https://github.com/UB-Quantic/Qubit-Calibration

Qubit Calibration

Raquel García Bellés

IFAE Summer Fellowship @ Quantum Computing Technology Group

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Institut de Física d'Altes Energies

EXCELENCIA SEVERO OCHOA

BIST Barcelona Institute of Science and Technology

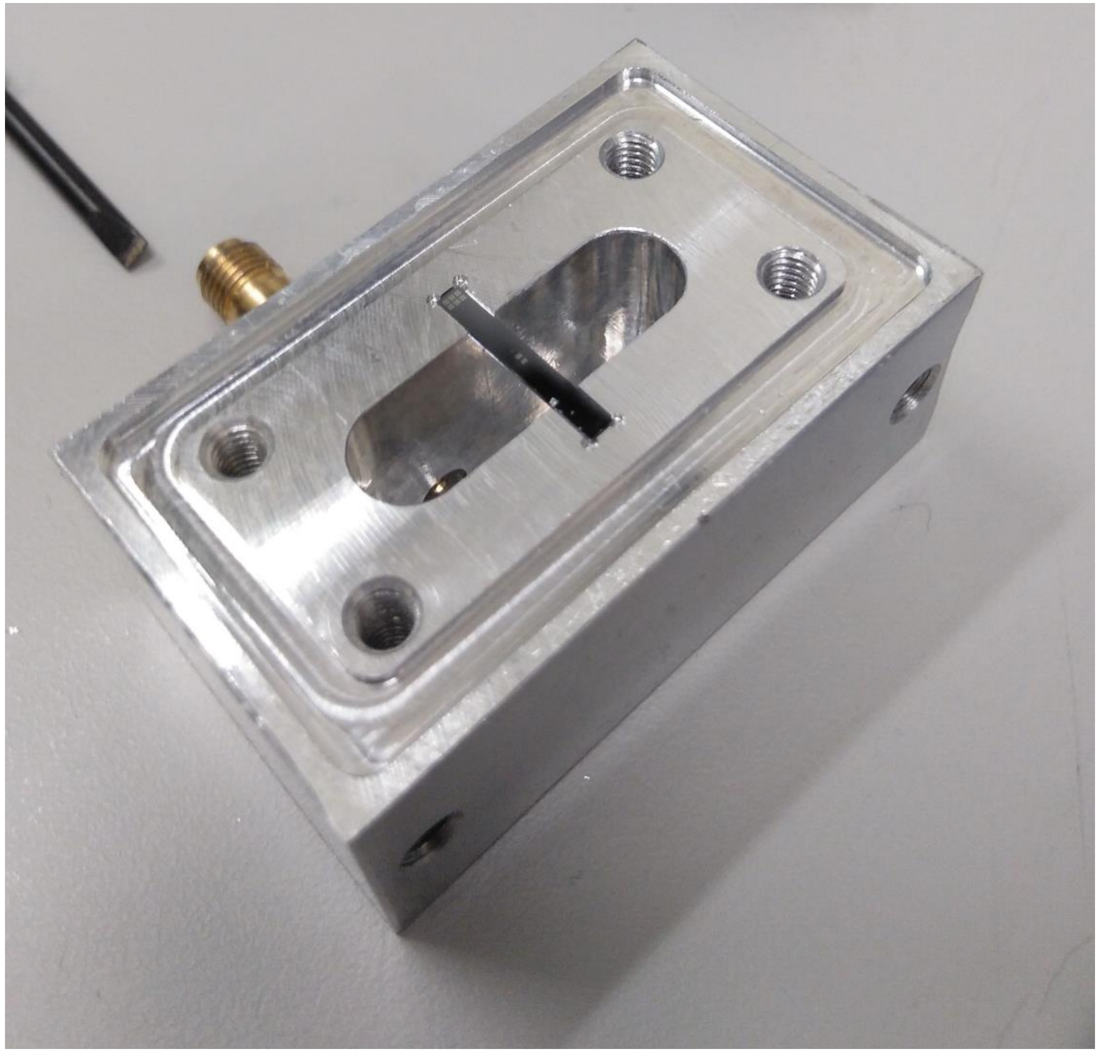
Outline

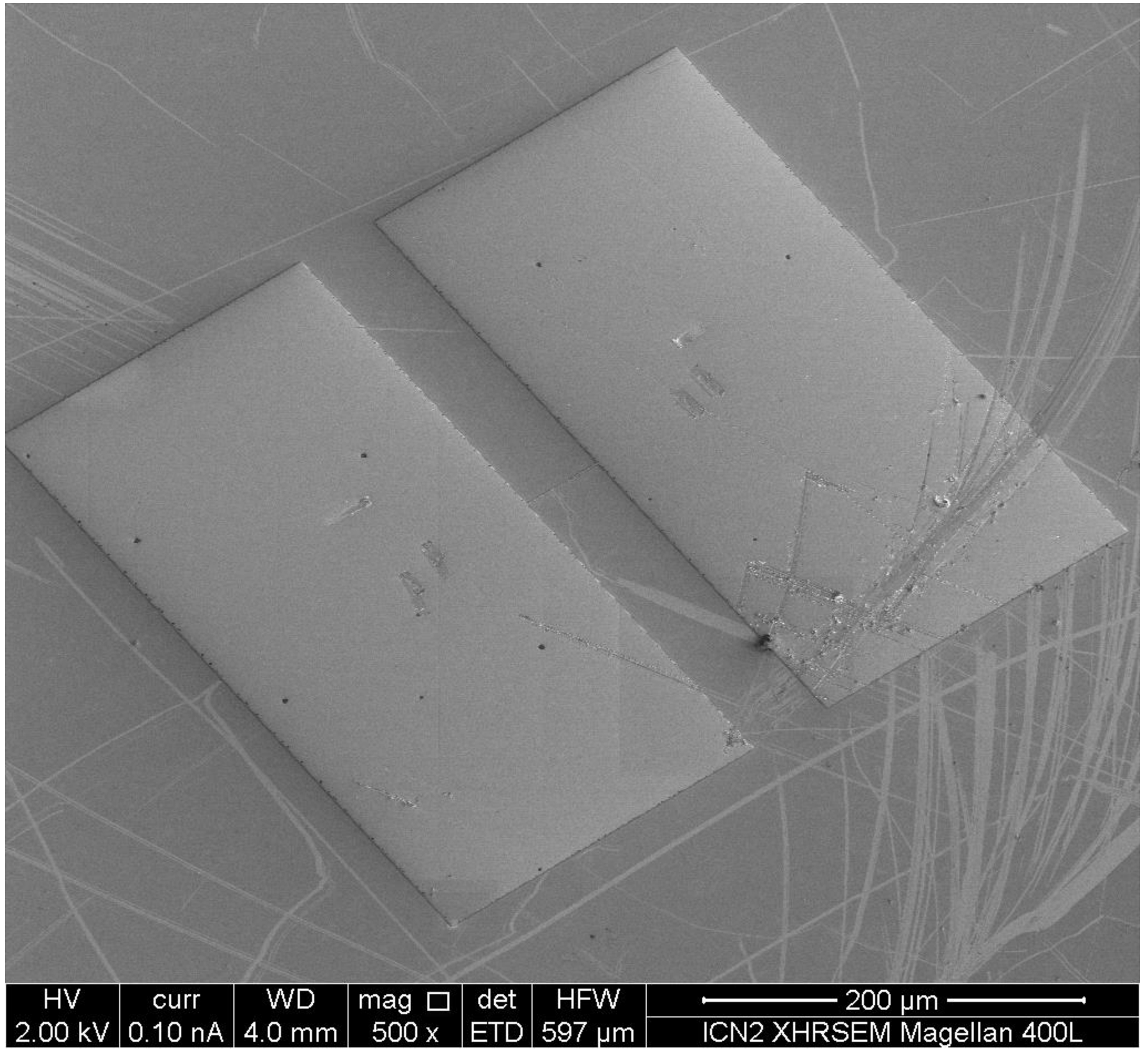
- Theoretical Background
- Technical Aspects
- Calibration Results
- DRAG scaling constant
- Reset Pulse

Theoretical Background

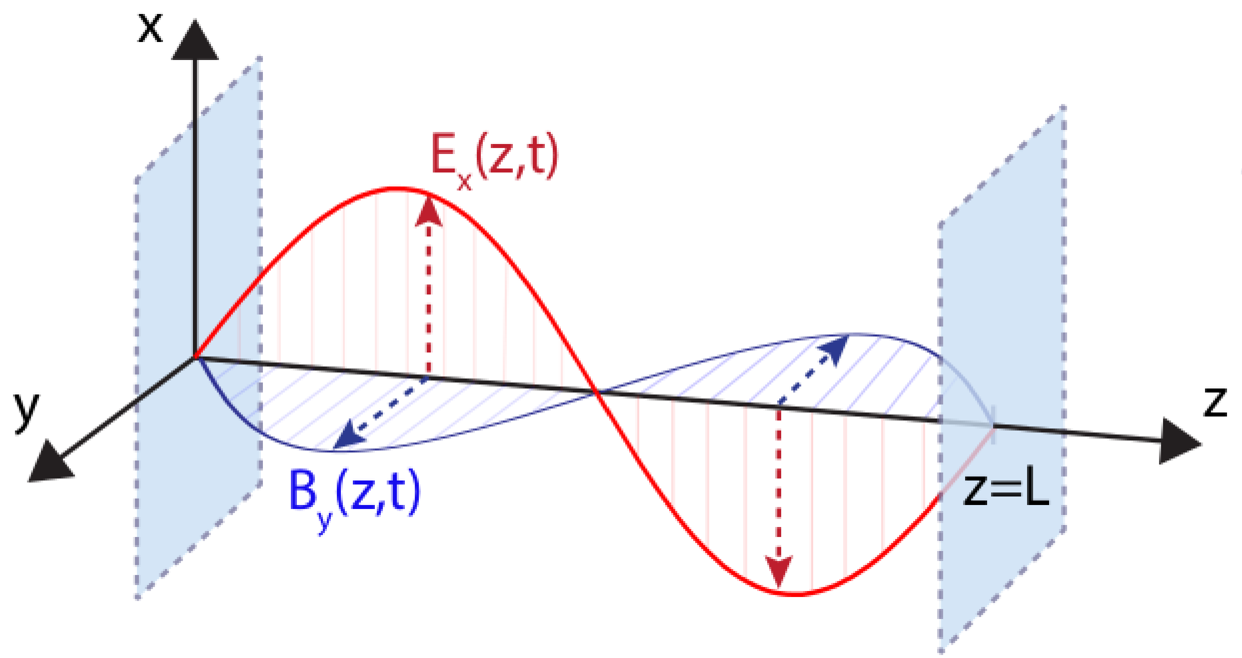
[1] - P. Krantz, M. Kjaergaard, F. Yan, T. P. Orlando, S. Gustavsson, and W. D. Oliver, A quantum engineer's guide to superconducting qubits, Appl. Phys. Rev. 6, 021318 (2019).
[2] - Naghiloo, M. (2019). Introduction to experimental quantum measurement with superconducting qubits. arXiv preprint arXiv:1904.09291.
[6] - Sangil Kwon and Akiyoshi Tomonaga and Gopika Lakshmi Bhai and Simon J. Devitt and Jaw-Shen Tsai, Tutorial: Gate-based superconducting quantum computing. arXiv preprint arXiv:2009.08021, (2020)

Cavity Quantum Electrodynamics (cQED)





The cavity



Ref. [2]

$$\hat{H} = \omega_c\left(\hat{a}^{\dagger}\hat{a} + \frac{1}{2}\right)$$

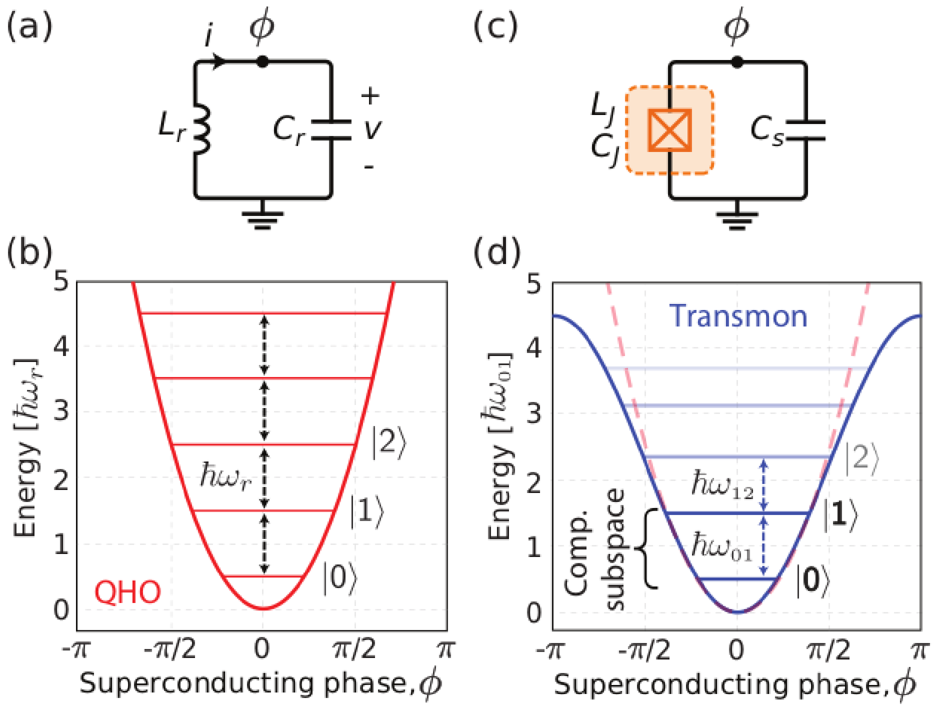
Photon number or Fock states

$$|n\rangle \qquad n = 0, 1, 2, \ldots$$

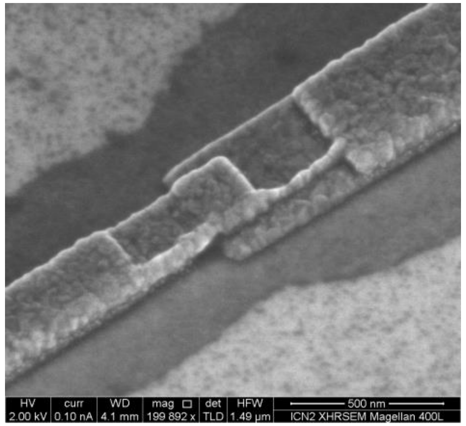
Coherent state

$$|\alpha\rangle = \sum_n c_n\,|n\rangle$$

The qubit



Ref. [1]



QCT @ IFAE

Nonlinear oscillator

$$\hat{H} = \omega_{01}\hat{b}^{\dagger}\hat{b} + \frac{\alpha}{2}\hat{b}^{\dagger}\hat{b}^{\dagger}\hat{b}\hat{b}$$

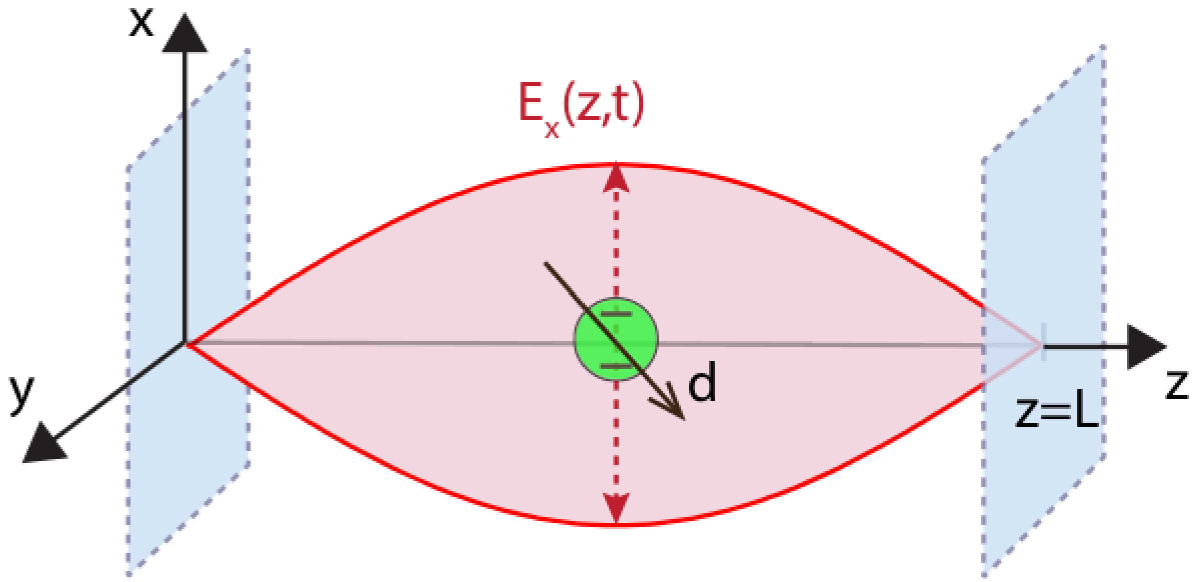
Reasonable anharmonicity:

$$\frac{\alpha}{2\pi} = E_{12} - E_{01} \sim -300\ MHz$$

Two-level system:

$$\hat{H} = -\frac{\omega_q}{2}\sigma_z$$

Jaynes-Cummings model



Dipole interaction

$$\hat{H}_{int} = -\hat{d}\cdot\hat{E}_x\left(\frac{L}{2},t\right)$$
$$= -g(\hat{a}^\dagger + \hat{a})(\sigma_+ + \sigma_-)$$

