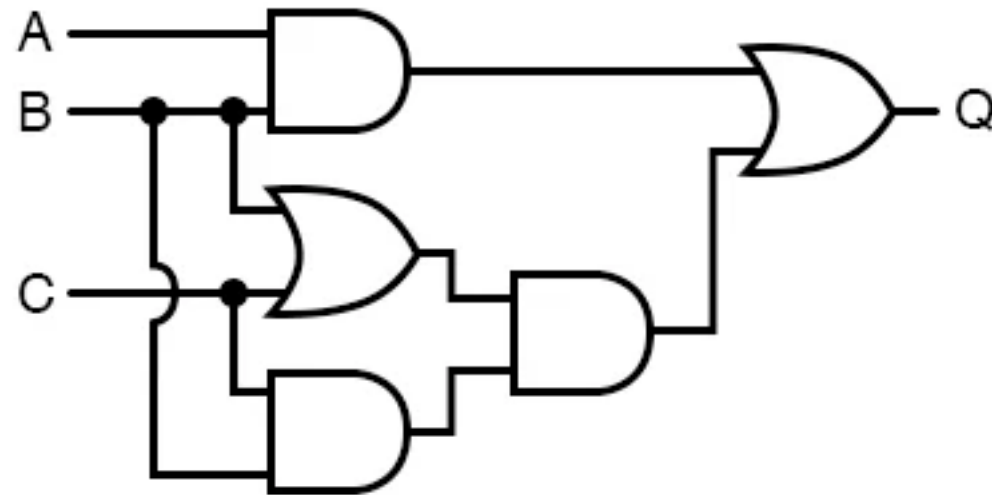


Jeu de portes universel

Circuit logique classique

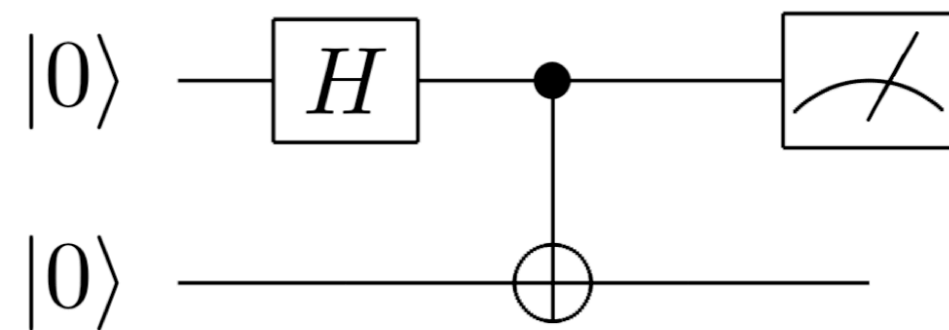
- Irréversible
- Dissipation thermique

AND & NOT

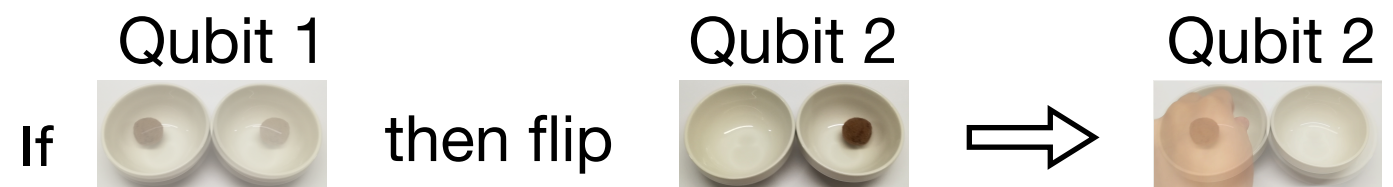


Circuit Quantique

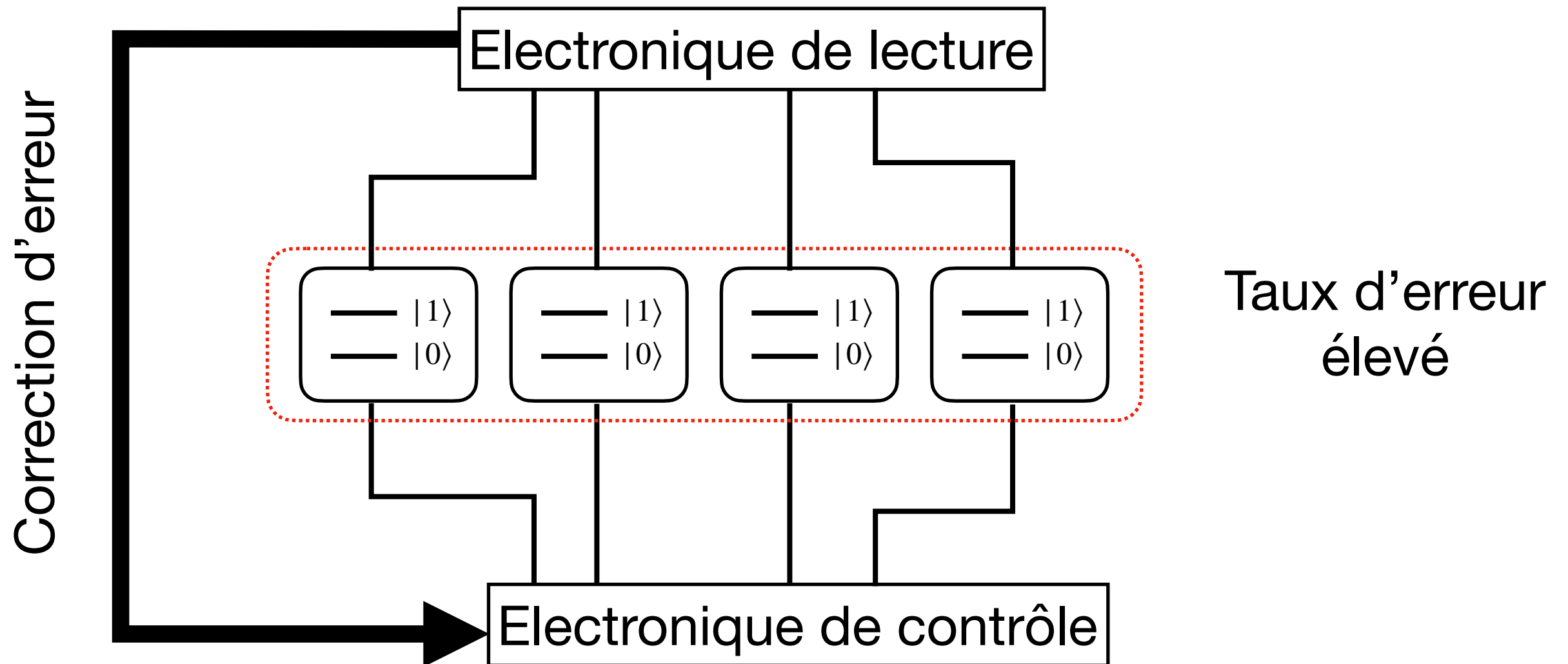
- Réversible
- Non dissipatif



Porte à un qubit &
CNOT



Electronique Micro-onde pour les qubits



Flux important de données à traiter en temps réel

Electronique pour les qubits supra

- Amplis à la limite quantique
- Simulation micro-onde 2D/3D & Modélisation
- Filtres, isolateurs cryogéniques
- Amplis HEMT cryogéniques
- Modulation demodulation IQ 4-8 GHz
- Programmation FPGA



Electronique pour les qubits supra

- Amplis à la limite quantique
 FPGA / Synthèse de signaux à 4K/20 mK
- Simulation micro-onde 2D/3D & Modélisation
- Filtres, isolateurs cryogéniques
- Amplis HEMT cryogéniques
- Modulation demodulation IQ 4-8 GHz
- Programmation FPGA

Physique



Electronique

Electronique pour les qubits supra

- Amplis à la limite quantique
- Simulation micro-onde 2D/3D & Modélisation
- Filtres, isolateurs cryogéniques
- Amplis HEMT cryogéniques
- Modulation demodulation IQ 4-8 GHz
- Programmation FPGA





