Characterization of transmon qubits in 3D cavities

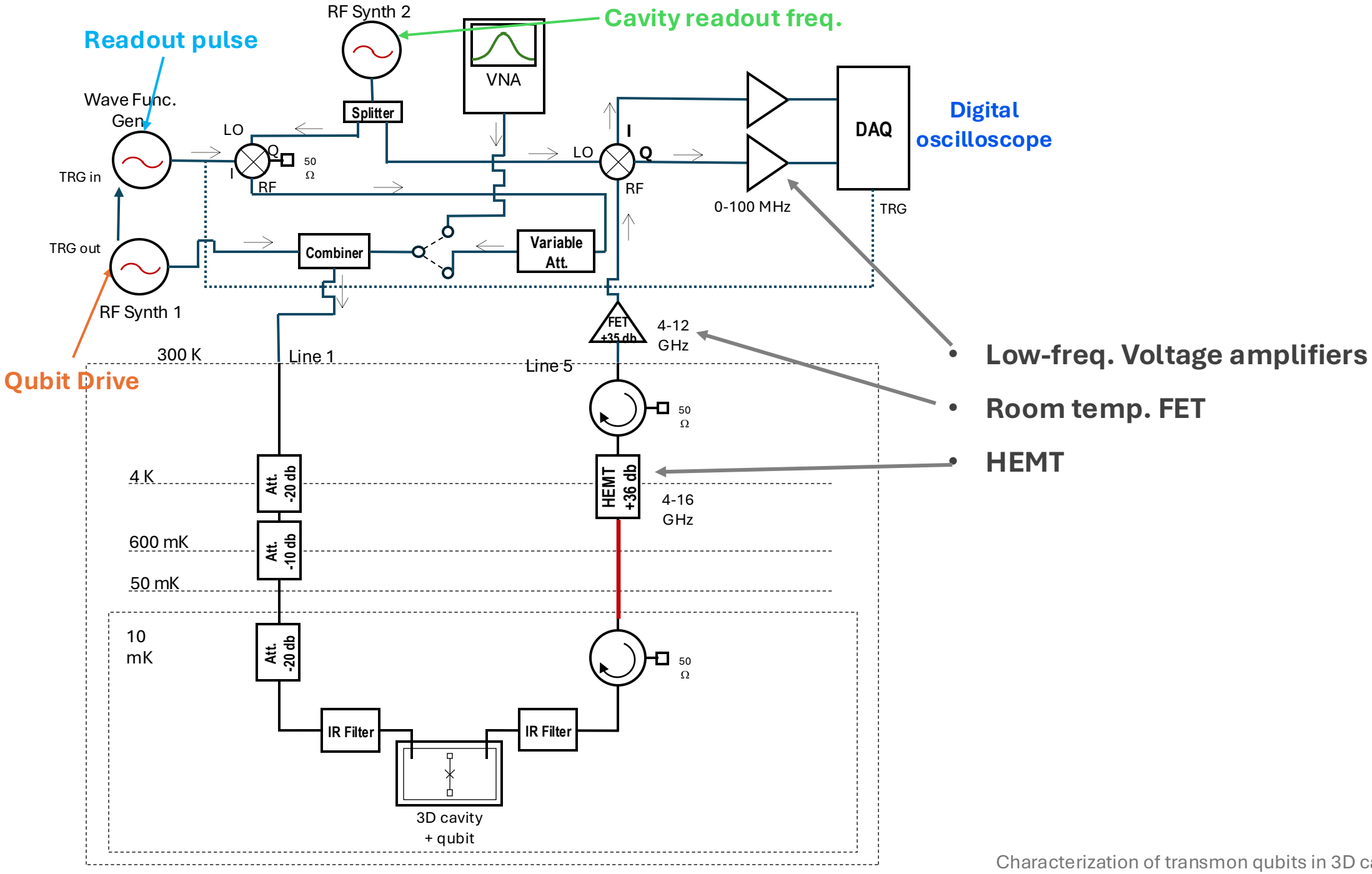
Alessio Rettaroli – INFN LNF

WP7 Characterization, measurement and demonstration

QUART&T kick-off — 21/Feb/2025

Contents

- **RF and low-frequency schemes to measure qubits**
  - **Type of measurements and set of parameters**
    - **TII (Abu Dhabi) qubit**
      - **CNR (Rome) qubit**


Readout pulse
RF Synth 2
Cavity readout freq.
VNA
Wave Func. Gen
Splitter
LO
Q
I
RF
50 Ω
TRG in
TRG out
RF Synth 1
Combiner
Variable Att.
LO
I
Q
RF
DAQ
Digital oscilloscope
0-100 MHz
TRG
FET +35 db
4-12 GHz
Qubit Drive
300 K
Line 1
Line 5
4 K
600 mK
50 mK
10 mK
Att. -20 db
Att. -10 db
Att. -20 db
HEMT +36 db
4-16 GHz
IR Filter
IR Filter
3D cavity + qubit
• Low-freq. Voltage amplifiers
• Room temp. FET
• HEMT