Total Hamiltonian:

$$\hat{H} = \omega_c\left(\hat{a}^\dagger\hat{a} + \frac{1}{2}\right) - \frac{\omega_q}{2}\sigma_z - g(\hat{a}^\dagger + \hat{a})(\sigma_+ + \sigma_-)$$

No interaction (g=0):

Bare states $\{|g\rangle|n\rangle, |e\rangle|n\rangle\}$

After RWA:

$$\hat{H}_{JC} = \omega_c\left(\hat{a}^\dagger\hat{a} + \frac{1}{2}\right) - \frac{\omega_q}{2}\sigma_z - g(\hat{a}^\dagger\sigma_- + \hat{a}\sigma_+)$$

$$\theta_n = \frac{1}{2}\tan^{-1}(2g\sqrt{n+1}/\Delta)$$
$$\Delta = \omega_q - \omega_c$$

Dressed states

$$|0,-\rangle = |g\rangle|0\rangle$$
$$|n,-\rangle = \cos\theta_n\,|g\rangle|n+1\rangle - \sin\theta_n\,|e\rangle|n\rangle$$
$$|n,+\rangle = \sin\theta_n\,|g\rangle|n+1\rangle + \cos\theta_n\,|e\rangle|n\rangle$$

Dispersive regime $\Delta \gg g$

$$\hat{H}_{JC} = \omega_c\left(\hat{a}^\dagger\hat{a} + \frac{1}{2}\right) - \frac{\omega_q}{2}\sigma_z - g(\hat{a}^\dagger\sigma_- + \hat{a}\sigma_+)$$

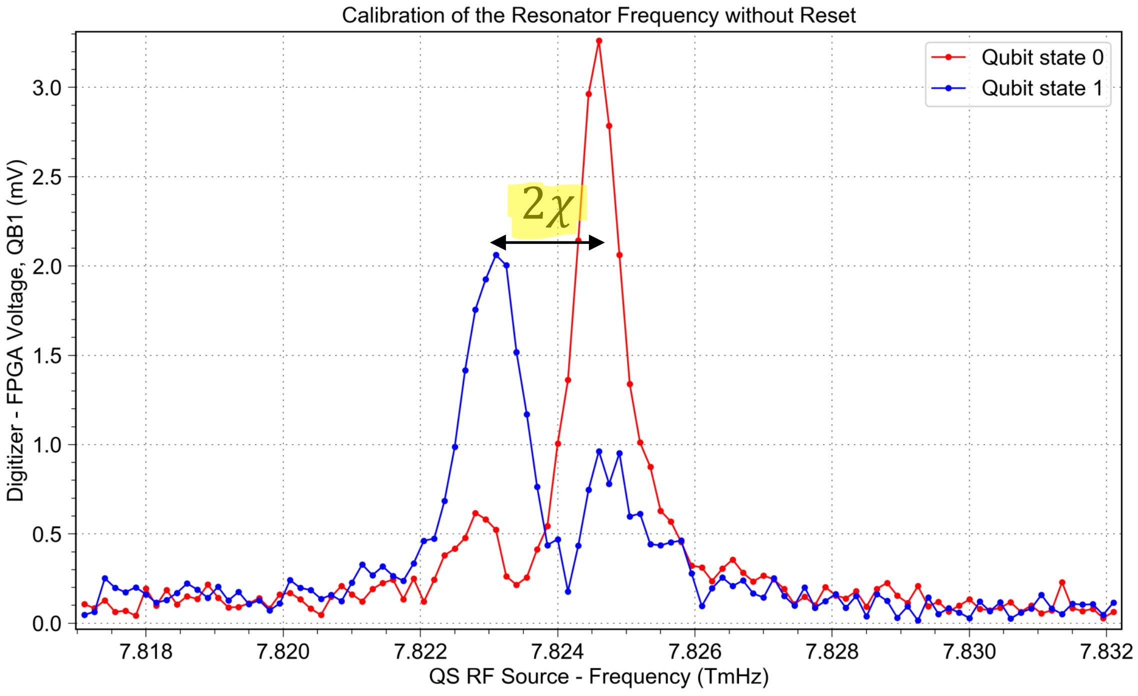
Unitary transformation

$$\hat{T} = e^{\frac{g}{\Delta}(\sigma_- a^\dagger - \sigma_+ a)}$$

$$\hat{H}_{dis} = \omega_c\hat{a}^\dagger\hat{a} - \frac{1}{2}\omega_q\sigma_z - \frac{g^2}{\Delta}\hat{a}^\dagger\hat{a}\sigma_z$$

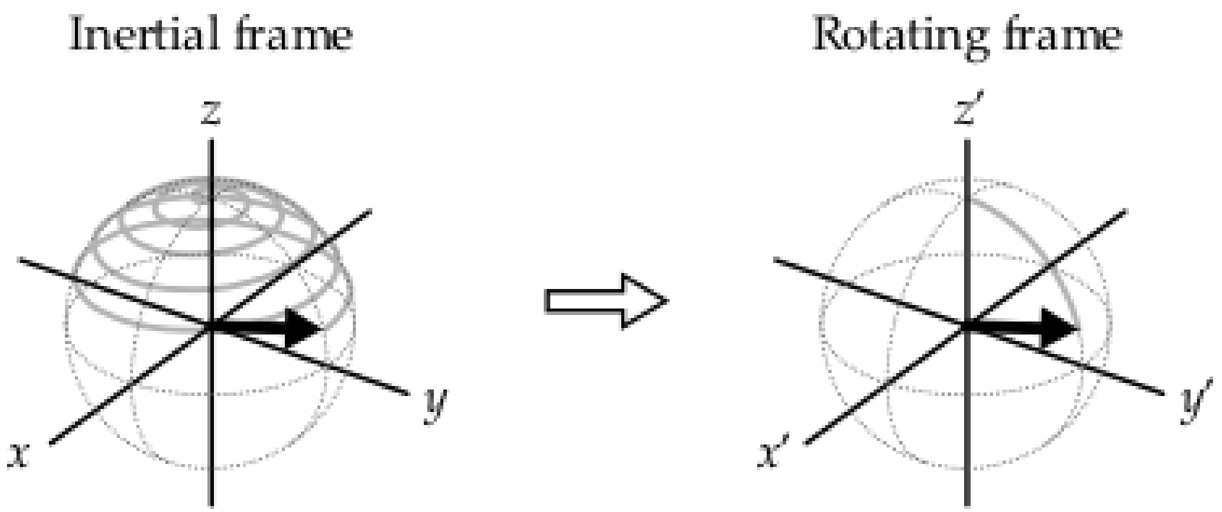
$$\boxed{\hat{H}_{dis} = (\omega_c - \chi\sigma_z)\hat{a}^\dagger\hat{a} - \frac{1}{2}\omega_q\sigma_z}$$

$$\hat{H}_{dis} = \omega_c\hat{a}^\dagger\hat{a} - \frac{1}{2}(\omega_q + 2\chi\bar{n})\sigma_z$$



$\chi = \frac{g^2}{\Delta}$ Dispersive shift

Driven qubit



Ref. [6]

$$H = \underbrace{-\frac{\omega_q}{2}\sigma_z}_{H_0} + \underbrace{\Omega V_0 v(t)\sigma_y}_{H_d}$$

$\downarrow$ Rotating frame

$$H = \underbrace{0}_{\widetilde{H}_0} + \underbrace{\Omega V_0 v(t)(\cos(\omega_q t)\,\sigma_y - \sin(\omega_q t)\sigma_x)}_{\widetilde{H}_d}$$

$\downarrow$ RWA

$$\widetilde{H}_d = -\frac{\Omega}{2} V_0 s(t) \begin{pmatrix} 0 & e^{i(\delta\omega t+\phi)} \\ e^{-i(\delta\omega t+\phi)} & 0 \end{pmatrix}$$

$$\begin{aligned} v(t) &= s(t)\sin(\omega_d t + \phi) \\ &= s(t)\,(\cos\phi\,\sin(\omega_d t) + \sin\phi\,\cos(\omega_d t)) \\ &= s(t)(I\sin(\omega_d t) + Q\cos(\omega_d t)) \end{aligned}$$

$$I = \cos\phi$$
$$Q = \sin\phi$$

Without detuning:

$$\boxed{\widetilde{H}_d = -\frac{\Omega}{2} V_0 s(t)(I\sigma_x + Q\sigma_y)}$$

Rabi drive:

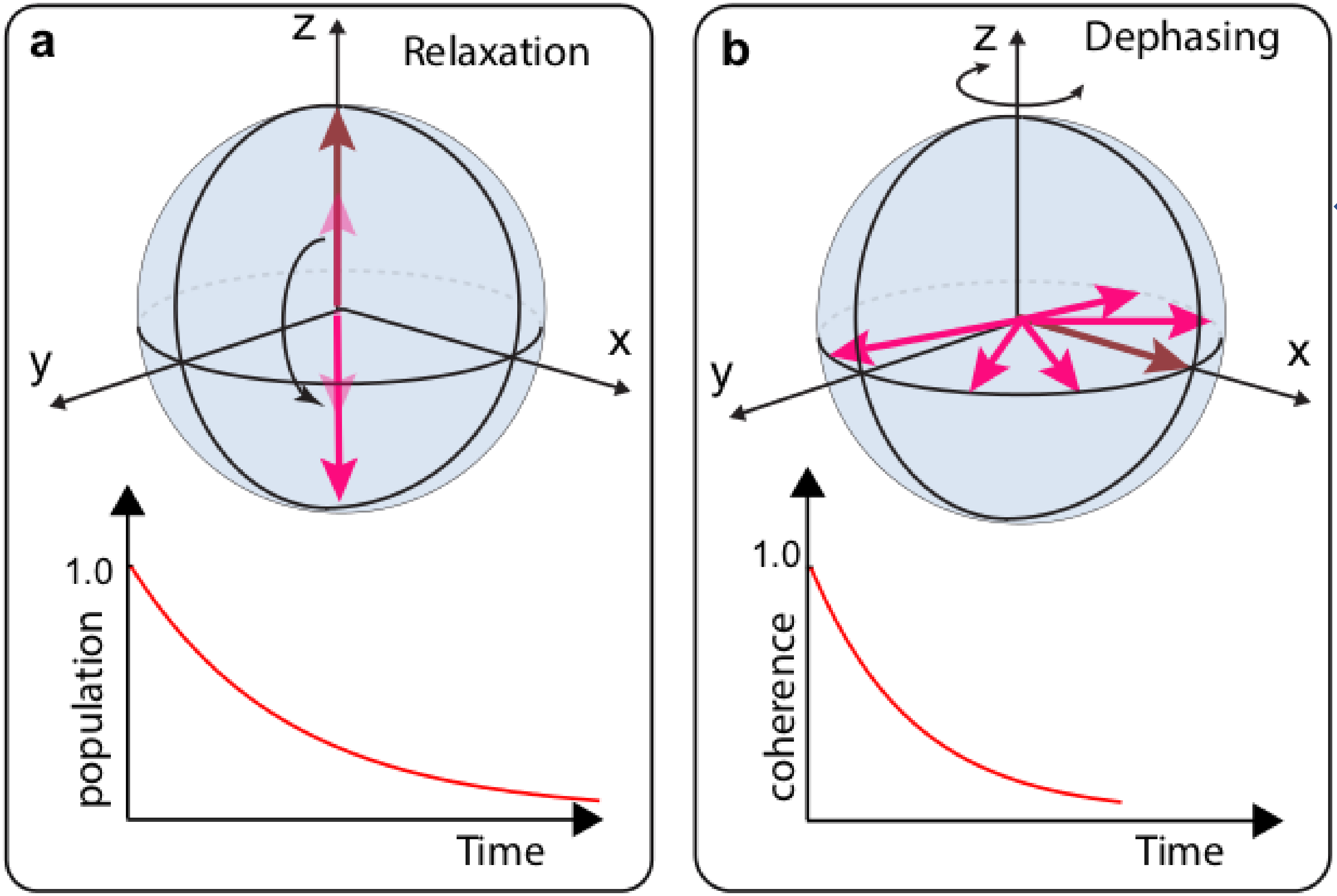
$$U_{rf,}^{\phi=0}(t) = \exp(\left[\frac{i}{2}\Omega V_0 \int_0^t s(t')dt'\right]\sigma_x)$$

Dissipation

$$P_e(t) = P_e(0)e^{-t/T_1}$$

T_2

T_φ

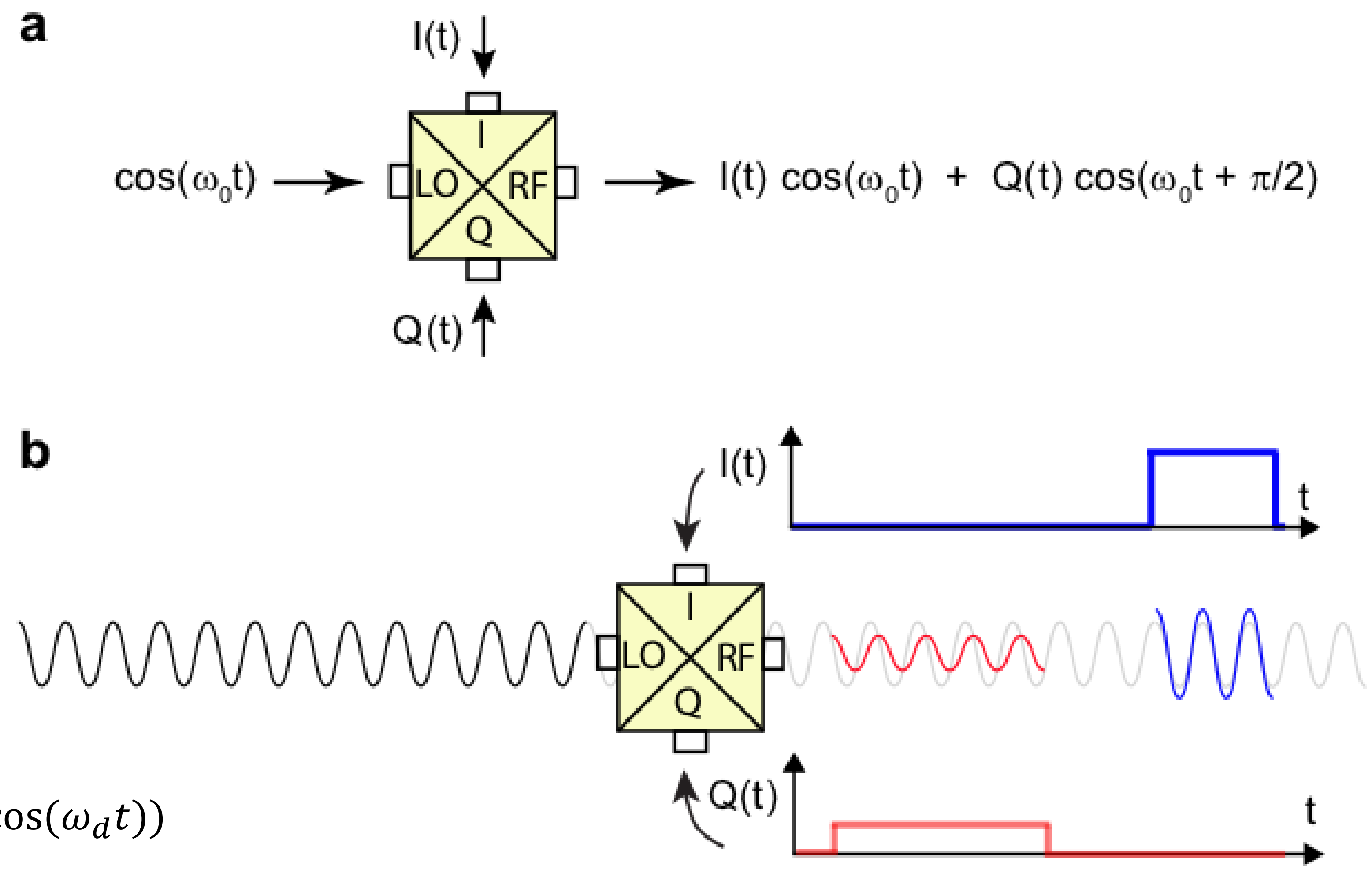


$$\boxed{\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\varphi}}$$

Ref. [2]