FPGA / Synthèse micro-onde



QUANTUM MACHINES

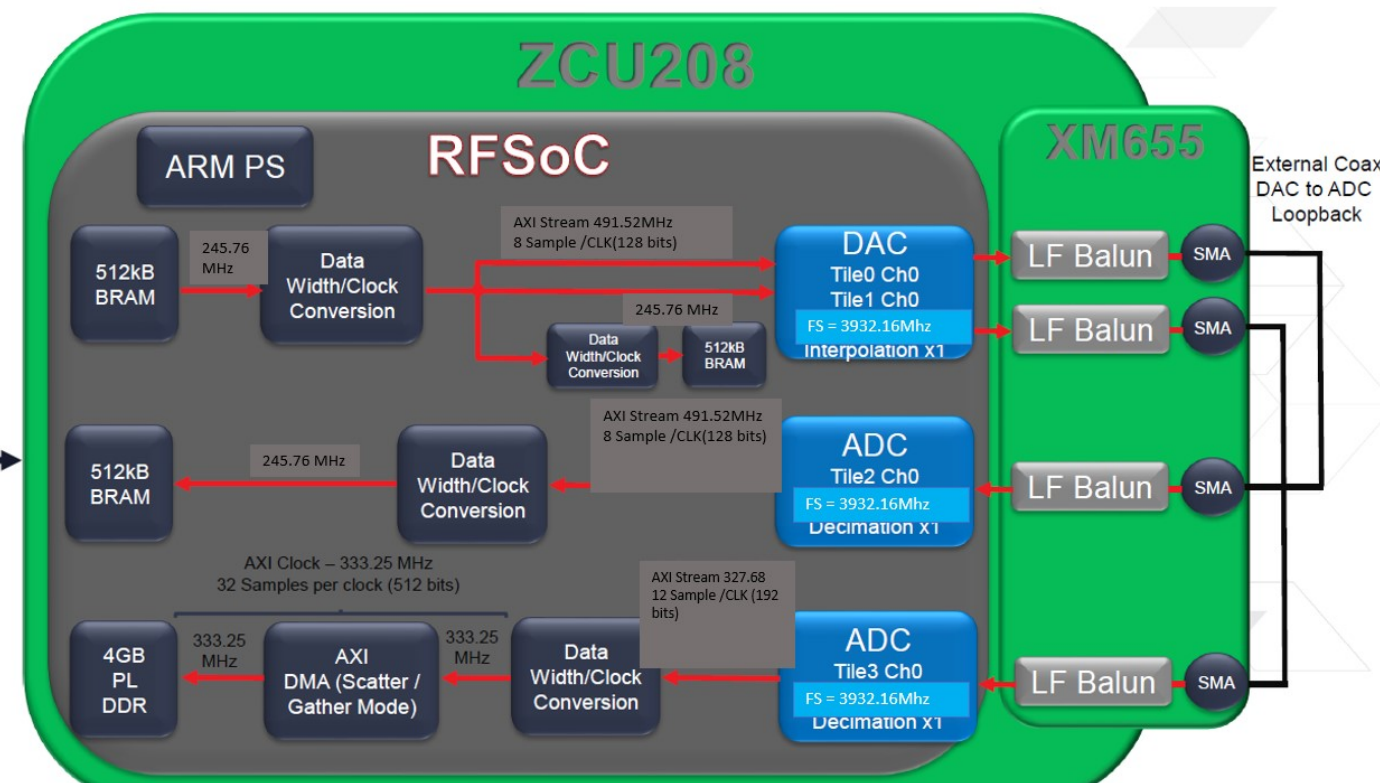


- Architecture
- Traitement du signal



Laptop

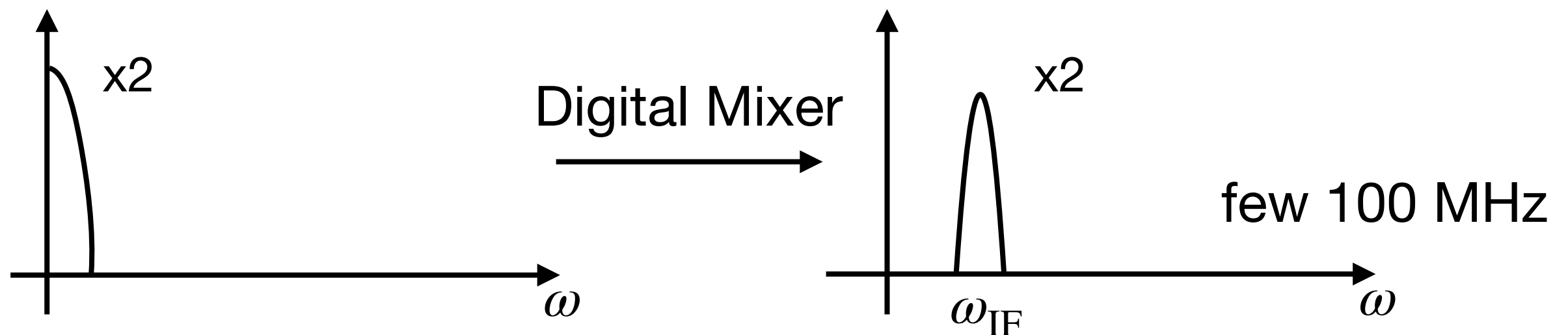
- Vivado
- Vitis
- MATLAB or Octave
- JTAG Interface to ZCU208