Python code to drive instruments and acquire data

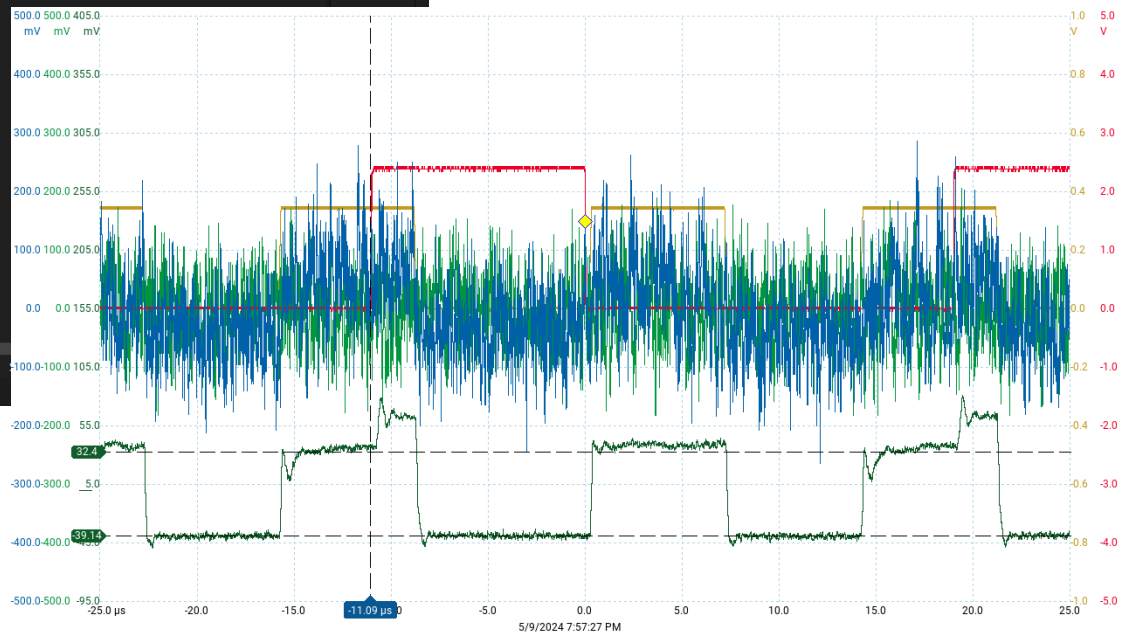
ColdLibraryv3.py 7

```python
import nidaqmx
import matplotlib.pyplot as plt
import numpy as np
import pyvisa #keysight & ReS & VNA
import ctypes
from time import sleep
from picosdk.ps5000a import ps5000a as ps  #per picoscope
from picosdk.device import Device #per picoscope
import qcodes.instrument_drivers.rohde_schwarz.SGS100A as SGS100A  #per R&S
import smdevice.sm_api as sm # per SIGNAL HOUND SPECTRUM ANALYZER
from picosdk.functions import adc2mV, assert_pico_ok, mV2adc


def setget(inst,command,*value): #Funzione che permette di leggere o scrivere
    if len(value)==0:
        value = inst.query(command+'?')
        print(f'{command}:',value)
    else:
        inst.write(command+f' {value[0]}')
        value = 0
    return value


class VNA(): ···

class NIDAQ(): ···

class K335():
    def __init__(self, address="GPIB0::10::INSTR"):
        rm = pyvisa.ResourceManager()
        self.inst = rm.open_resource(address)

    def __enter__(self):
        return self

    def __exit__(self, exc_type, exc_val, exc_tb):
        self.inst.close()

    def waveform(self, *type):
        return setget(self.inst,'FUNC',*type)

    def output(self, *state):
        return setget(self.inst,'OUTP',*state)

    def amp(self, *amp):
```

main.py 1

```python
#%%
from ColdLibraryv3 import *
import matplotlib.pyplot as plt
import visa
from tkinter.filedialog import asksaveasfilename as filesave
from tkinter.filedialog import askopenfilename as fileload
import datetime
import time

modules = {
        "Keysight" : "GPIB0::10::INSTR",
        "Keysight_black": "GPIB0::12::INSTR",
        "RS_SGS100A": "TCPIP0::192.168.2.103::inst0::INSTR",
        "RS_SMA100B" : "TCPIP0::192.168.2.102::inst0::INSTR",
        "SignalHound" : "20044268",
        "picoscope": "GQ8850099",
        "VNA" : "GPIB0::17::INSTR"
        }

def VNASpectroscopy(start,stop,N): ···

def Tuning(start,stop,N): ···


def Rabi(period,start,stop,N):
    with K335( modules['Keysight']) as ks, RS(modules['RS_SMA100B']) as rs, RS(modules['RS_SGS100A']) as l
        ## Local oscillator
        lo.freq(7.4394e9)
        lo.power(21)
        lo.phase_ref('EXT')
        lo.output('ON')

        ##Readout pulse
        #setget(ks.inst,'TRIG:LEV',4)
        ks.waveform('PULS')
        ks.burst_state(1)
        ks.burst_cycles(2)
        ks.burst_period(14e-6)
        ks.trigger_src('EXT') #INT, EXT, BUS
        ks.trigger_slope('NEG') #POS,NEG
        ks.load('INF')
        ks.low(0)
        ks.high(0.6)
        #ks.offset(0.25)
```

Developed python software which calls routines to remotely control instrumentations



The main measurements

- **Qubit spectroscopy** → χ, α, g
  - **Rabi** → π pulse
    - **Coherence** → T_1
      - **Ramsey** → T_2