Technical Aspects

IQ mixing



$$v(t) = s(t)\,(\tilde{I}\sin(\omega_d t) + \tilde{Q}\cos(\omega_d t))$$

$$\boxed{\widetilde{H}_d = -\frac{\Omega}{2} V_0 s(t)(\tilde{I}\sigma_x + \tilde{Q}\sigma_y)}$$

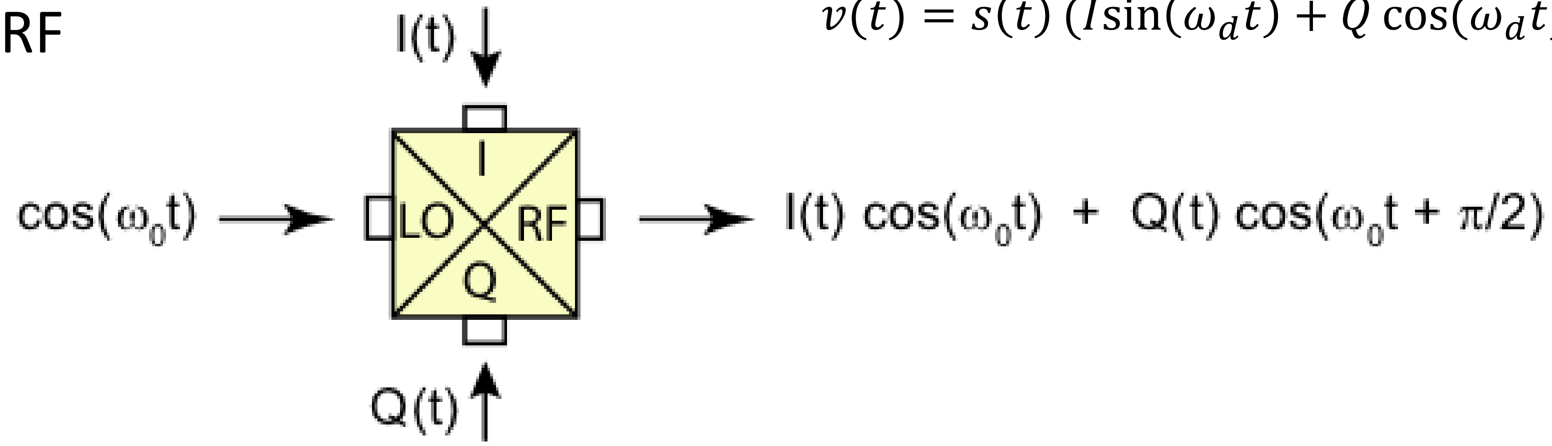
Single Sideband Modulation (SSB)

Signal leakage from LO to RF

$$\omega_{LO} = \omega_d + \omega_{SSB}$$

$$\omega_{SSB} \sim 70MHz$$

$$v(t) = s(t)\,(\tilde{I}\sin(\omega_d t) + \tilde{Q}\cos(\omega_d t))$$



Labber generates:

$$I(t) = \mathrm{s(t)}(\tilde{I}\cos(\omega_{SSB}t - \phi) - \tilde{Q}\cos\left(\omega_{SSB}t - \phi + {}^{\pi}/_{2}\right))$$

$$Q(t) = \mathrm{s(t)}(-\tilde{I}\sin(\omega_{SSB}t - \phi) + \tilde{Q}\sin(\omega_{SSB}t - \phi + {}^{\pi}/_{2}))$$

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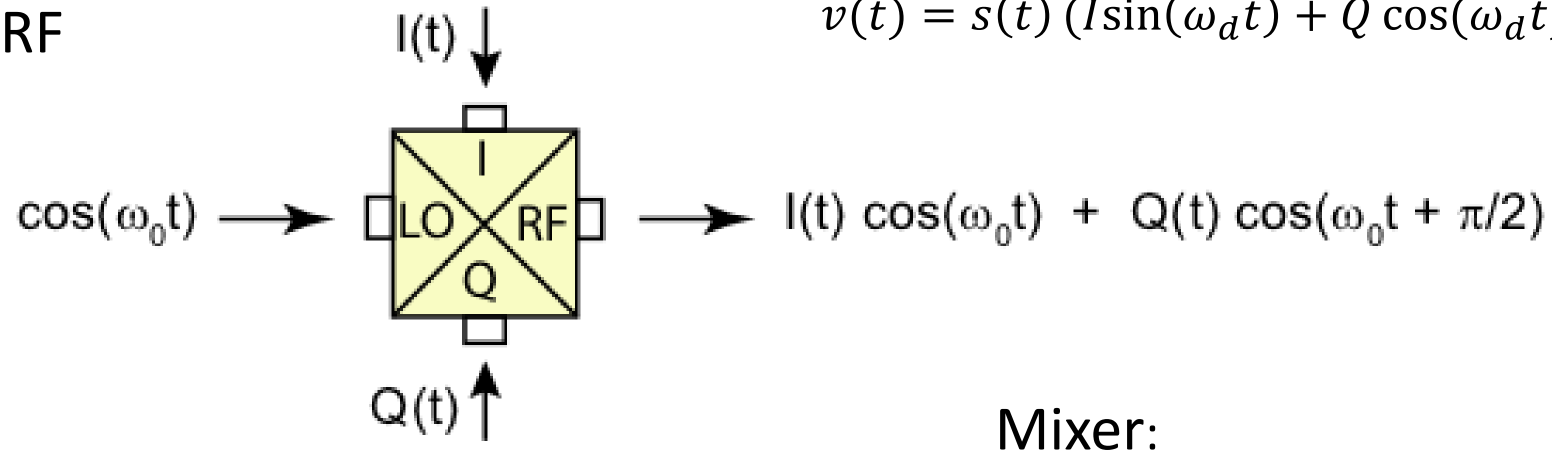

$$v(t) = s(t)\,(\tilde{I}\sin(\omega_d t) + \tilde{Q}\cos(\omega_d t))$$

Labber generates:

Mixer:

$$I(t) = \mathrm{s(t)}(\tilde{I}\cos(\omega_{SSB}t - \phi) - \tilde{Q}\cos\left(\omega_{SSB}t - \phi + {}^{\pi}/_{2}\right)) \quad \times \cos(\omega_{LO}t)$$

$$Q(t) = \mathrm{s(t)}(-\tilde{I}\sin(\omega_{SSB}t - \phi) + \tilde{Q}\sin(\omega_{SSB}t - \phi + {}^{\pi}/_{2})) \quad \times \cos\left(\omega_{LO}t + {}^{\pi}/_{2}\right)$$

Single Sideband Modulation (SSB)

Signal leakage from LO to RF

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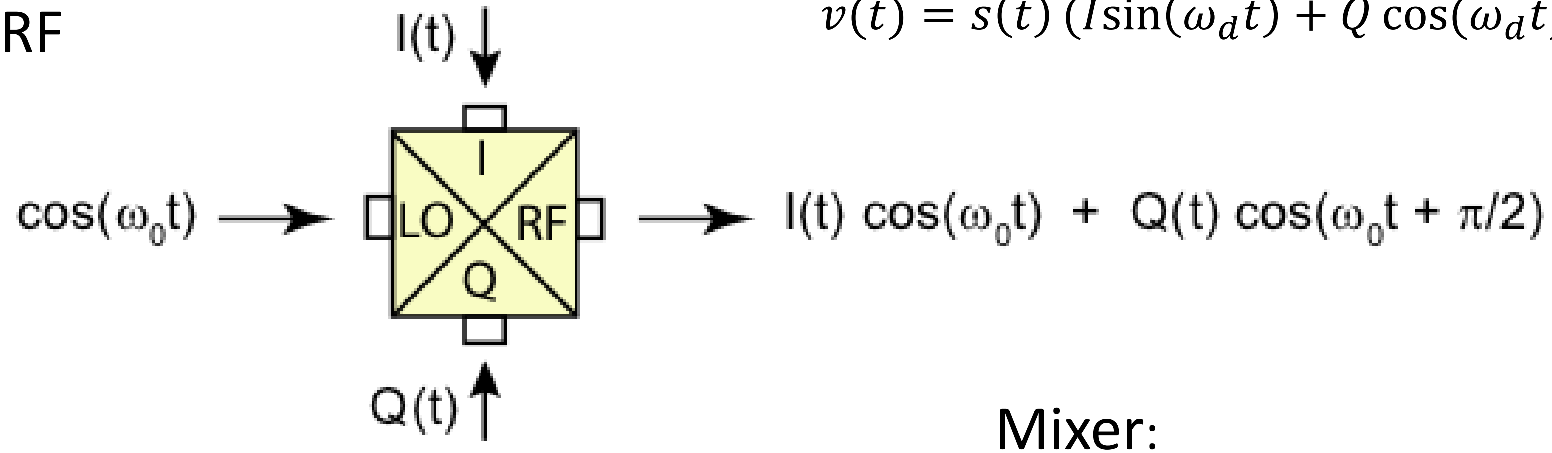

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$+$

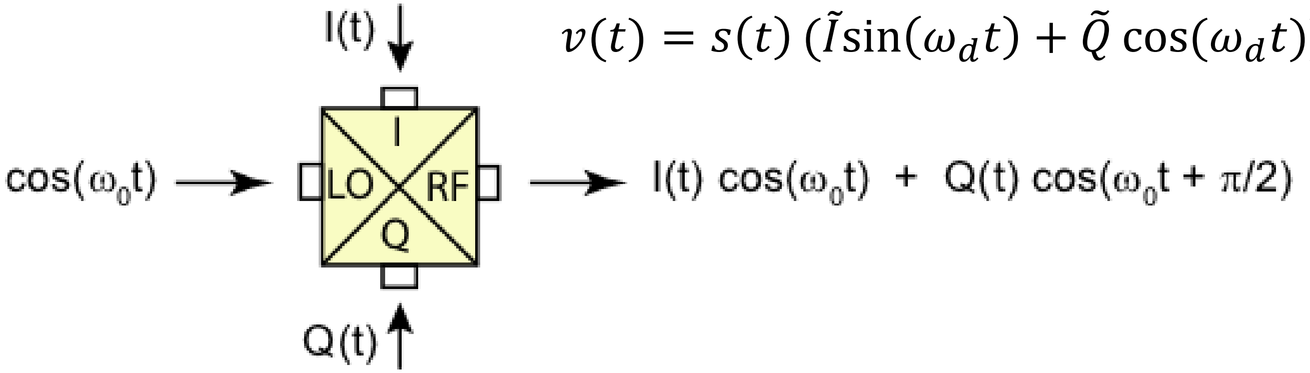
$$Q(t) = \mathrm{s(t)}(-\tilde{I}\sin(\omega_{SSB}t - \phi) + \tilde{Q}\sin(\omega_{SSB}t - \phi + {}^{\pi}/_{2})) \quad \times \cos\left(\omega_{LO}t + {}^{\pi}/_{2}\right)$$

$$\mathrm{s(t)}(\tilde{I}\cos\left((\omega_{LO} - \omega_{SSB})t + \phi\right) - \tilde{Q}\sin\left((\omega_{LO} - \omega_{SSB}\right)t + \phi))$$

Derivative Reduction by Adiabatic Gate (DRAG)

- **Leakage errors**: Excitations outside of the computational subspace

- **Phase errors**: Accumulation of a phase



$$v(t) = s(t)\,(\tilde{I}\sin(\omega_d t) + \tilde{Q}\cos(\omega_d t))$$

$$\boxed{s(t) \to \tilde{s}(t) = \begin{cases} s(t) & \text{on} \quad \tilde{I} \\ \beta s'(t) & \text{on} \quad \tilde{Q} \end{cases}}$$

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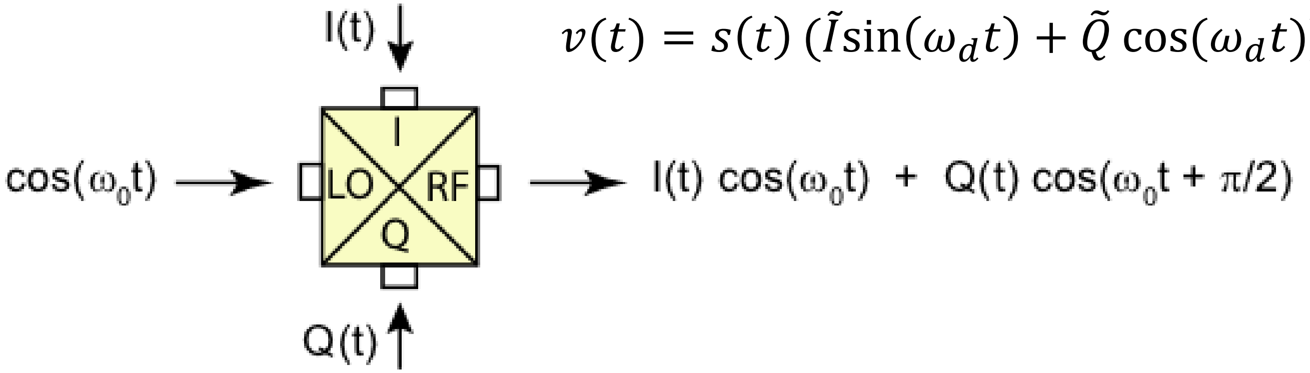

$v(t) = s(t)\,(\tilde{I}\sin(\omega_d t) + \tilde{Q}\cos(\omega_d t))$

- **Phase errors**: Accumulation of a phase

$$\boxed{s(t) \rightarrow \tilde{s}(t) = \begin{cases} s(t) & \text{on} \quad \tilde{I} \\ \beta s'(t) & \text{on} \quad \tilde{Q} \end{cases}}$$

Labber generates:

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$$I(t) = s(t)\tilde{I}\cos(\omega_{SSB}t - \phi) - \beta s'(t)\tilde{Q}\cos\left(\omega_{SSB}t - \phi + {}^{\pi}/_{2}\right) \quad \times \cos(\omega_{LO}t)$$

$$+$$

$$Q(t) = -s(t)\tilde{I}\sin(\omega_{SSB}t - \phi) + \beta s'(t)\tilde{Q}\sin(\omega_{SSB}t - \phi + {}^{\pi}/_{2}) \quad \times \cos\left(\omega_{LO}t + {}^{\pi}/_{2}\right)$$