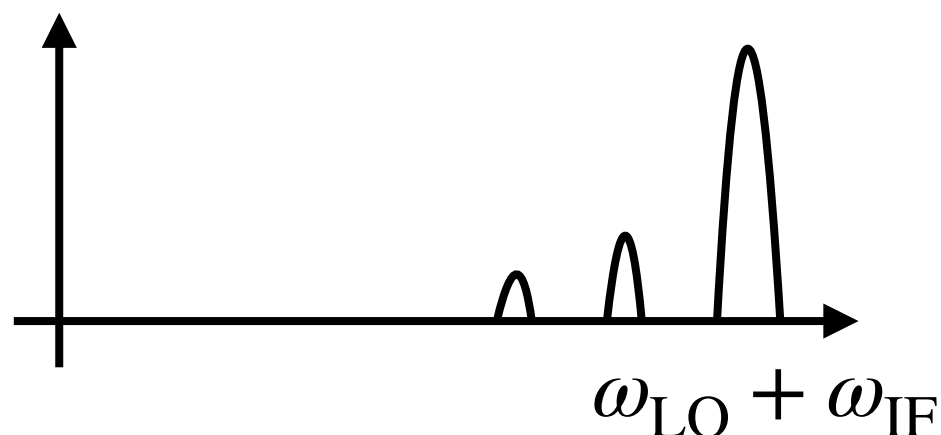
Synthèse Micro-onde : Modulation IQ

$$\begin{aligned} RF(t) &= I \cos(\omega_{LO} + \omega_{IF})t + Q \sin(\omega_{LO} + \omega_{IF})t \\ &= (I \cos \omega_{IF}t + Q \sin \omega_{IF}t) \cos \omega_{LO}t + (Q \cos \omega_{IF}t - I \sin \omega_{IF}t) \sin \omega_{LO}t \end{aligned}$$

Upconvert $I(t)$ and $Q(t)$ to intermediate frequency ω_{IF}



Mix with local oscillator to obtain single side band at $\omega_{LO} + \omega_{IF}$

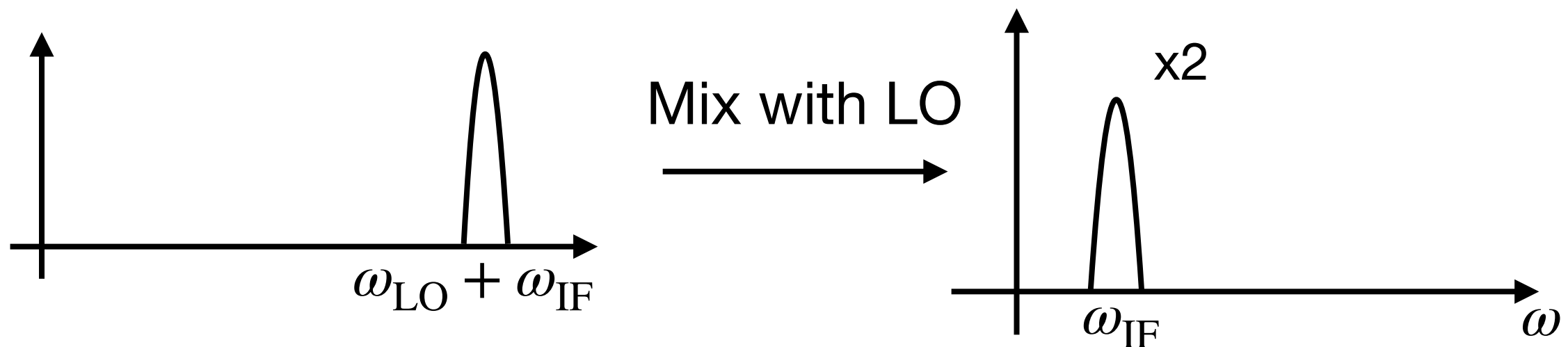


- No residual signal at $\omega_{LO} + \omega_{IF}$
- Frequency agility

Démodulation IQ

$$\begin{aligned} RF(t) &= I \cos(\omega_{LO} + \omega_{IF})t + Q \sin(\omega_{LO} + \omega_{IF})t \\ &= (I \cos \omega_{IF}t + Q \sin \omega_{IF}t) \cos \omega_{LO}t + (Q \cos \omega_{IF}t - I \sin \omega_{IF}t) \sin \omega_{LO}t \end{aligned}$$

Obtain $I(t)$ and $Q(t)$ by downconversion



- Record I and Q with an ADC
- Average over a time window which is a multiple of the IF period