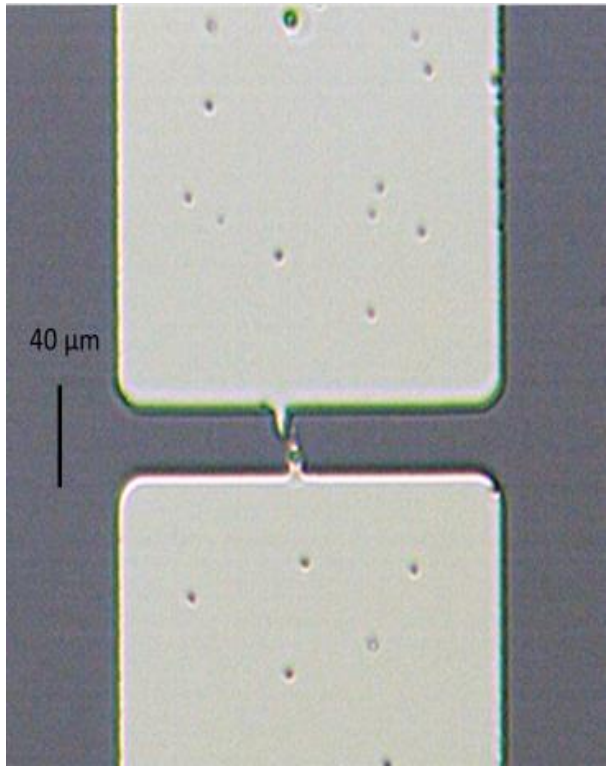
The TII qubit in Al cavity

Technology Innovation Institute

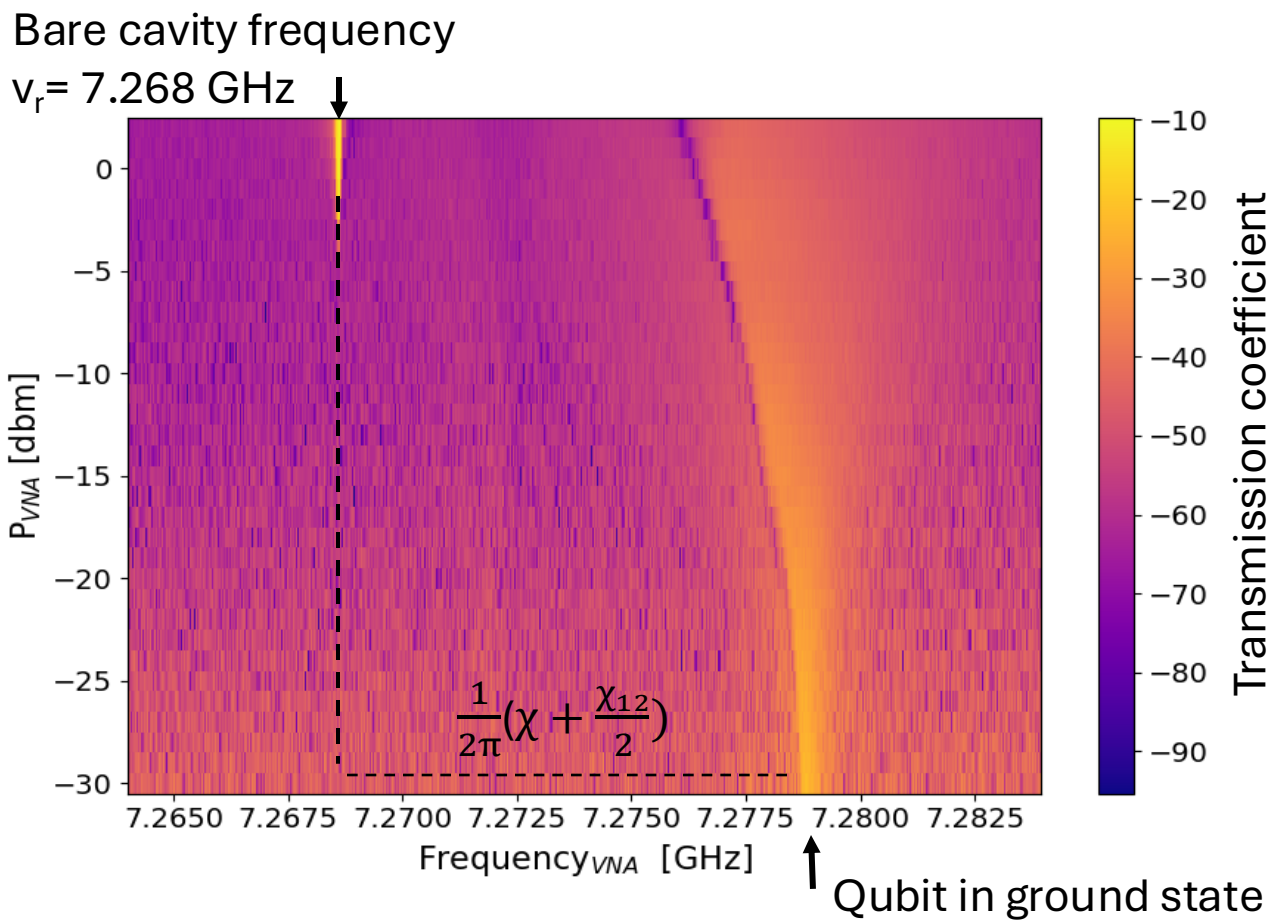
Qubit and cavity from Abu Dhabi

$$Q = (1.78 \pm 0.9) \cdot 10^5$$

Al alloy



1 tone spectroscopy



Parameters are defined as

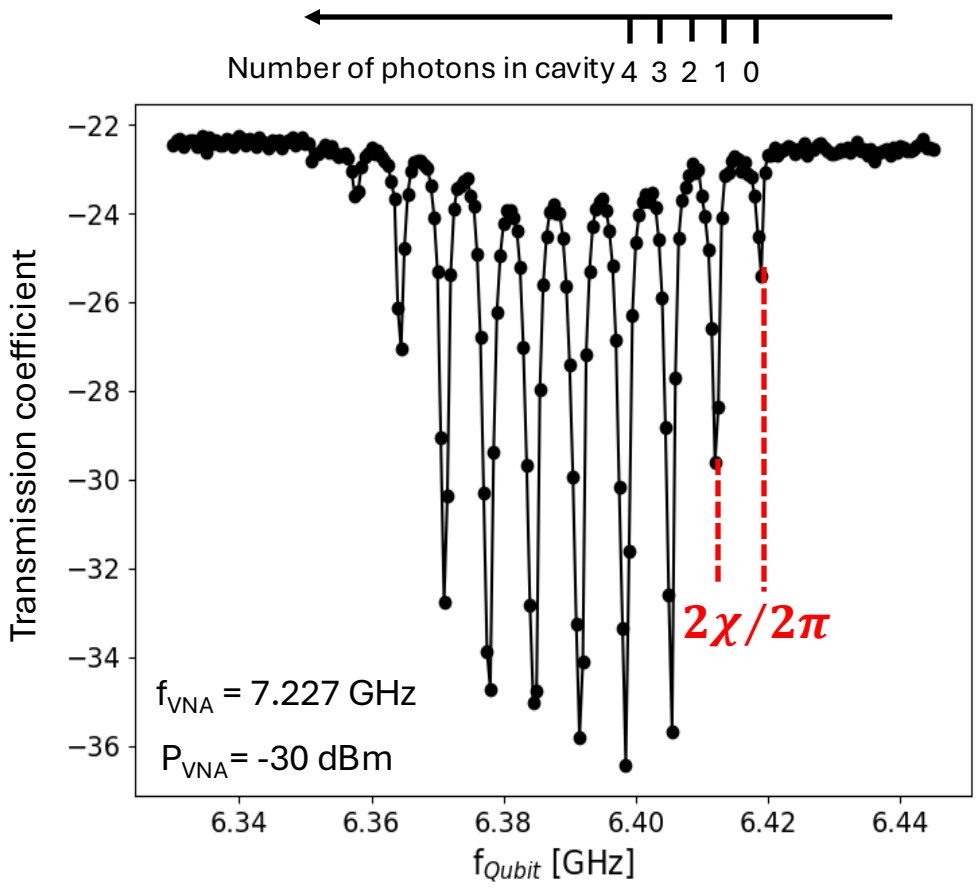
$$\chi = \chi_{01} - \frac{\chi_{12}}{2} \qquad \chi_{ij} = \frac{g_{ij}^2}{\Delta_{ij}}$$