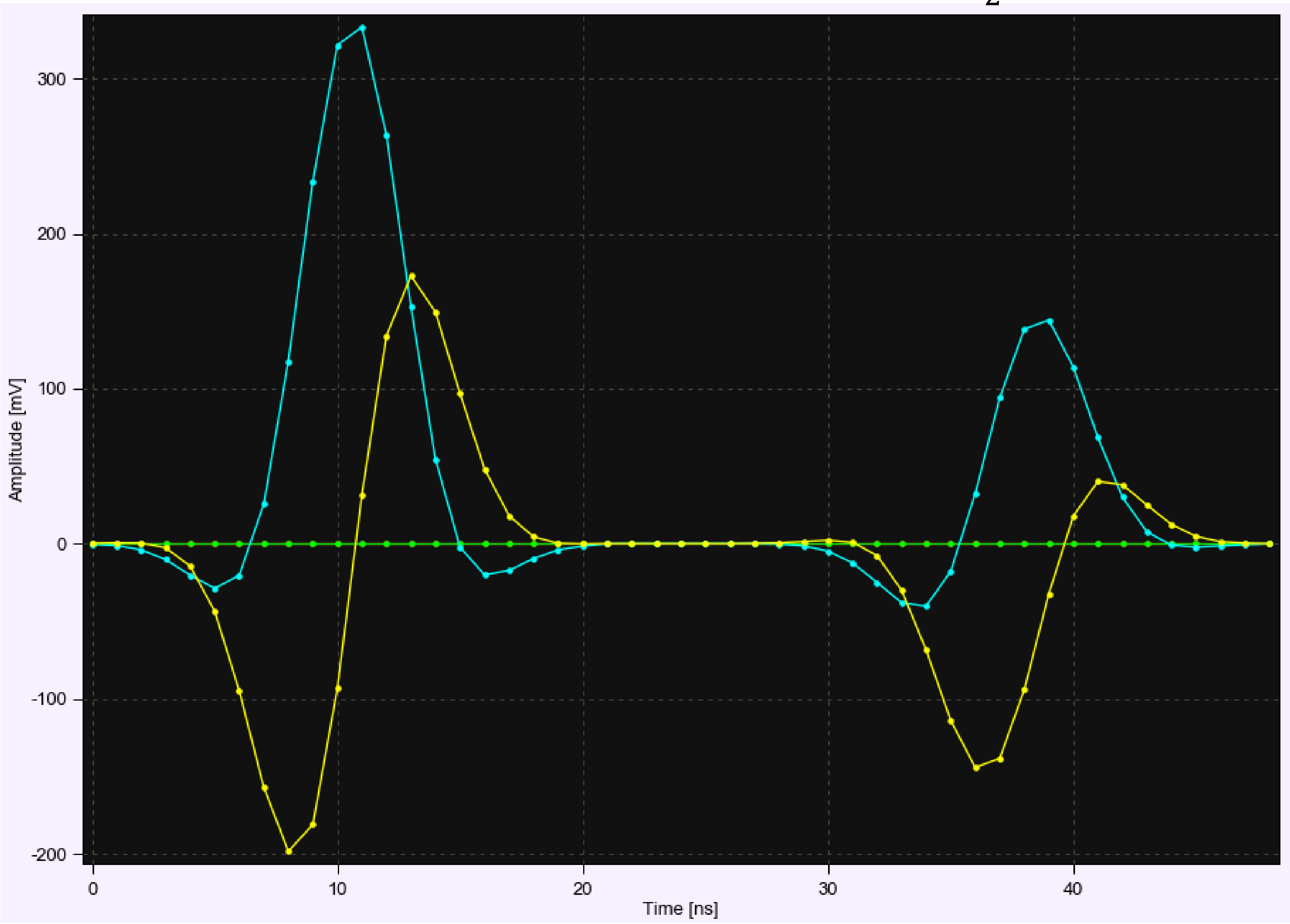
$$s(t)\tilde{I}\cos\big((\omega_{LO} - \omega_{SSB})t + \phi\big) - \beta s'(t)\tilde{Q}\sin\big((\omega_{LO} - \omega_{SSB})t + \phi\big)$$

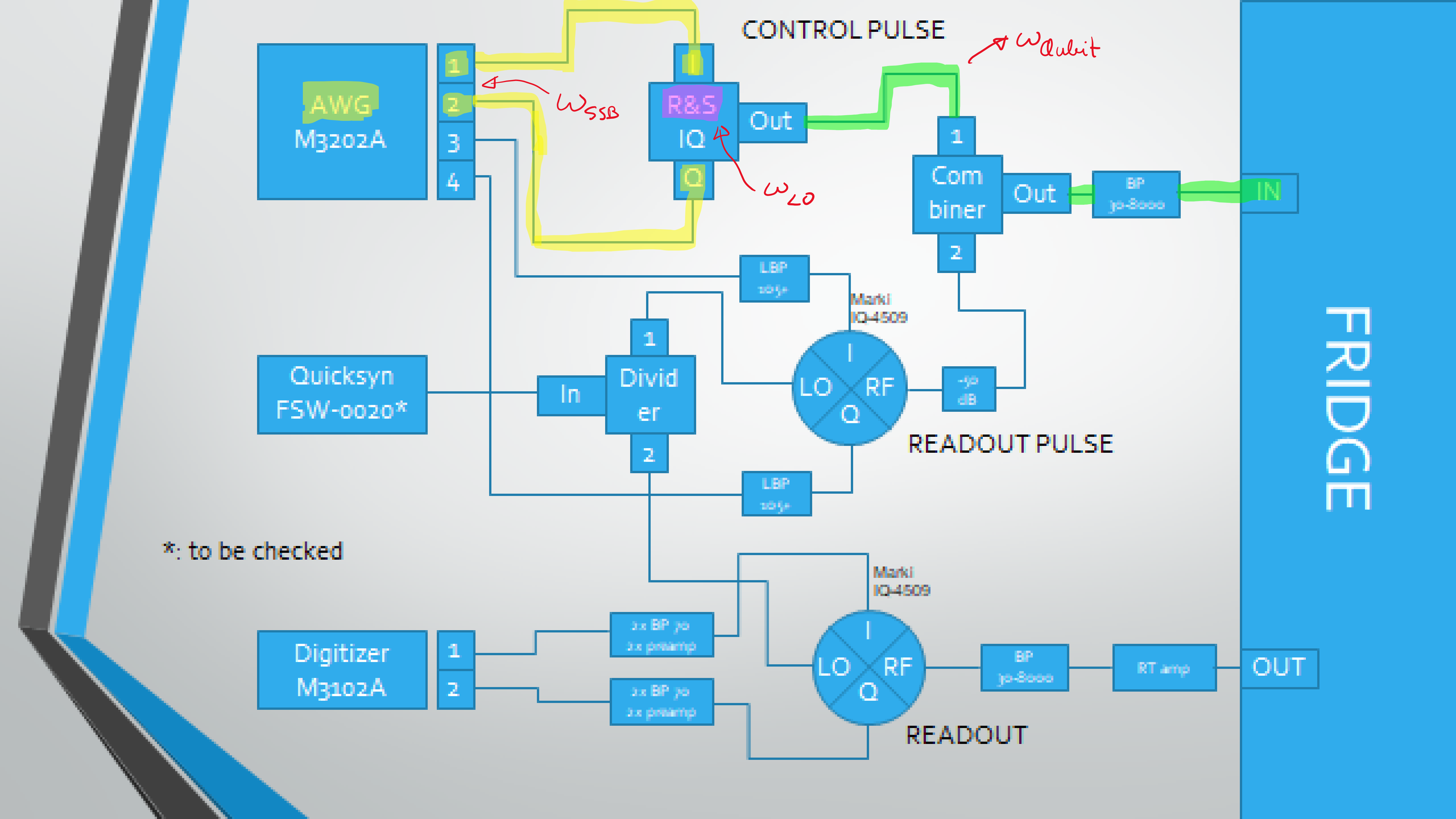
Pulses

- Gaussian envelope
- SSB and DRAG
- Fixed width
- Variable:
  - Amplitude (Volts)
  - Phase

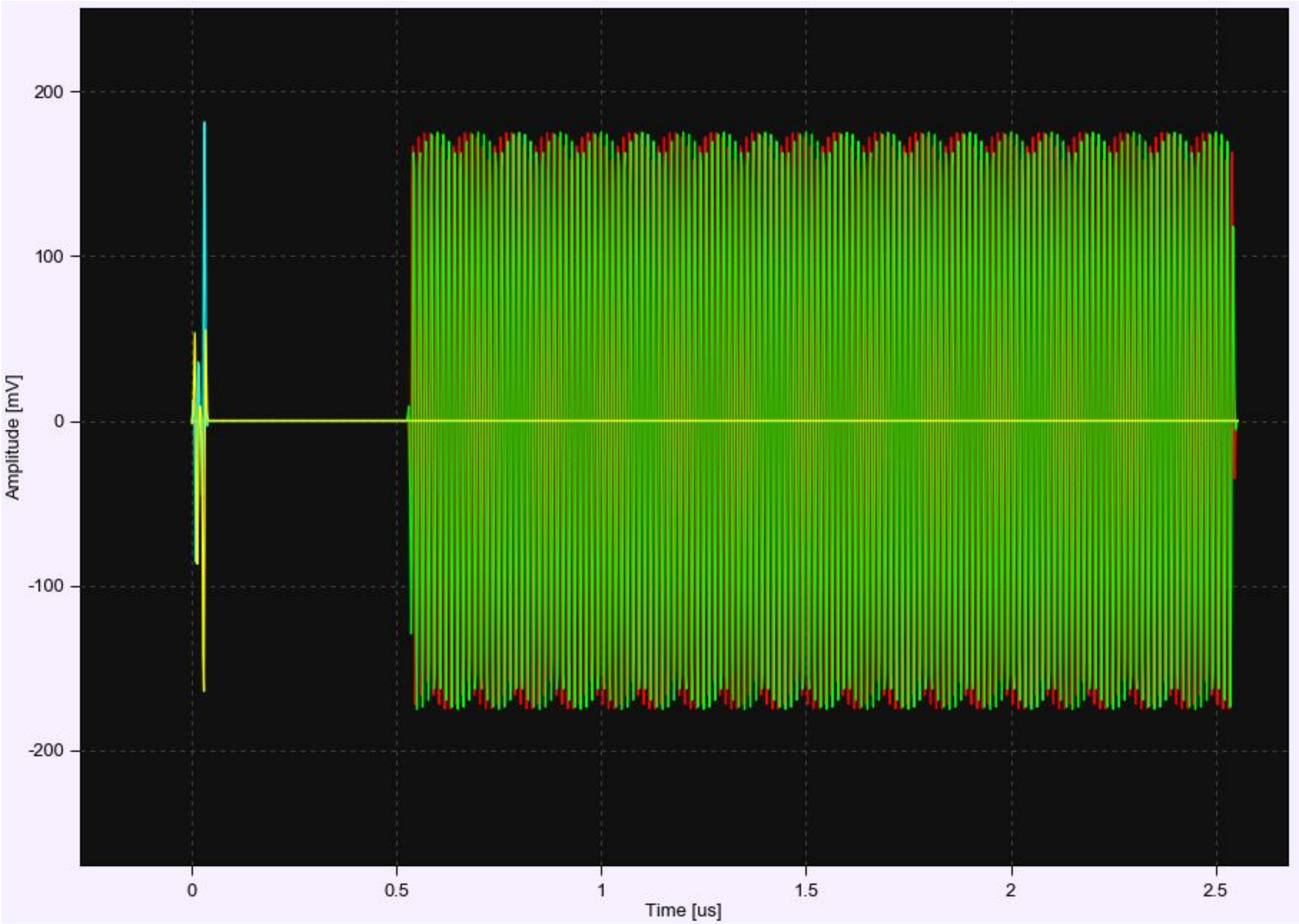
π- Pulse

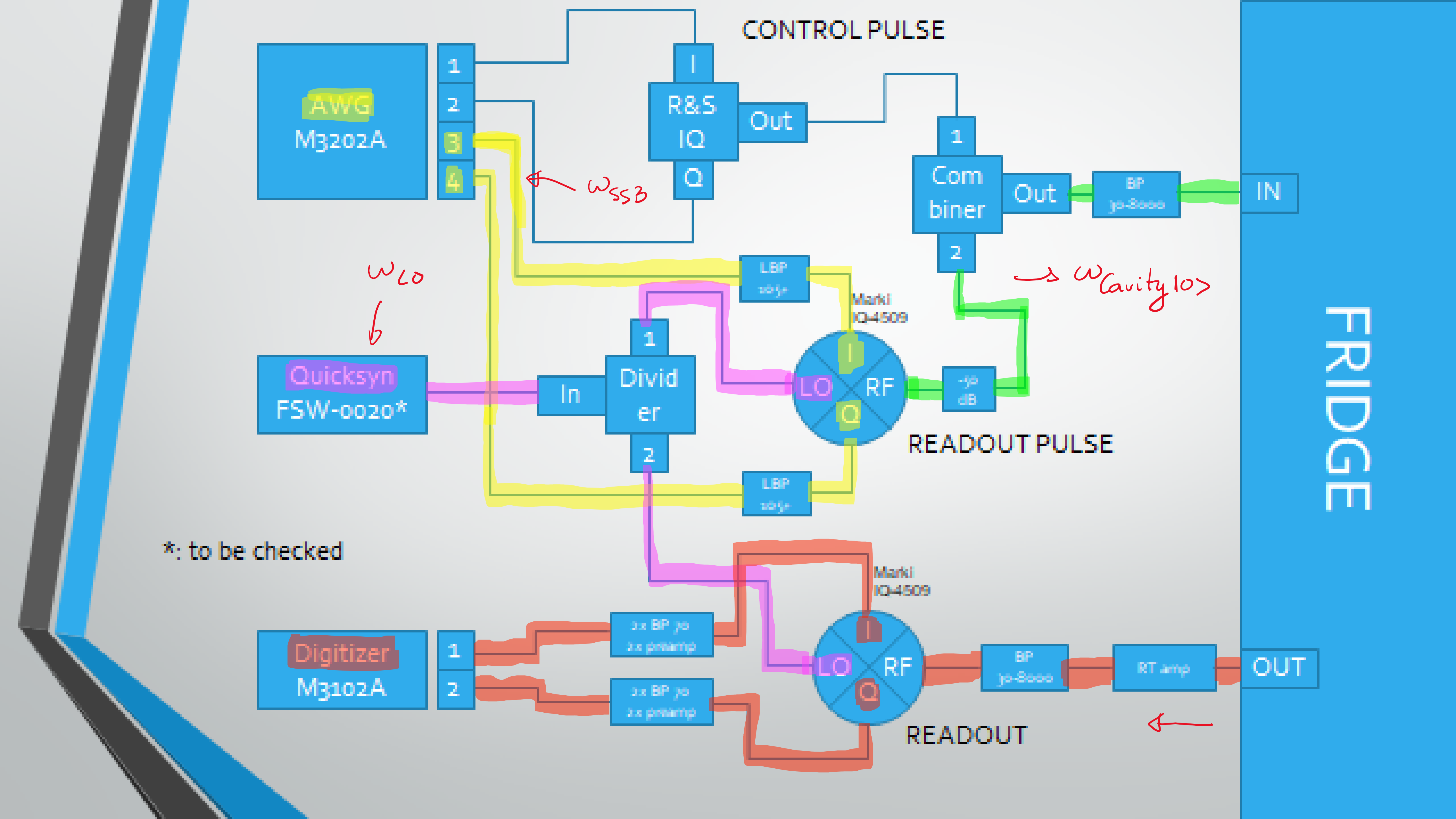
$\frac{\pi}{2}$ - Pulse




CONTROL PULSE
AWG
M3202A
1
2
3
4
R&S
IQ
I
Q
Out
ω_{SSB}
ω_{LO}
ω_{Qubit}
1
Com
biner
Out
2
IN
FRIDGE
Quicksyn
FSW-0020*
In
Divid
er
1
2
Marki
IQ-4509
I
LO
RF
Q
READOUT PULSE
LBP
*: to be checked
Digitizer
M3102A
1
2
Marki
IQ-4509
I
LO
RF
Q
RT amp
OUT
READOUT

Readout pulse




CONTROL PULSE
AWG
M3202A
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ωCavity|0>
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Quicksyn
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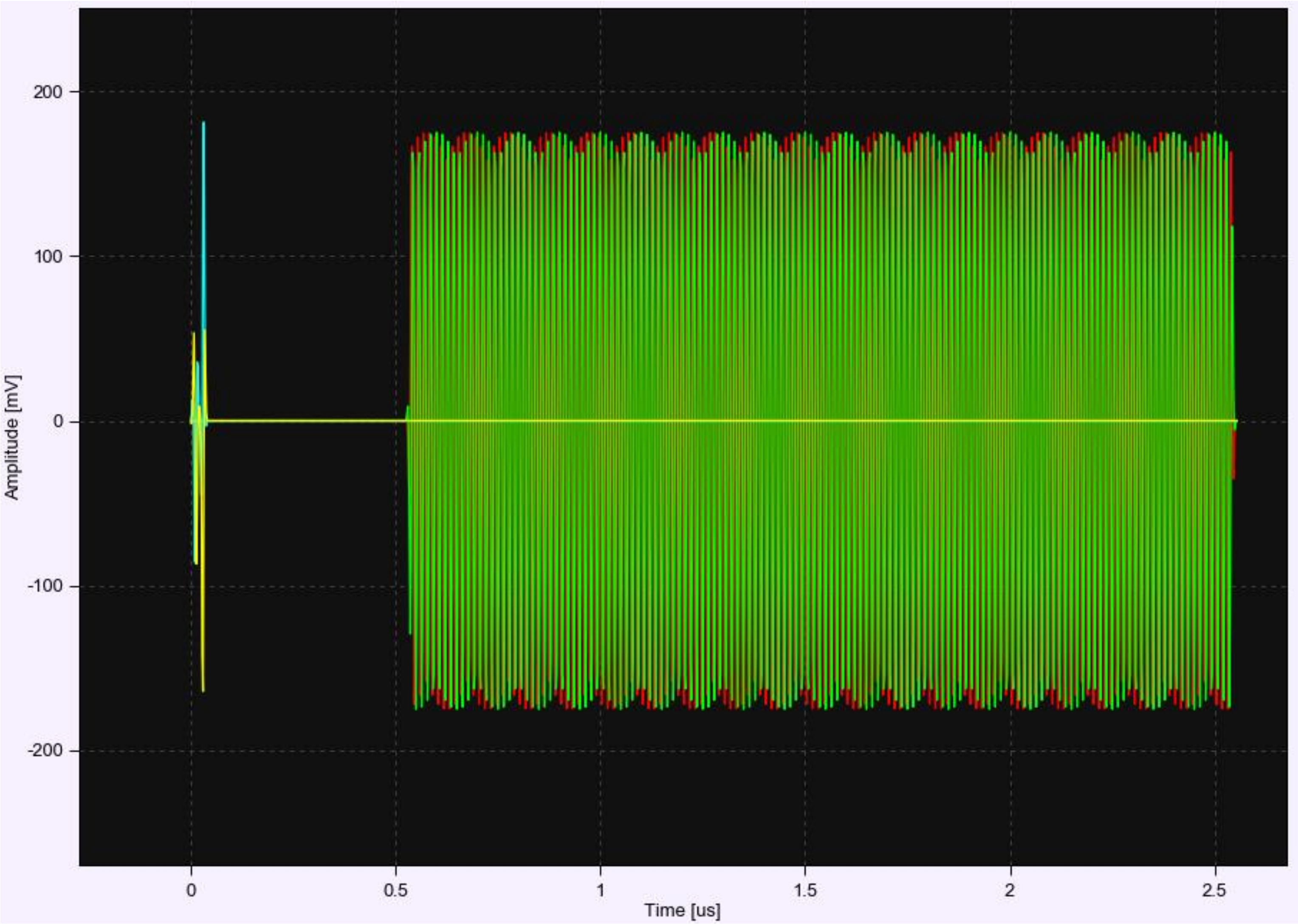
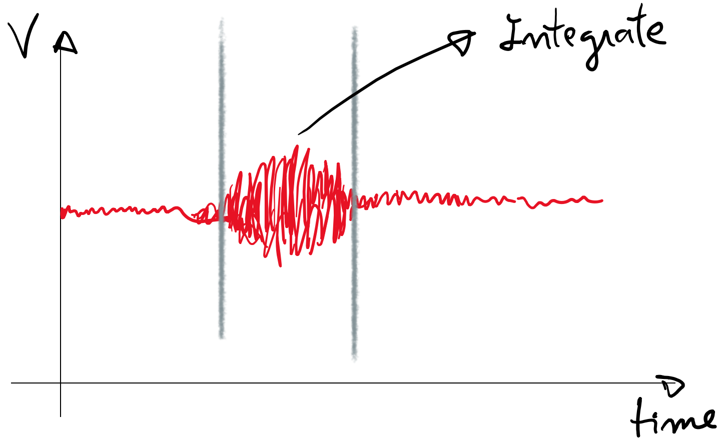
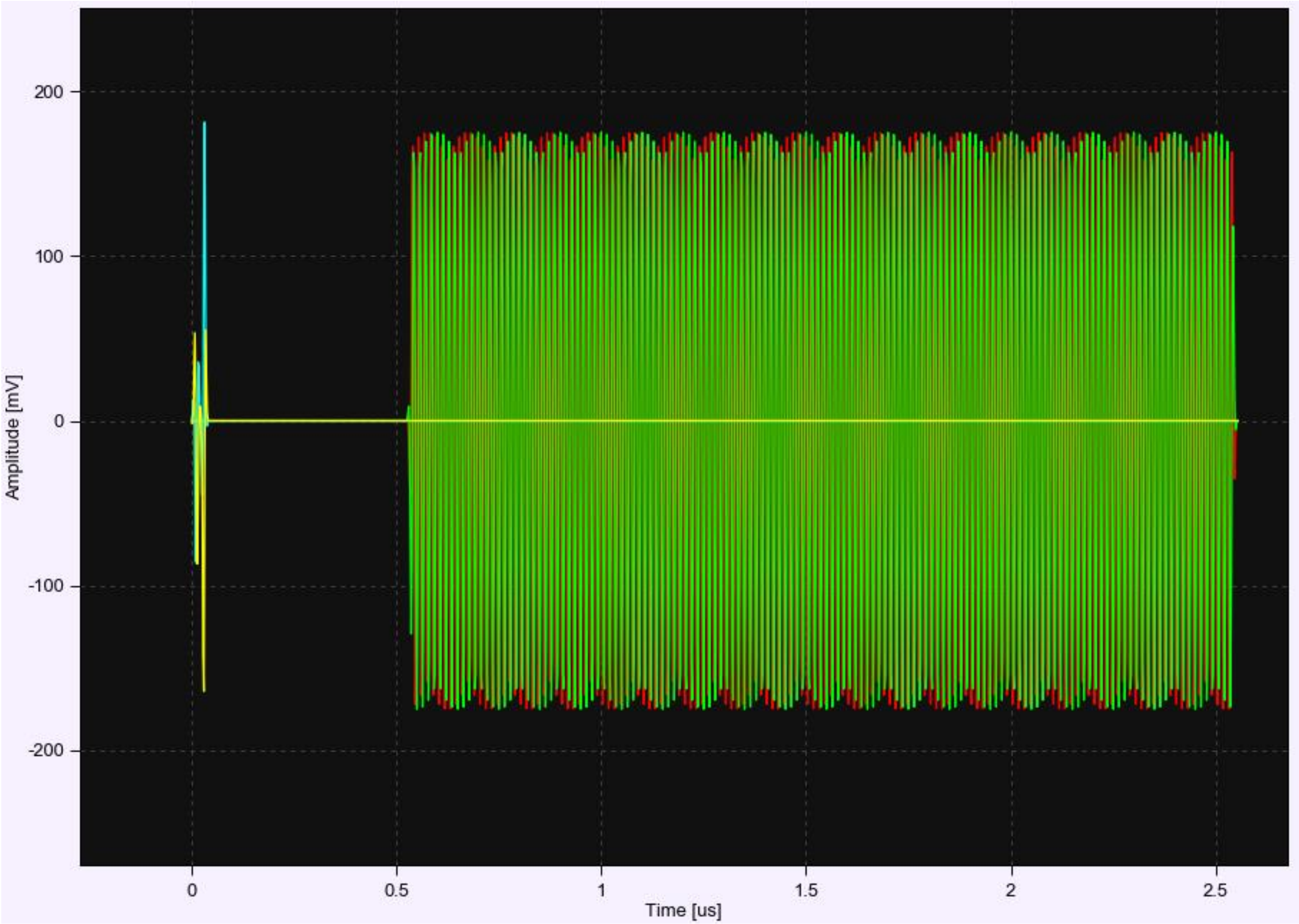
Readout pulse



Digitizer signal



Readout pulse



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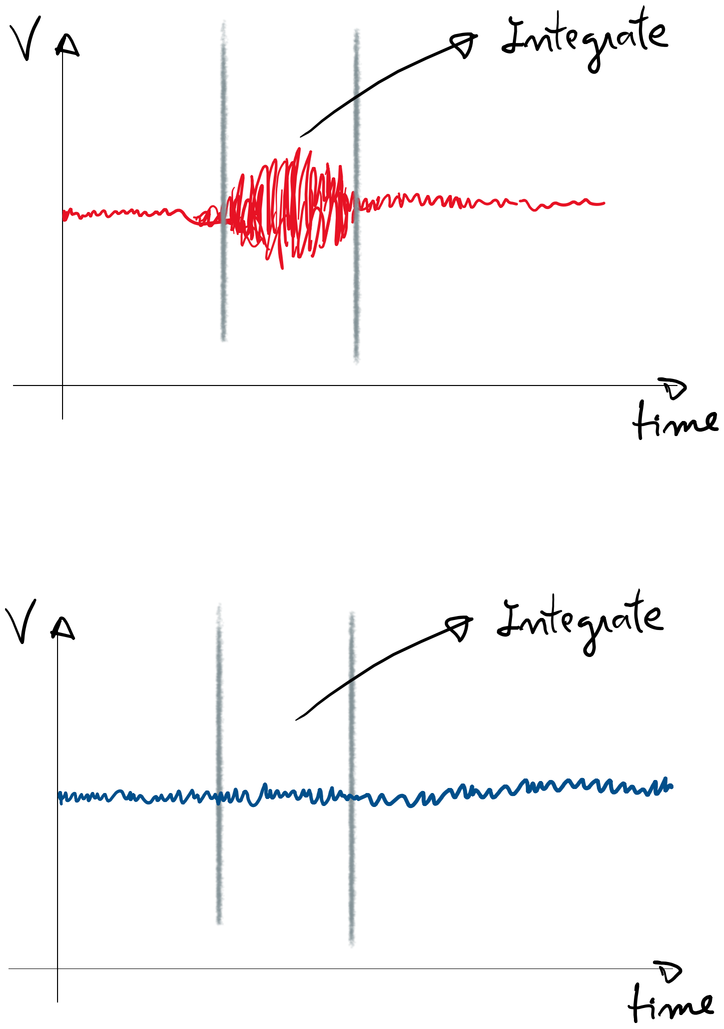
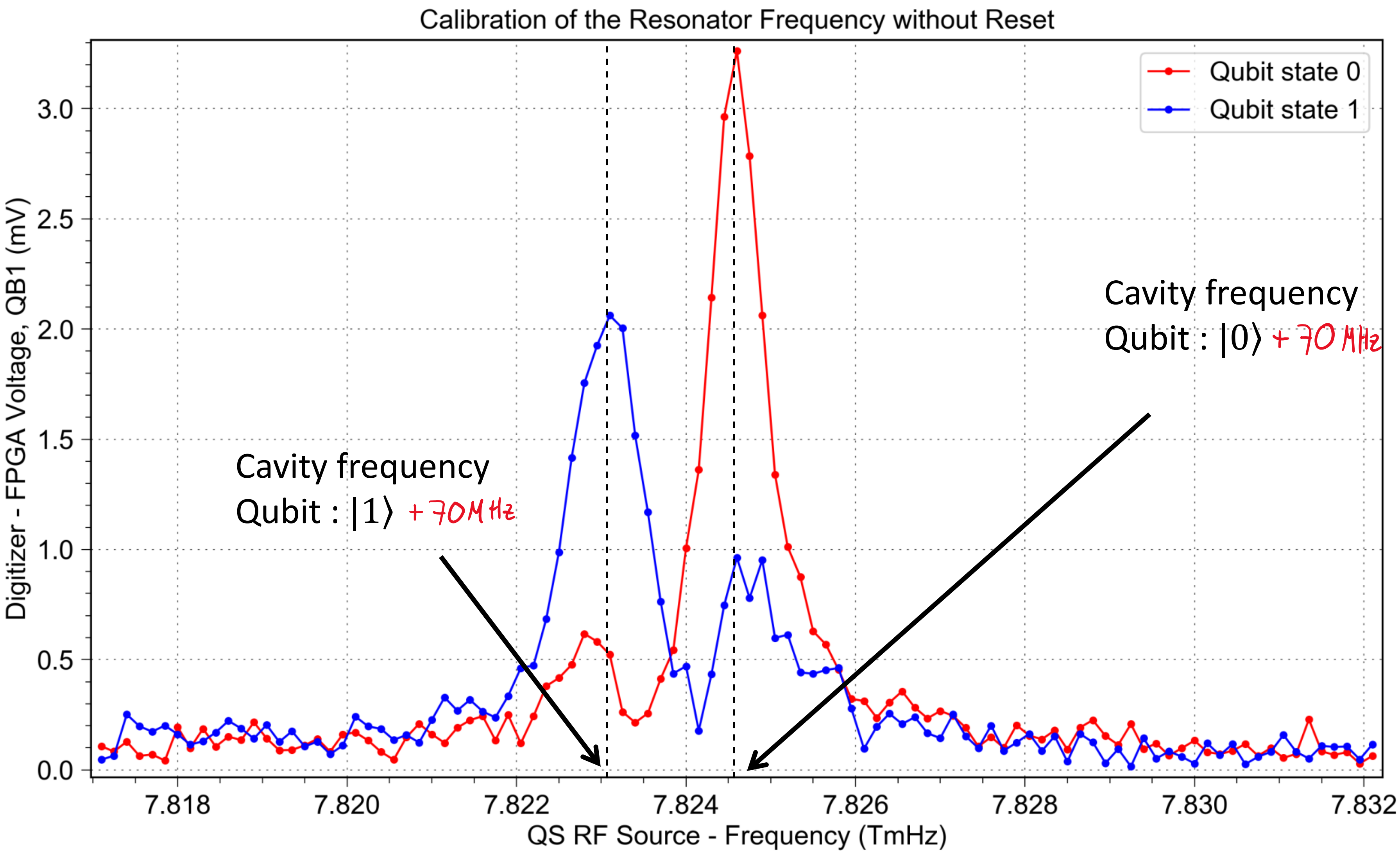
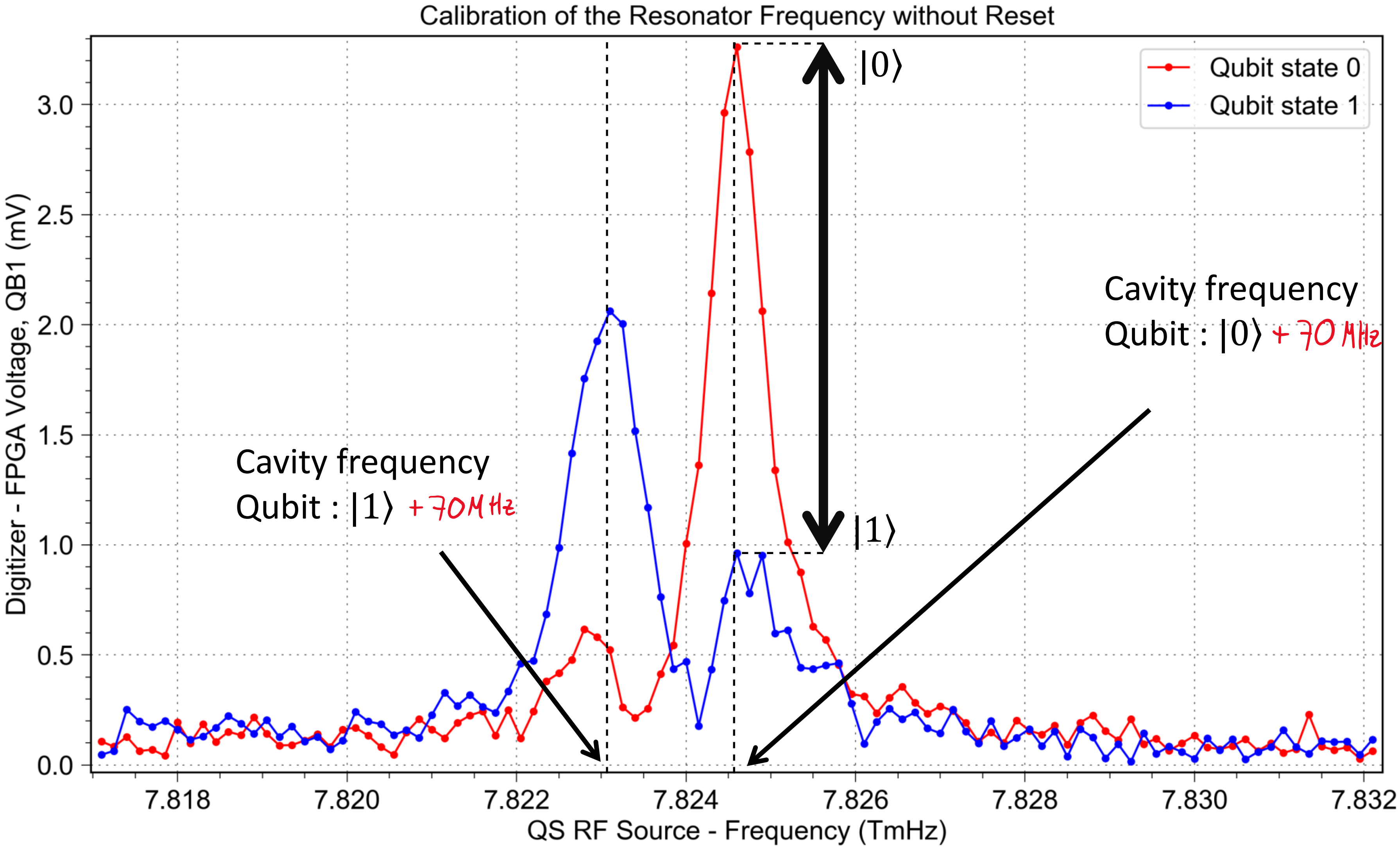