$\Delta_{01}=\omega_q-\omega_r$

From 1-tone spectroscopy extract χ_{01}

$$\frac{1}{2\pi}(\chi + \frac{\chi_{12}}{2}) = -10.2 \pm 0.1\ MHz$$

2 tone spectroscopy



$$\frac{\chi_{01}}{2\pi} = -10.2 \pm 0.2 \text{ MHz}$$

$$\frac{\chi}{2\pi} = -3.41 \pm 0.08 \text{ MHz}$$

$$\frac{\chi_{12}}{2\pi} = -13.6 \pm 0.3 \text{MHz}$$

From 2-tone spectroscopy extract 2χ

From the first peak extract the qubit frequency:

$$\frac{\omega_{|0\rangle}}{2\pi} = \frac{1}{2\pi}(\omega_q + \chi_{01}) = 6.4194 \text{ GHz}$$

$$\frac{\omega_q}{2\pi} = 6.4296 \text{ GHz}$$

Coupling and anharmonicity

From detuning and χ extract the coupling

$$\frac{\Delta_{01}}{2\pi} = \nu_q - \nu_r = -839\ \text{MHz}\ , \qquad \chi_{ij} = \frac{g_{ij}^2}{\Delta_{ij}} \quad \Longrightarrow \quad \boxed{\frac{g_{01}}{2\pi} = 92.5\pm1\ \text{MHz}}$$

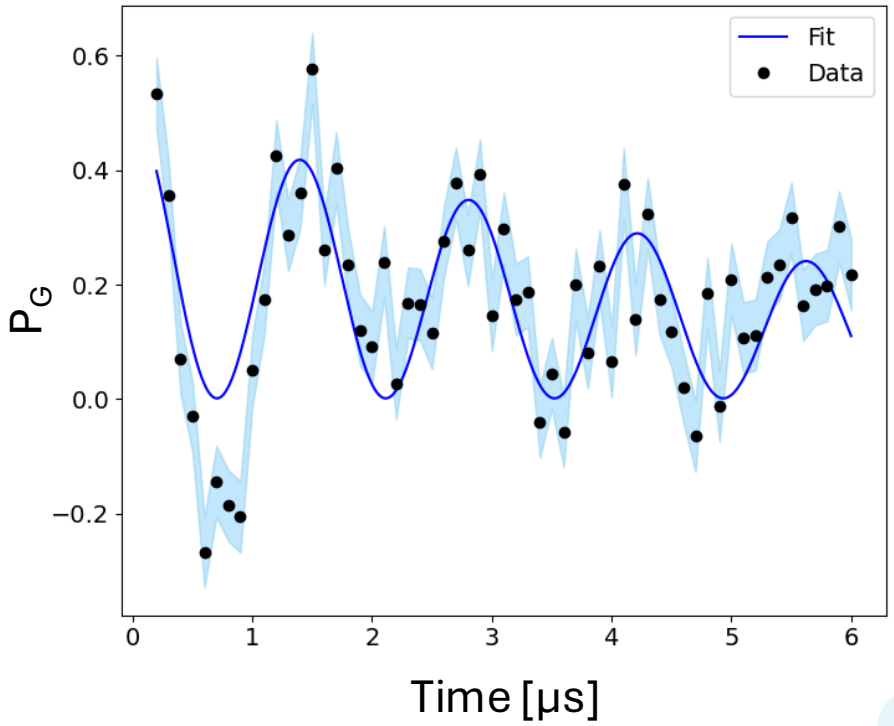
Similarly, estimate the Δ_{12} $\qquad \frac{\Delta_{12}}{2\pi} = -1260\pm40\ \text{MHz}$

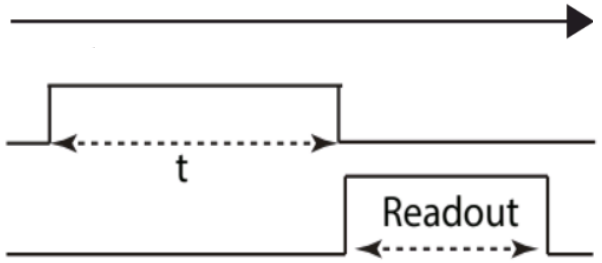
Now one can extract anharmonicity and capacity

$$\Delta_{01} - \Delta_{12} = \omega_{01} - \omega_{12} = 2\pi\alpha\ , \qquad \textbf{\textit{Anharmonicity}} = \alpha = 421\pm84\ \text{MHz}$$