Readout pulse



Readout pulse



The program

- calibration.py
- fittings.py
- Labber measurement configurations (.hdf5)
- parameters.txt
- StableParameters.txt

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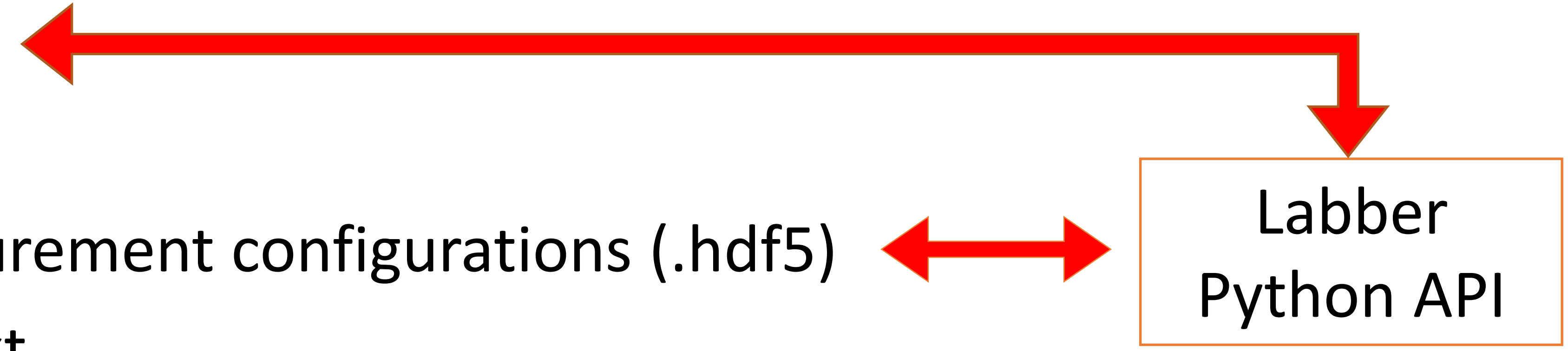

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Labber
Python API

The program

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Labber
Python API

jupyter

```
from calibration import *
%matplotlib inline
cal = Calibration('parameters.txt')
```

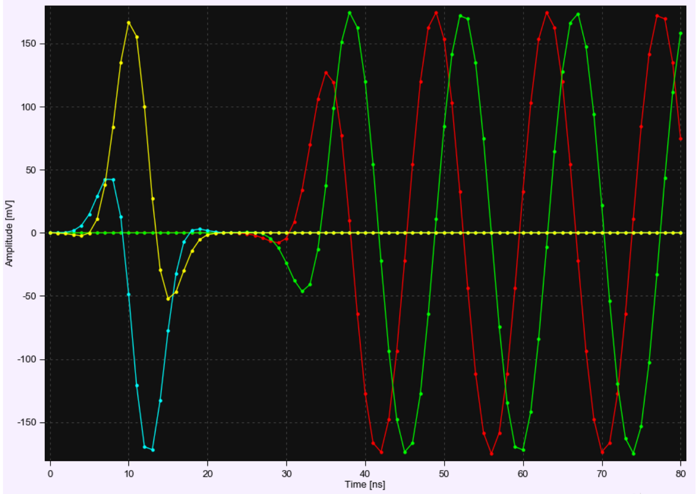
Calibration Results

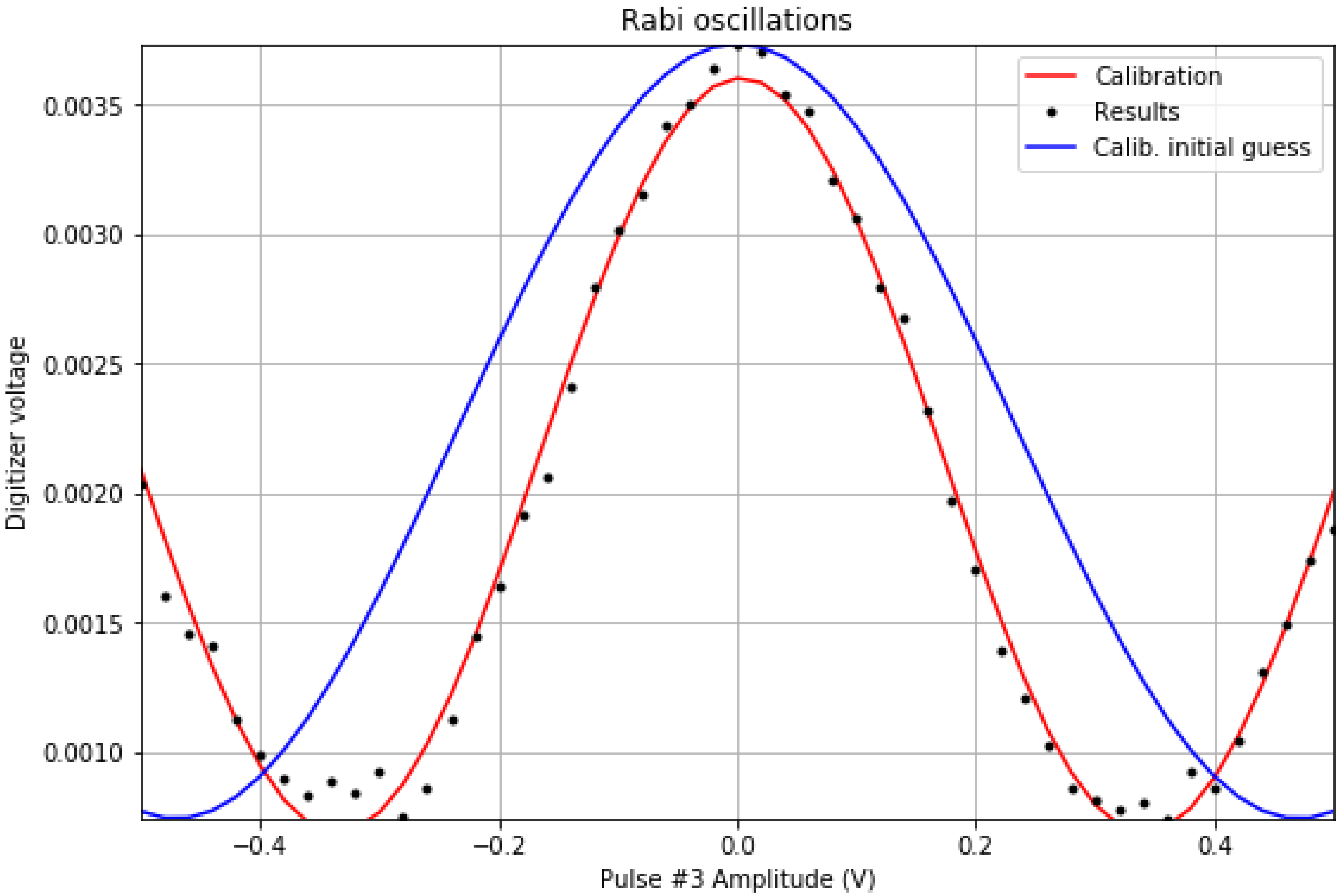
- Voltage amplitude of a Pi Pulse
- Coherence times: T_1, T_2 and $T_{\varphi, G}$
- Qubit Frequency
- Cavity frequencies

Pi Pulse calibration

$A\cos^2(2\pi x/\mathrm{T} + \phi) + \mathrm{c}$

cal.getPiPulse()





cal._PiPulse = 0.338 V

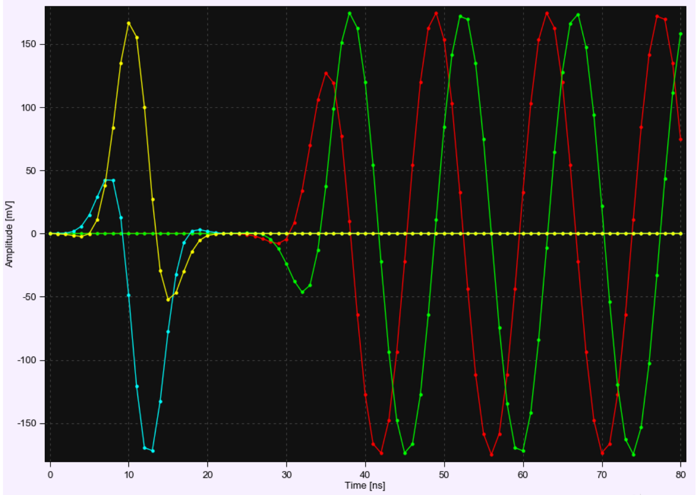
cal._Amax = 0.0036 V

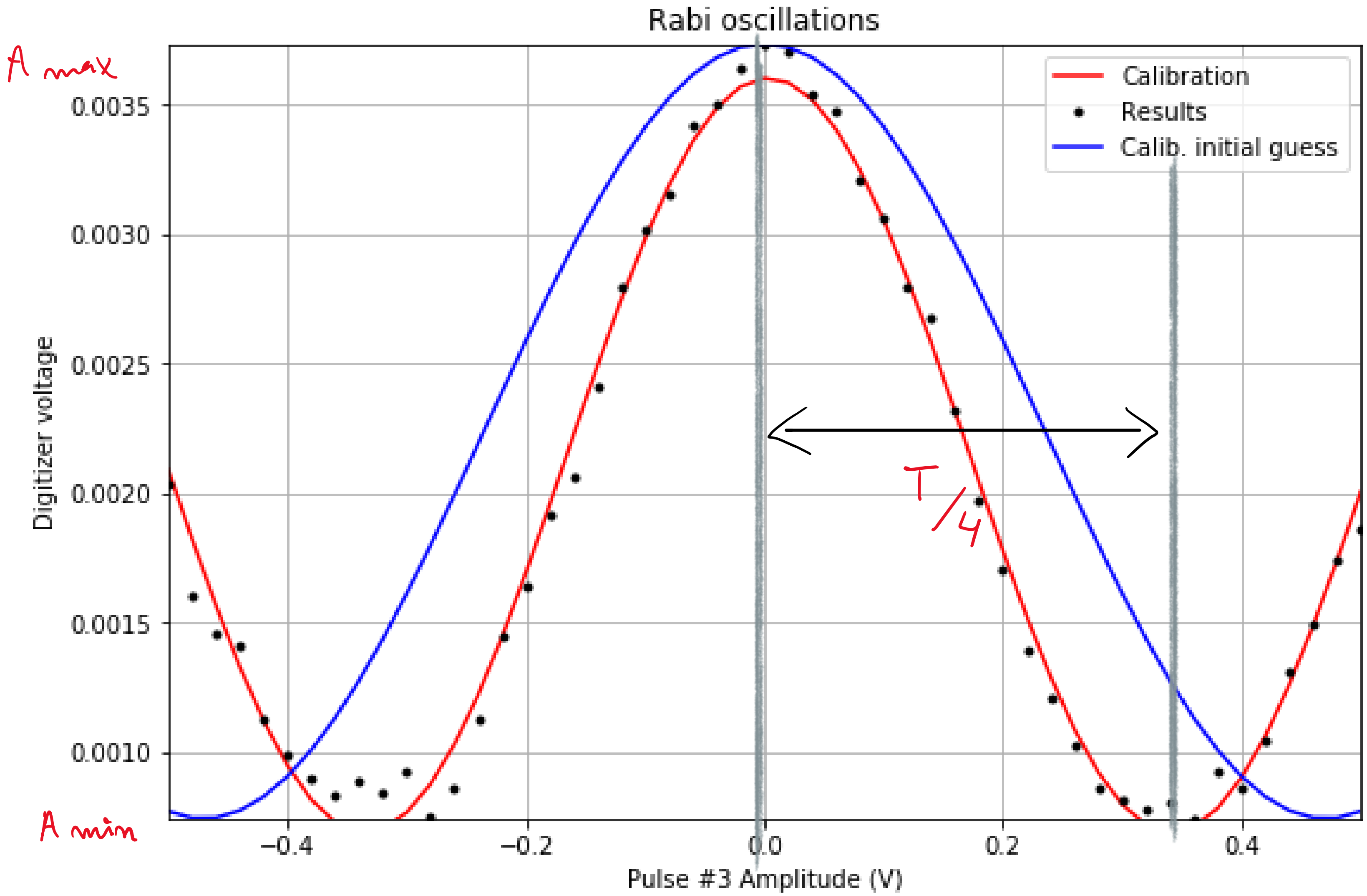
cal._Amin = 0.0007 V

Pi Pulse calibration

$A\cos^2(2\pi x/T + \phi) + c$

cal.getPiPulse()





cal._PiPulse = 0.338 V

cal._Amax = 0.0036 V

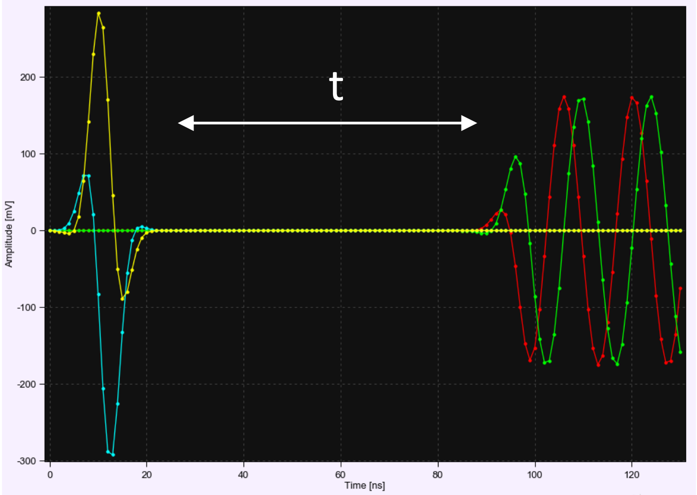
cal._Amin = 0.0007 V

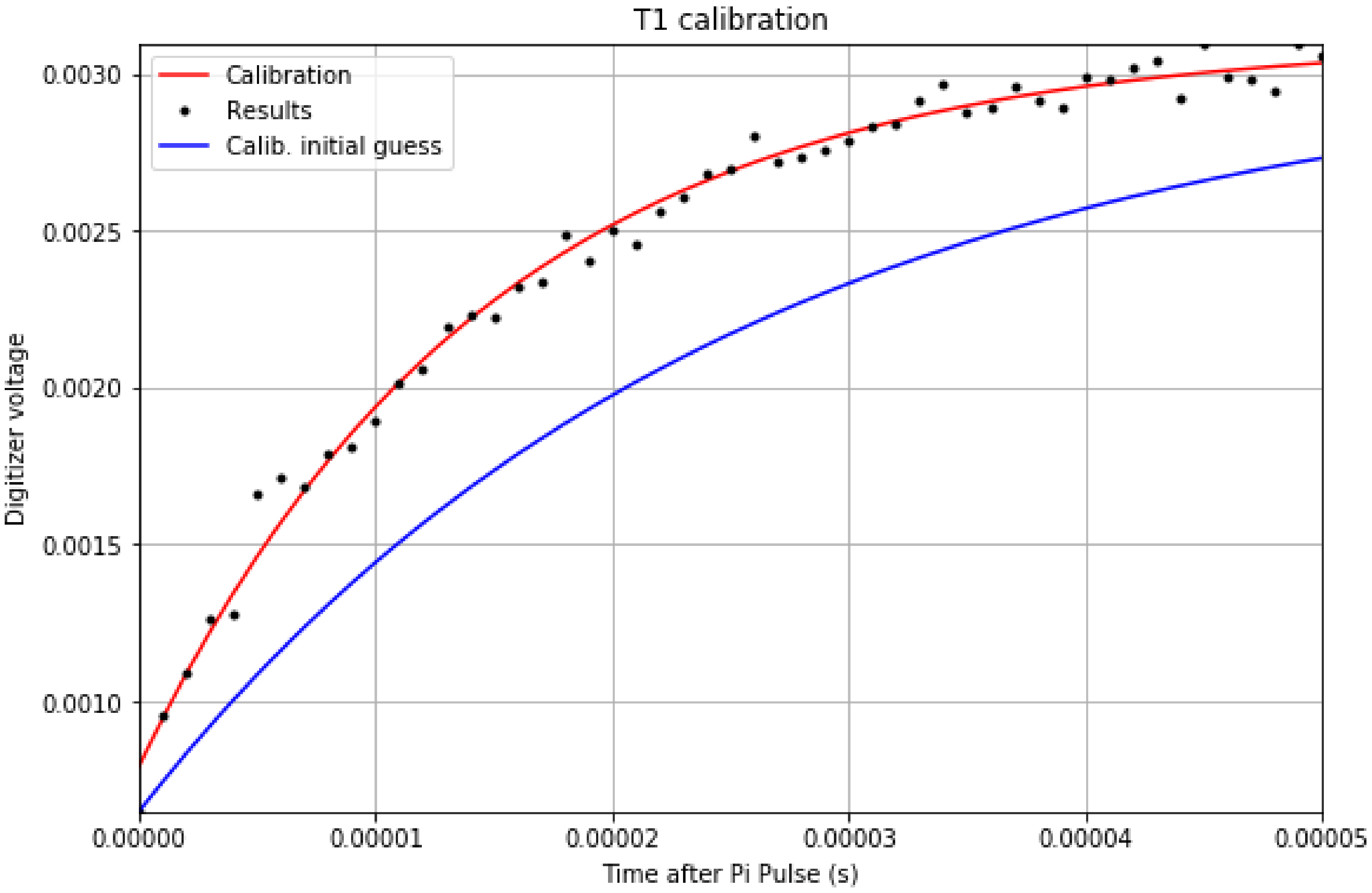
T1 calibration

$$A + Be^{-t/T_1}$$

cal.getT1()

$X\pi$ - pulse





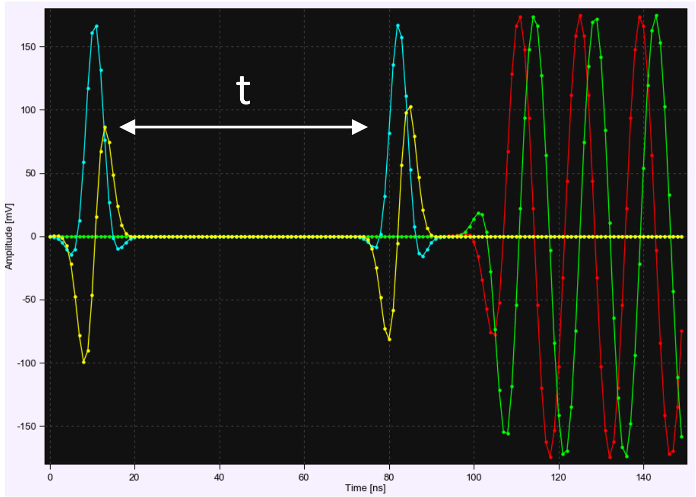
cal._T1 = 14.67 us

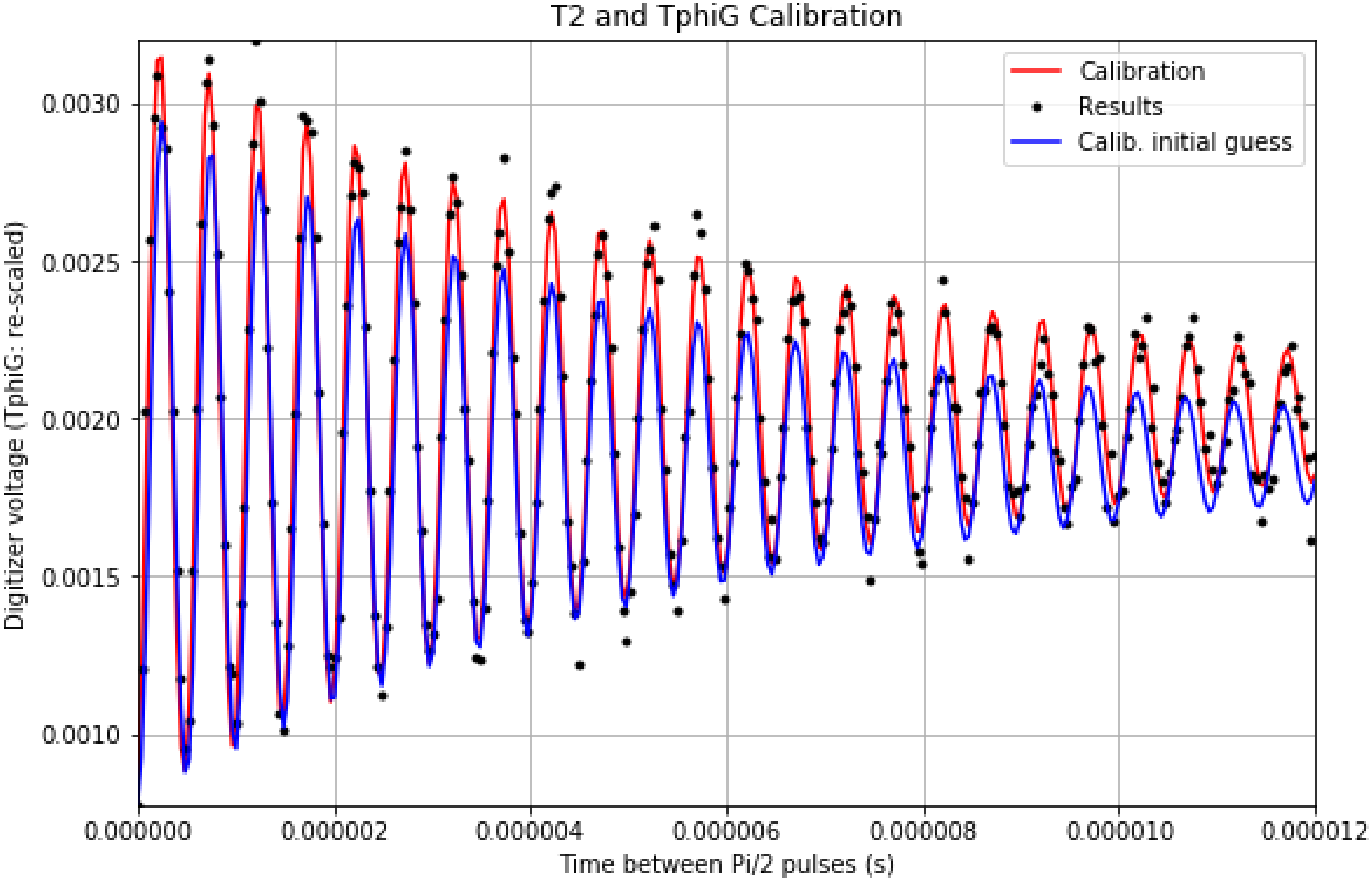
T_2 calibration (Ramsey)

$$\boxed{A + Be^{-t/T_2}\cos\left(\frac{2\pi t}{T} + \phi\right)}$$

cal.getT2Ramsey()

$X\frac{\pi}{2}$ - pulse $X\frac{\pi}{2}$ - pulse





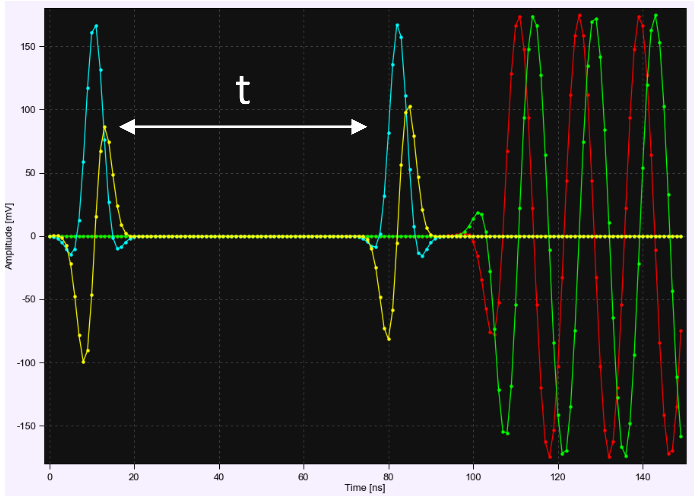
cal._T2Ramsey = 6.77 us

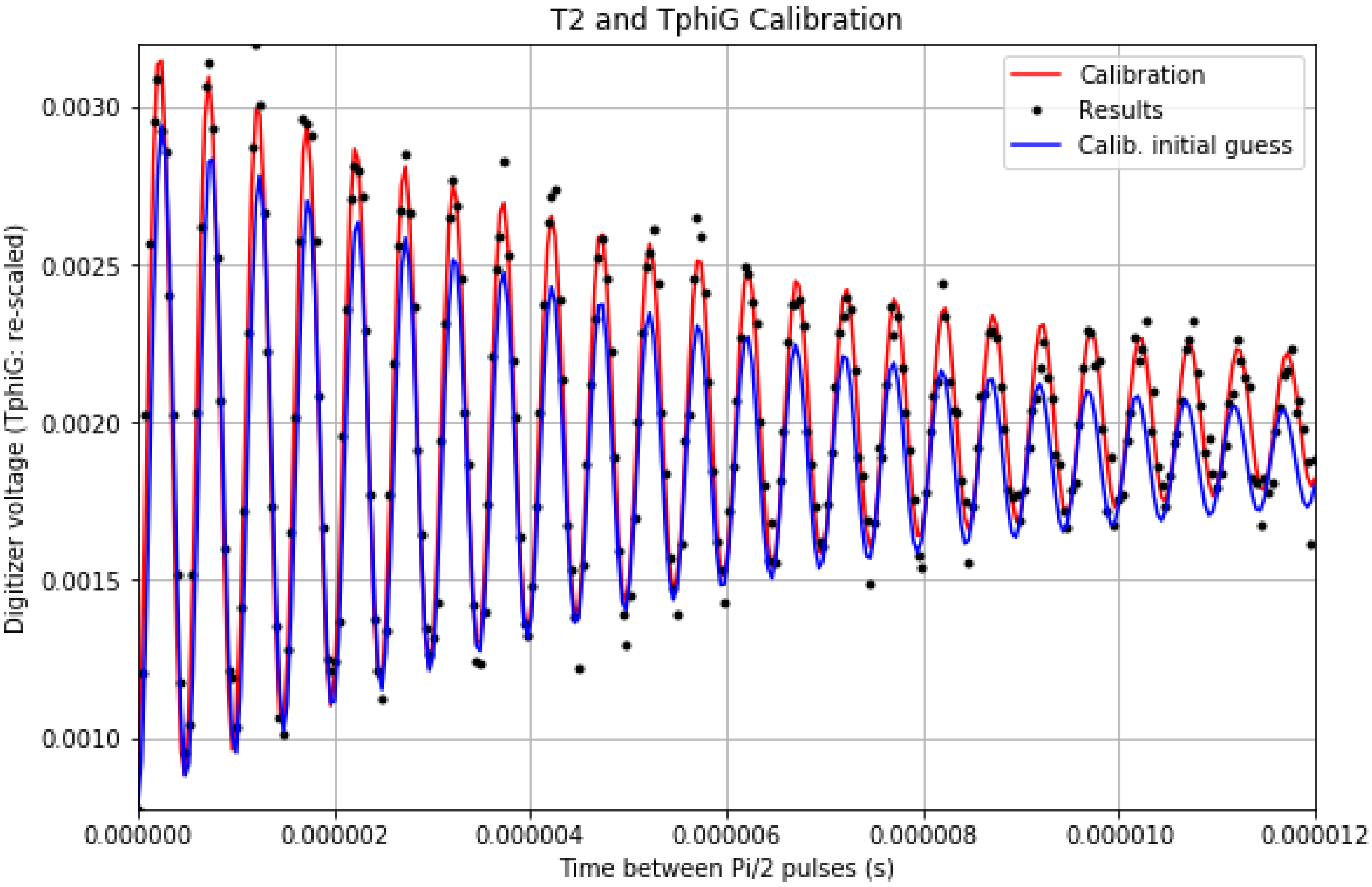
$T_{\varphi,G}$ calibration (Ramsey)

$$A + Be^{-t^2/T_{\varphi,G}^2} e^{-t/2T_1} \cos\left(\frac{2\pi t}{T} + \phi\right)$$

```
cal.getT2Ramsey(
TphiG = True)
```

$X\frac{\pi}{2}$ - pulse $X\frac{\pi}{2}$ - pulse



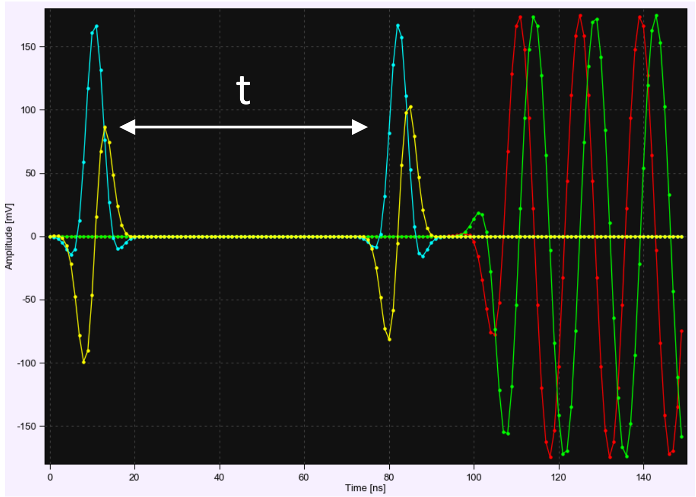


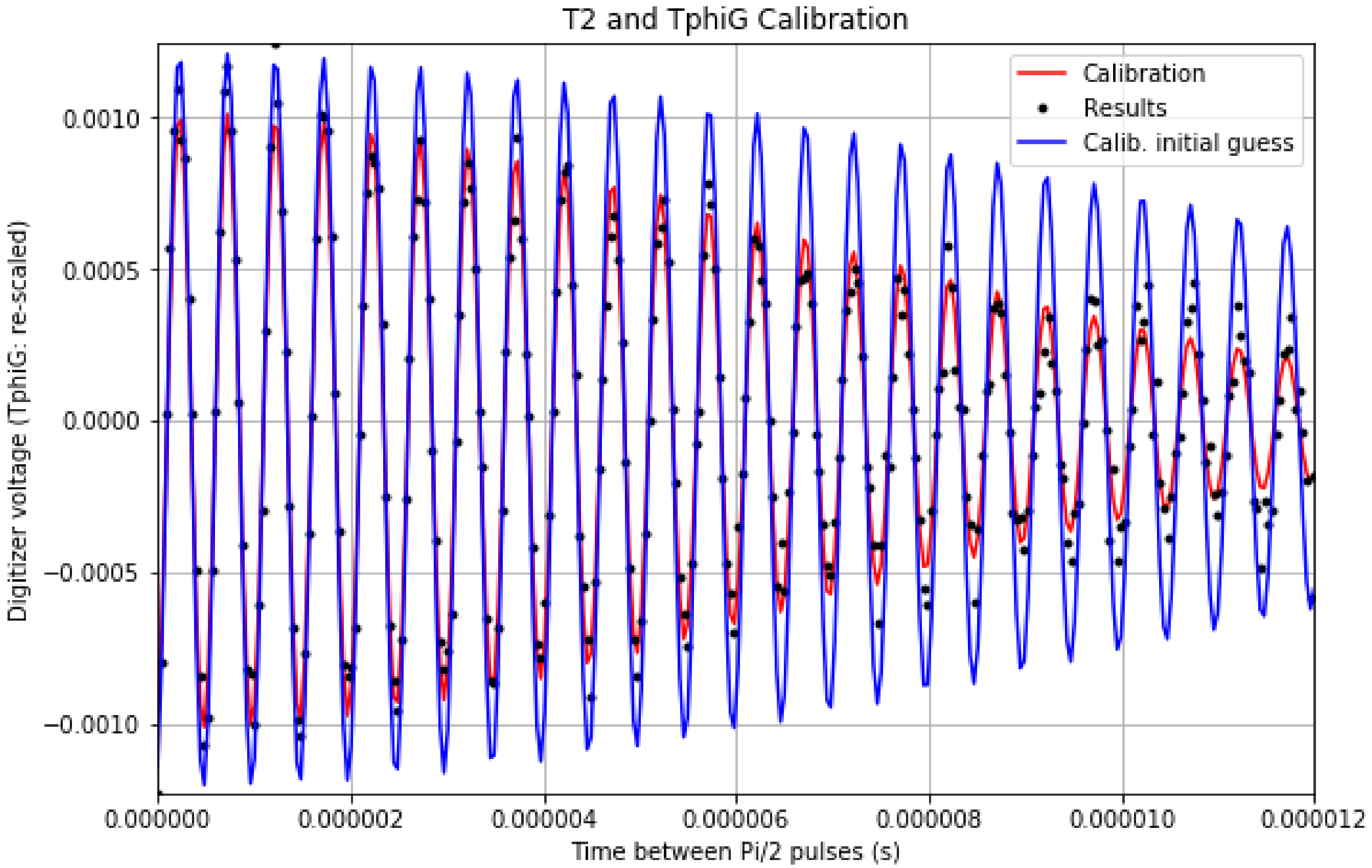
$T_{\varphi,G}$ calibration (Ramsey)

$$A + Be^{-t^2/T_{\varphi,G}^2}\cos\left(\frac{2\pi t}{T}+\phi\right)$$

cal.getT2Ramsey(
TphiG = True)