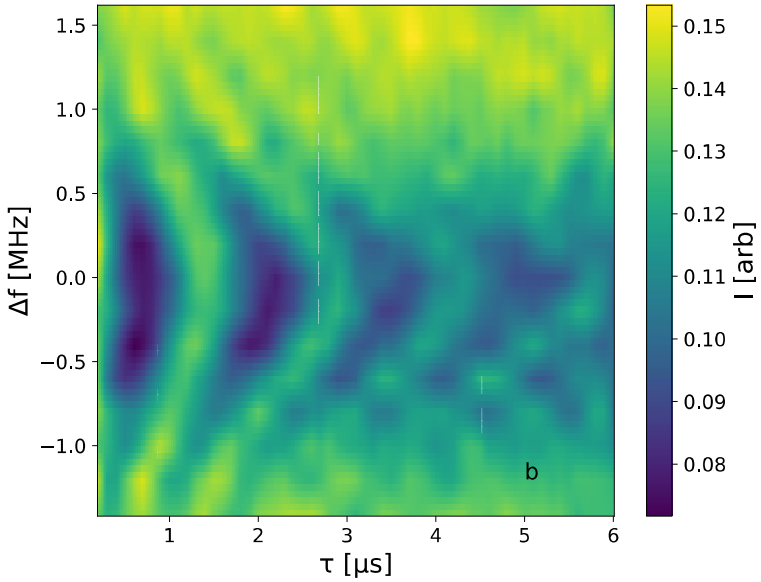
$$\Longrightarrow \qquad h\alpha = \frac{e^2}{2C} \qquad C = 46\pm5fF$$

Rabi





Chevron plot (Rabi measurements for different detunings)

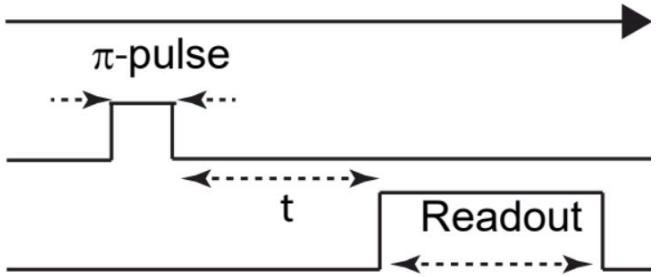


For every fixed pump frequency and power, one finds a π pulse from Rabi oscillations

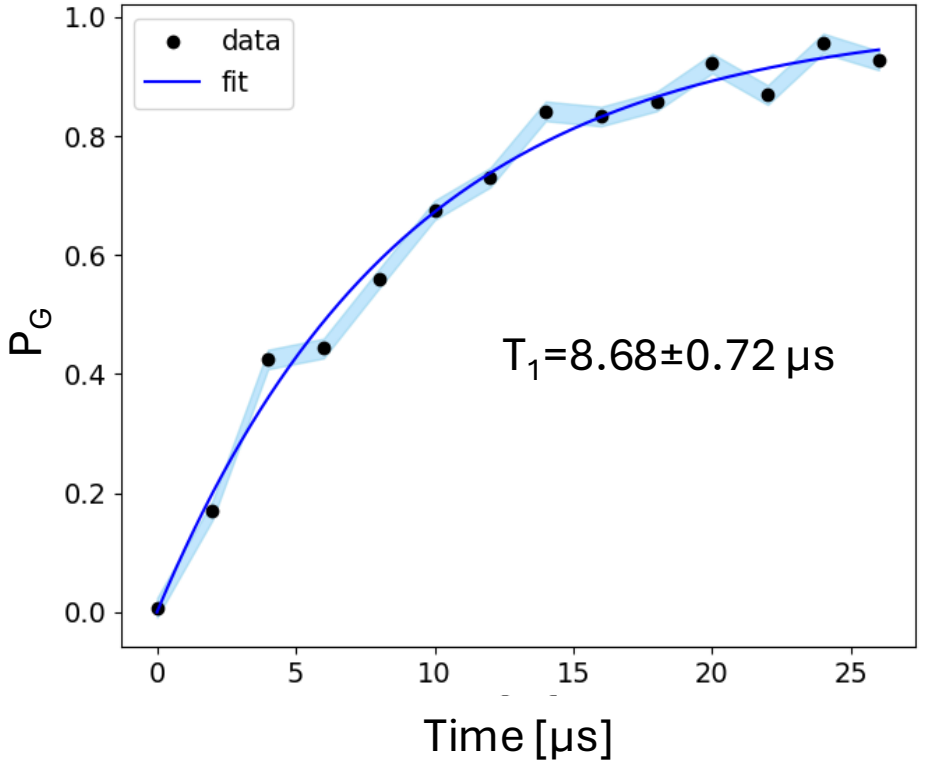
Fit function

$$P_g = A\cos(\Omega_R t)e^{-t/T_1}$$

Relaxation



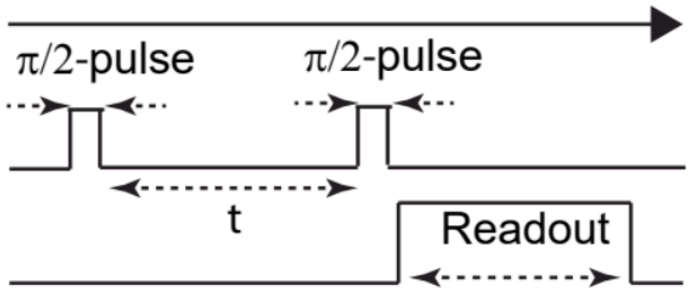
Fixing the π pulse, extract T_1 from decay measurements



Fit function

$$P_g = A\,(1 - e^{-t/T_1})$$

Ramsey (coherence)

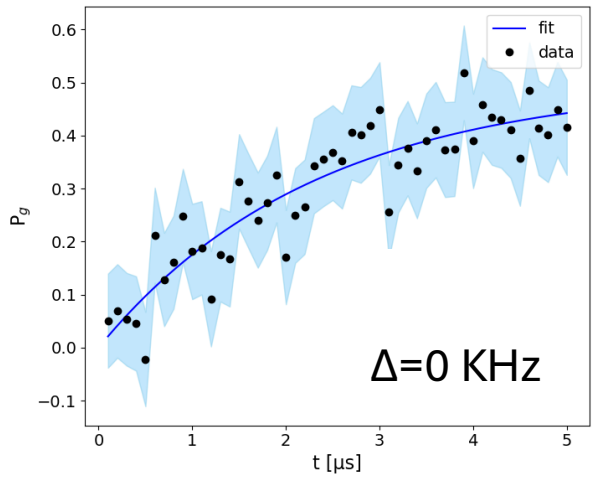


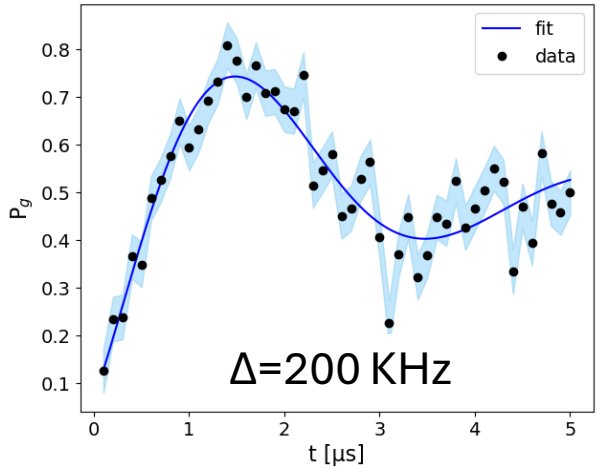
$$P_g = (1/2 - \sin(2\pi\Delta\, t))e^{-\frac{t}{2T_2}}$$

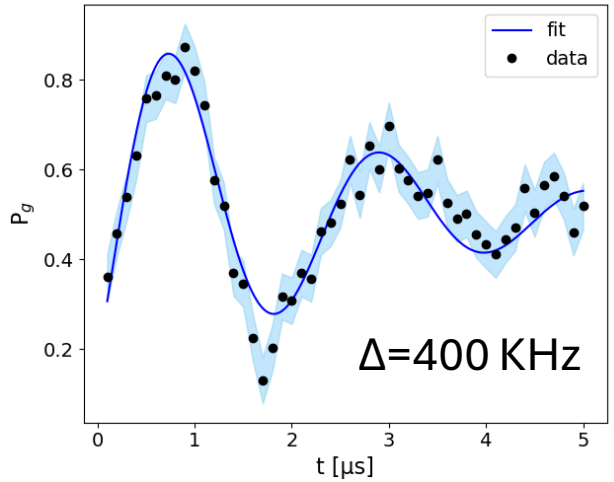
$$\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\phi}$$

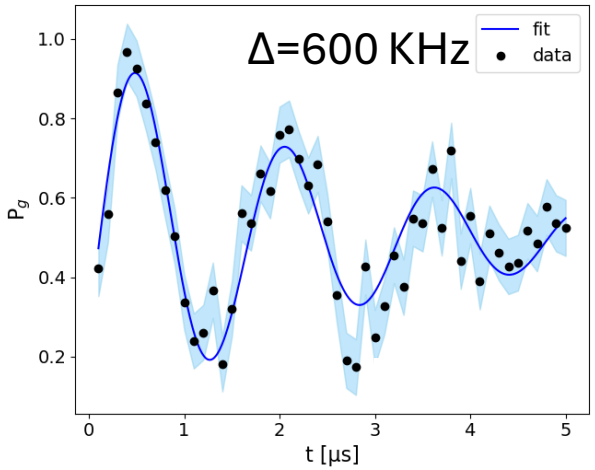
$$\boldsymbol{T_2 = 2.30 \pm 0.11\ \mu s}$$

$$\boldsymbol{T_\phi = 2.65 \pm 0.15\ \mu s}$$



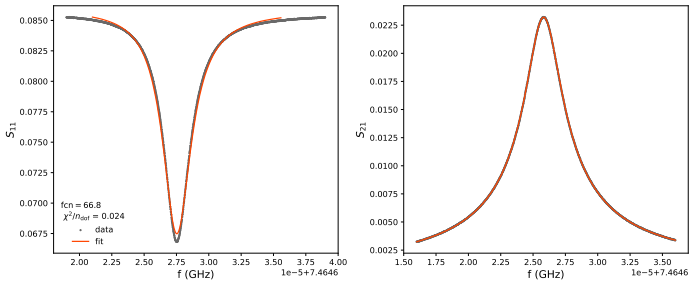




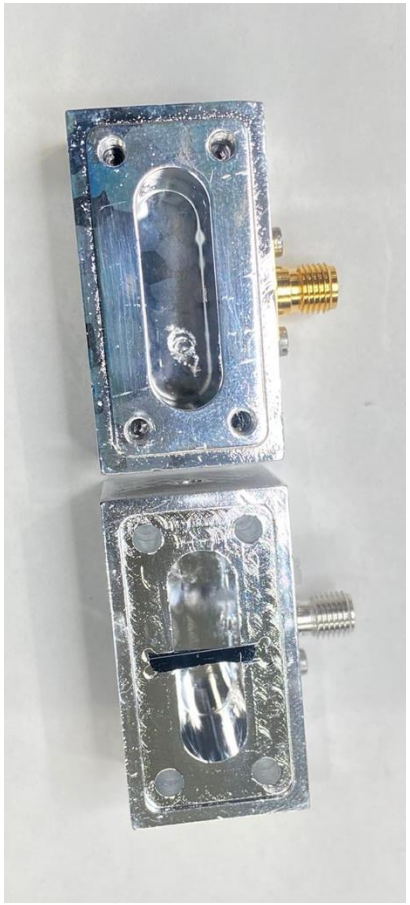


Al qubit in Al cavity

Pure Al cavity fabricated at LNL

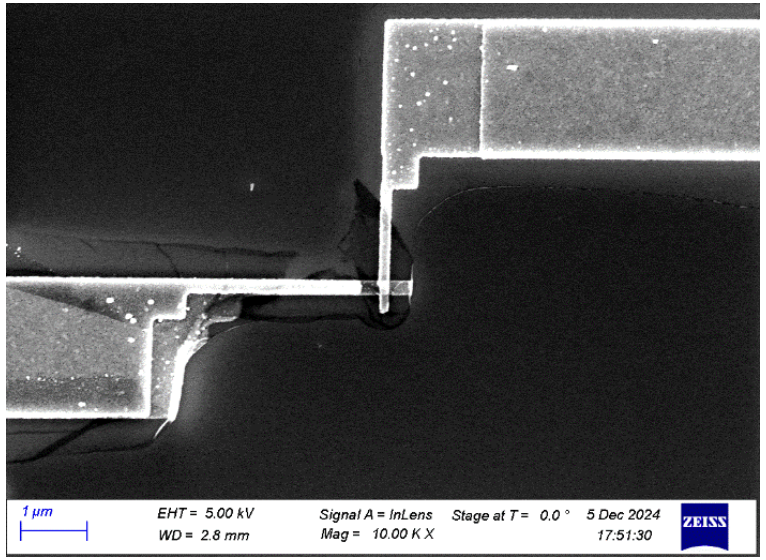


f_0	7.465 GHz
Q_0	$(3.7 \pm 0.4) \times 10^6$



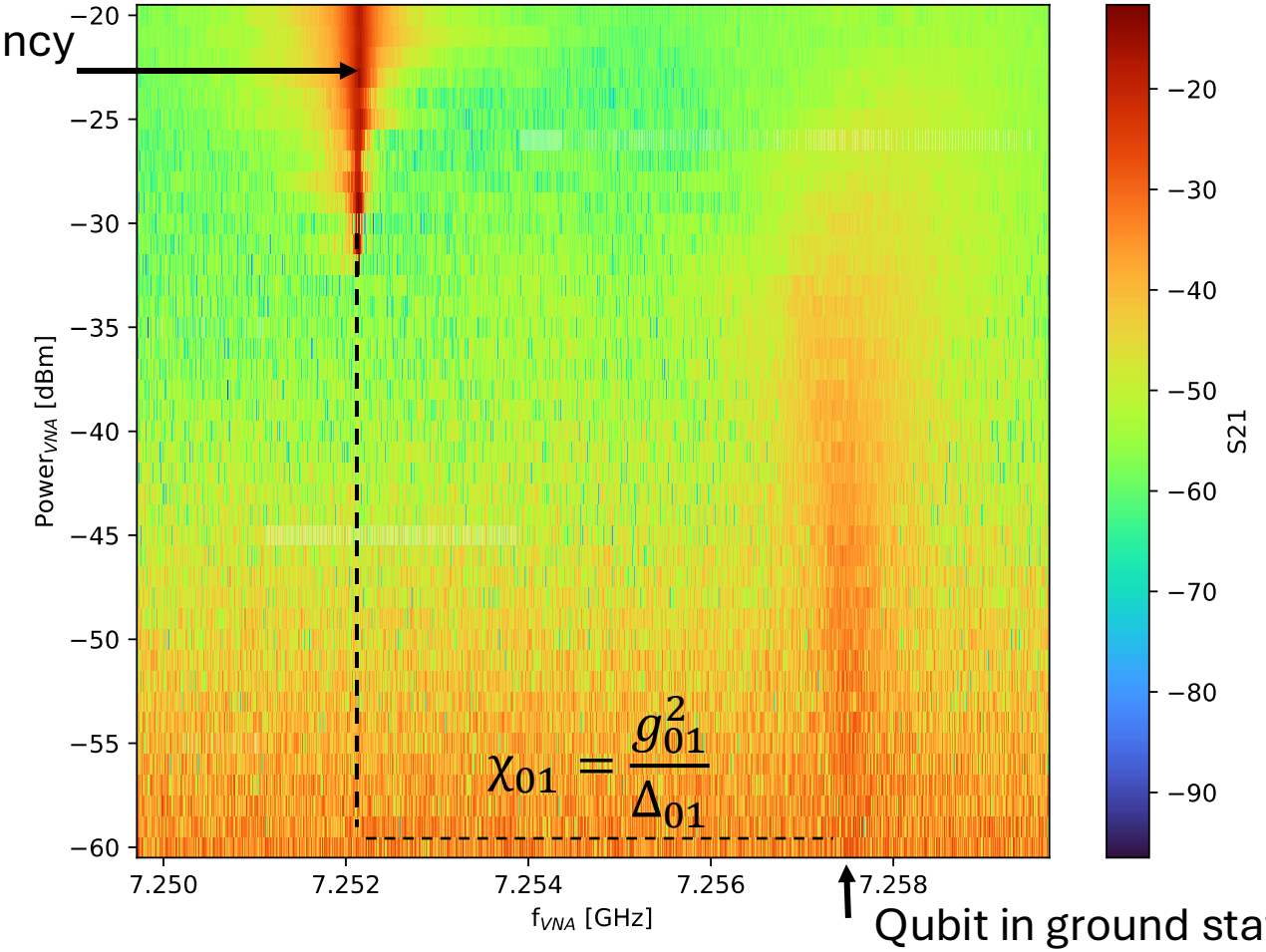
Qubit fabricated at CNR – IFN (Rome)

JJ Area: 216.4 x 147.8 nm²



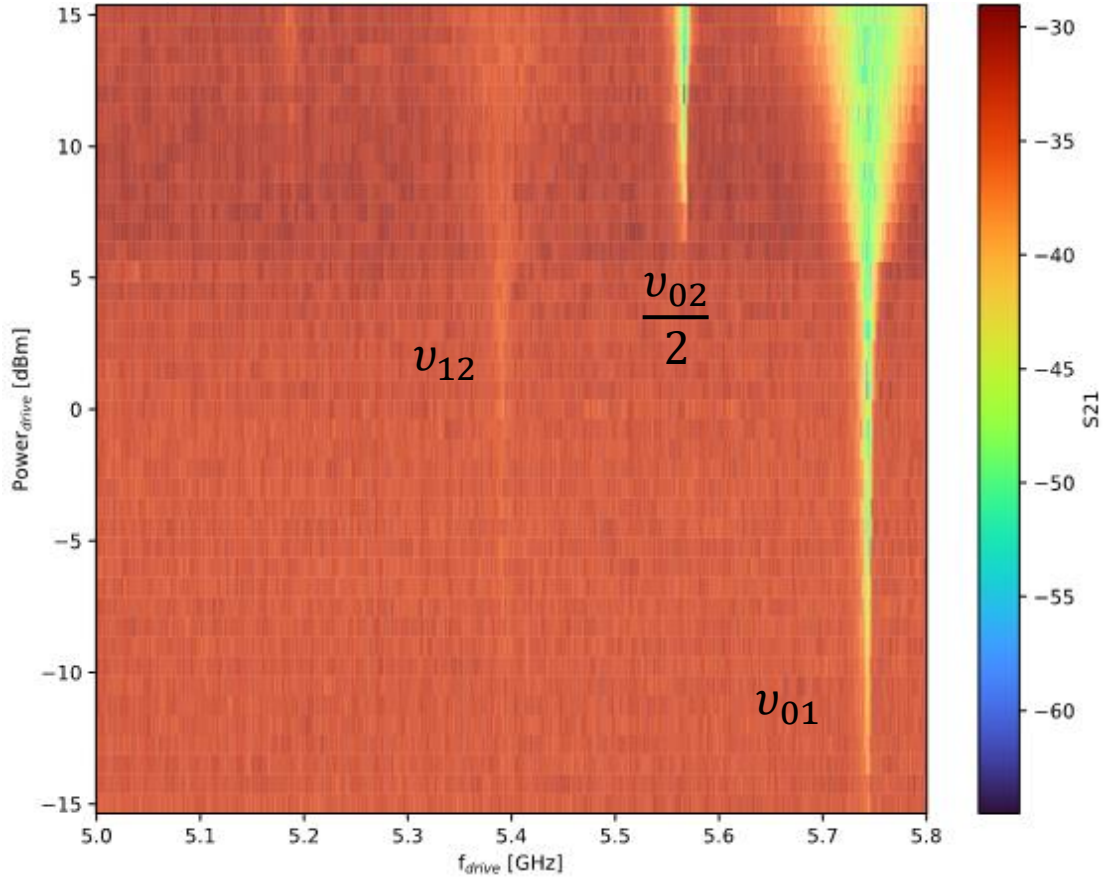
1 tone spectroscopy

Bare cavity frequency
v_r= 7.252 GHz



$$\chi_{01} = \frac{g_{01}^2}{\Delta_{01}} = -5.24\ MHz$$

2 tone spectroscopy (with varying pump power)

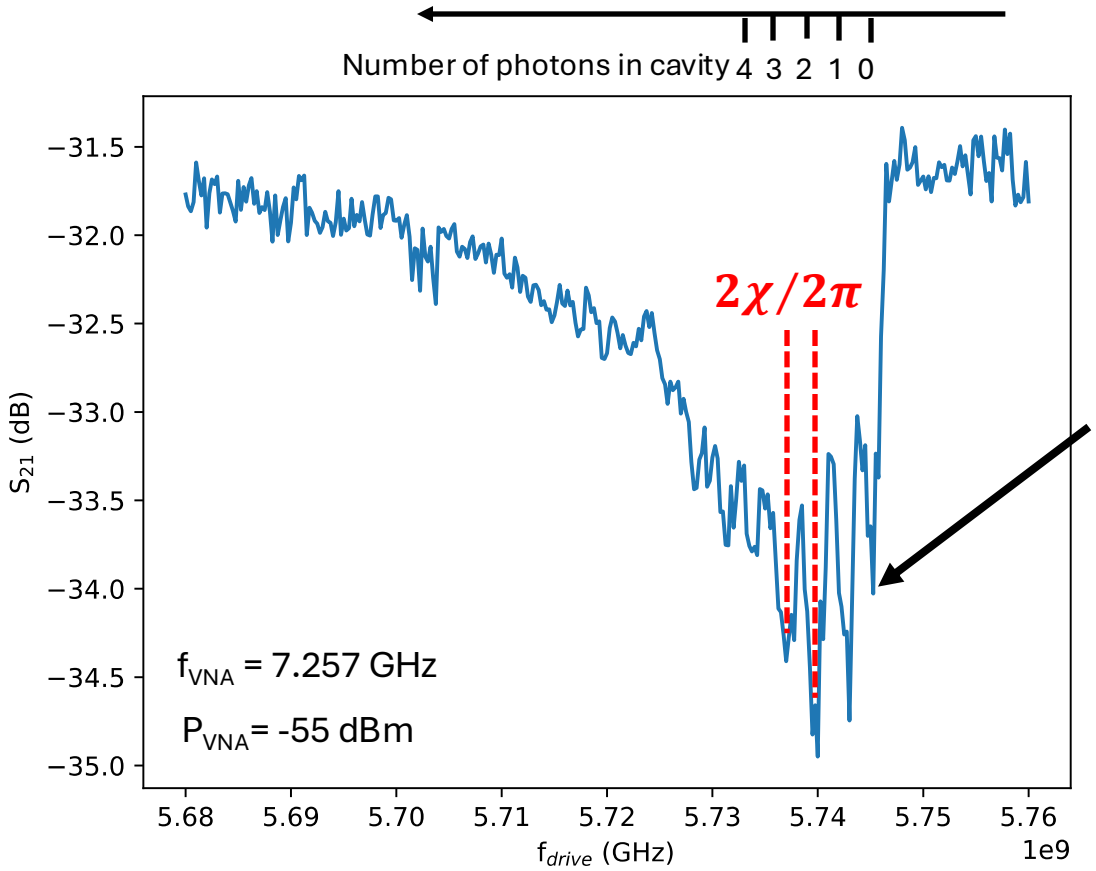


$$\upsilon_{01} - \upsilon_{12} = 2\pi\alpha$$

$$\alpha = \mathbf{353}\ \boldsymbol{MHz}$$

$$C = \mathbf{54.87}\ \boldsymbol{fF}$$

2 tone spectroscopy



$$\frac{\chi}{2\pi} = -1.2\ MHz$$

$$\frac{\omega_{|0\rangle}}{2\pi} = \frac{1}{2\pi}(\omega_q + \chi_{01}) = 5.7452 GHz$$

$$\frac{\omega_q}{2\pi} = 5.739\ GHz$$

Detuning and coupling

Estimating the detuning one finds then the coupling

$$\begin{cases} \frac{\Delta_{01}}{2\pi} = \nu_q - \nu_r = -1.51\ \text{GHz} \\ \chi_{01} = \frac{g_{01}^2}{\Delta_{01}} \end{cases} \Longrightarrow \boxed{\frac{g_{01}}{2\pi} \cong \mathbf{90\ MHz}}$$