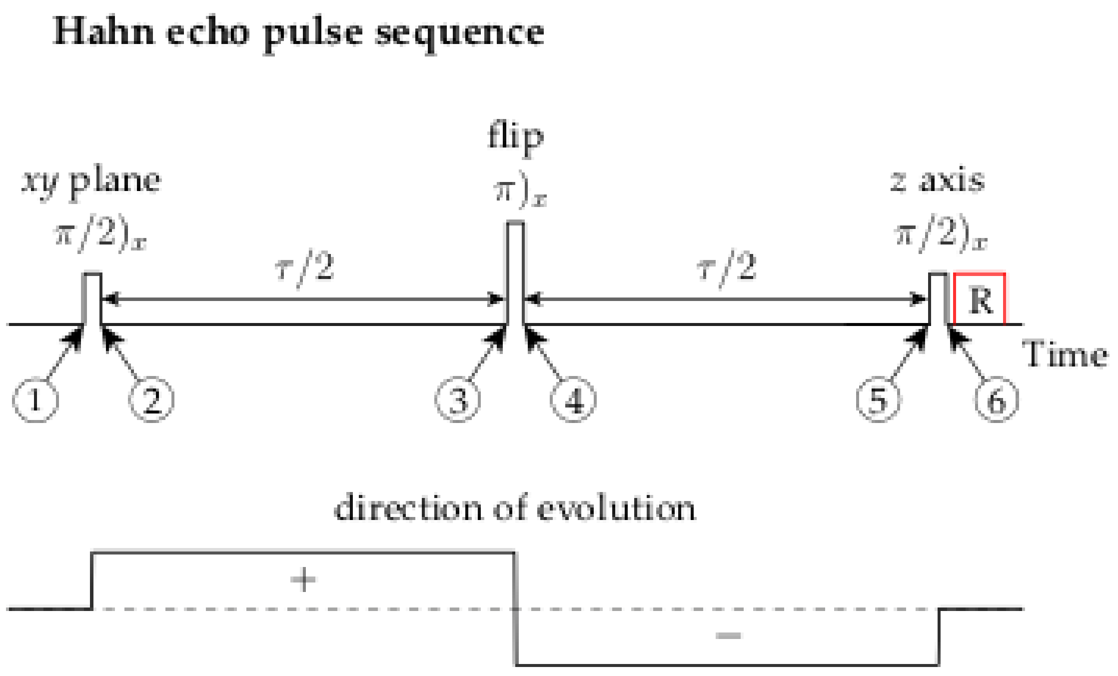
$X\frac{\pi}{2}$ - pulse $X\frac{\pi}{2}$ - pulse

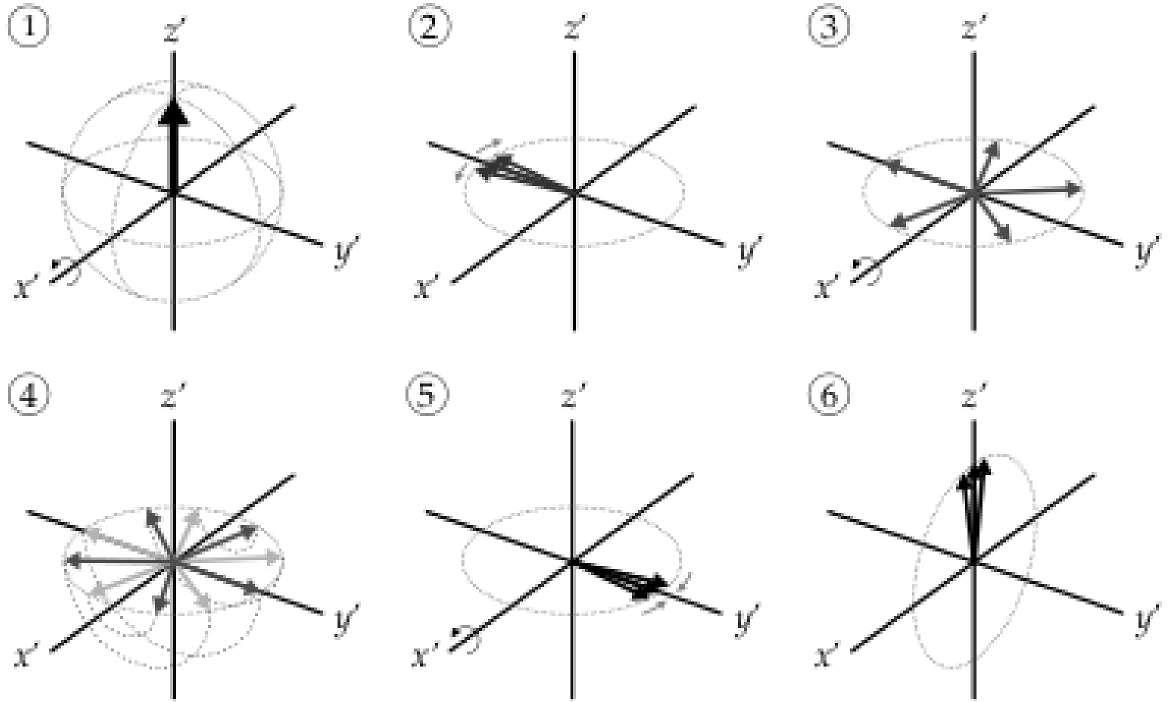




cal._TphiG = 9.35 us

T_2 calibration (Hahn Echo)





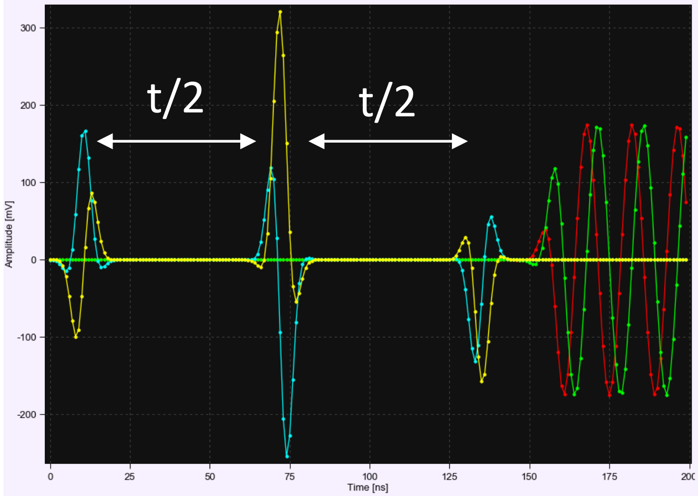
Ref. [6]

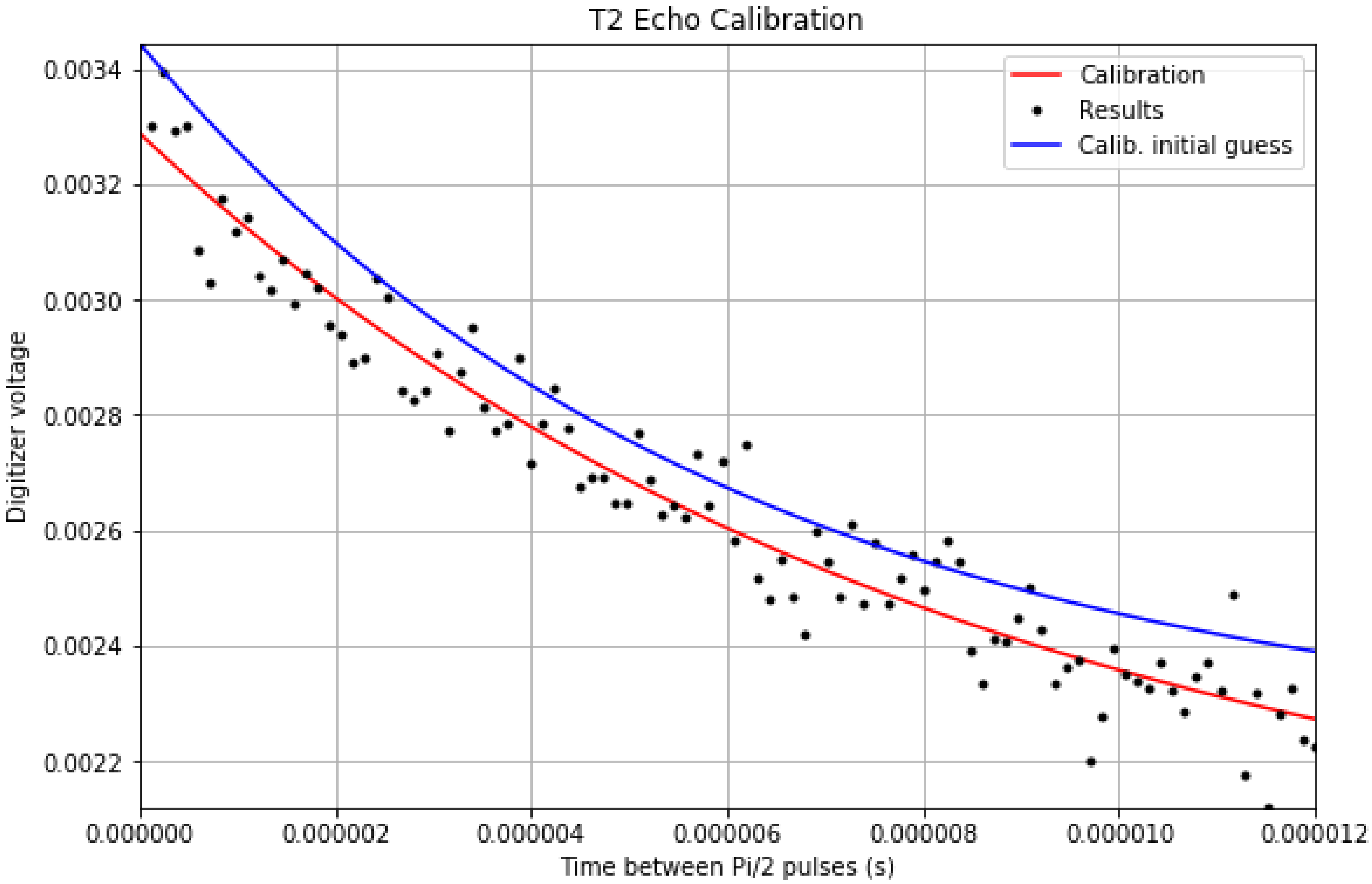
T_2 calibration (Hahn Echo)

$$A + Be^{-t/T_2}$$

cal.getT2Echo()

$X\frac{\pi}{2}$ - pulse $X\pi$ - pulse $X\frac{\pi}{2}$ - pulse





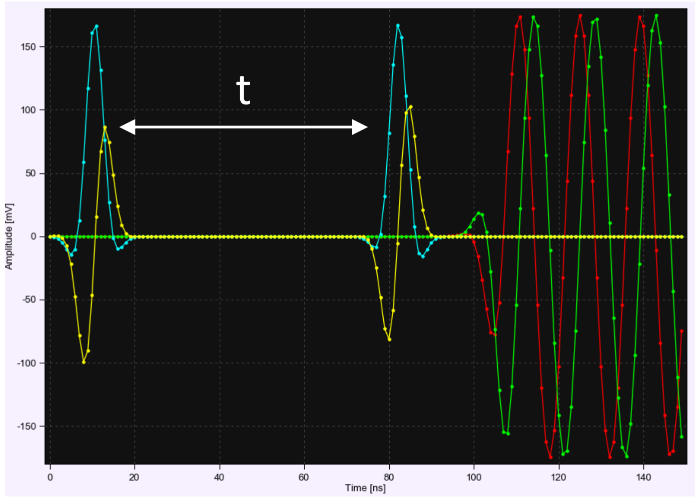
cal._T2Echo = 8.24 us

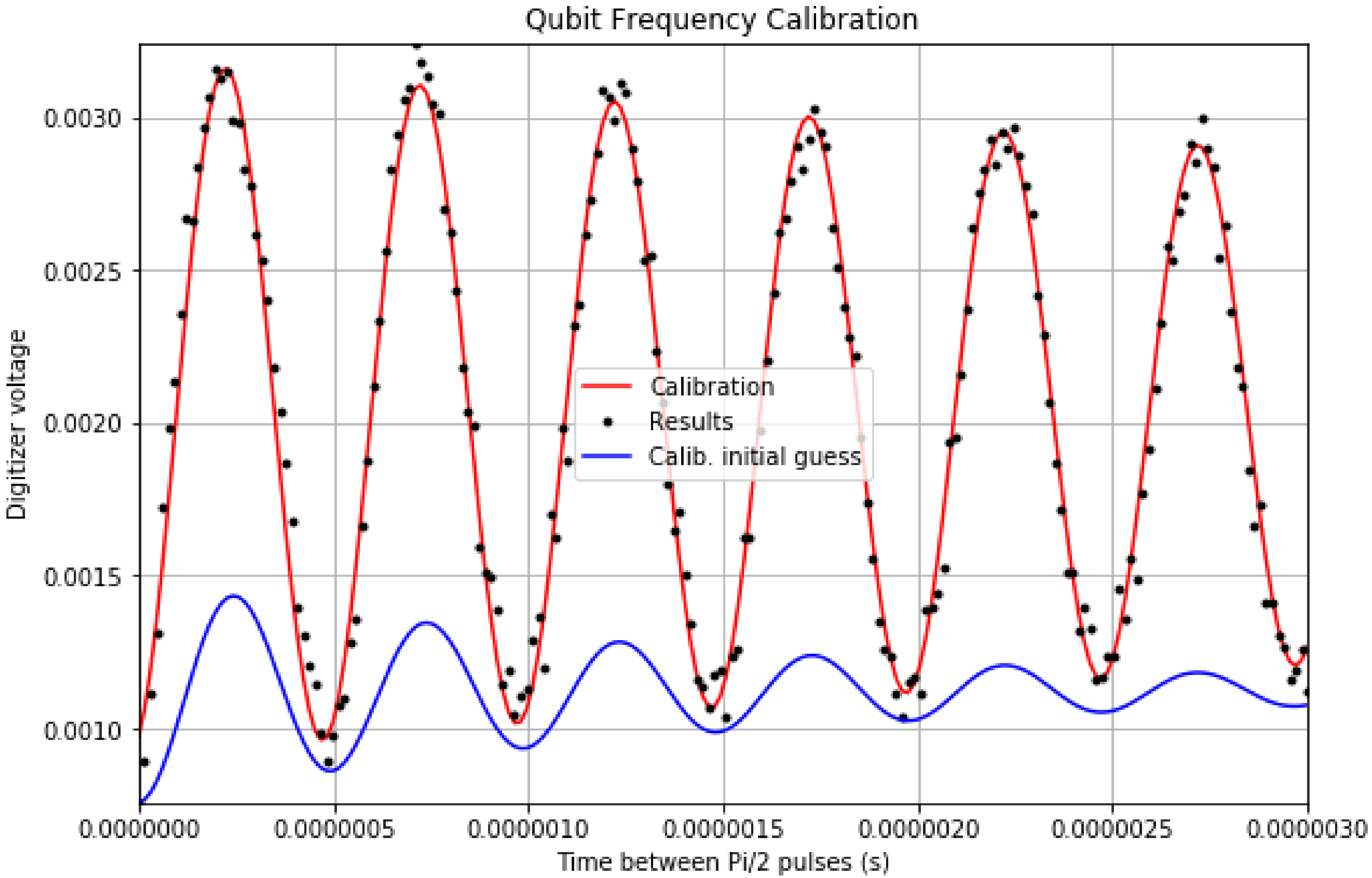
Qubit Frequency calibration

$$A + Be^{-t/T_2}\cos\left(\frac{2\pi t}{T} + \phi\right)$$

cal.getQubitFreq()

$X\frac{\pi}{2}$ - pulse $\qquad$ $X\frac{\pi}{2}$ - pulse





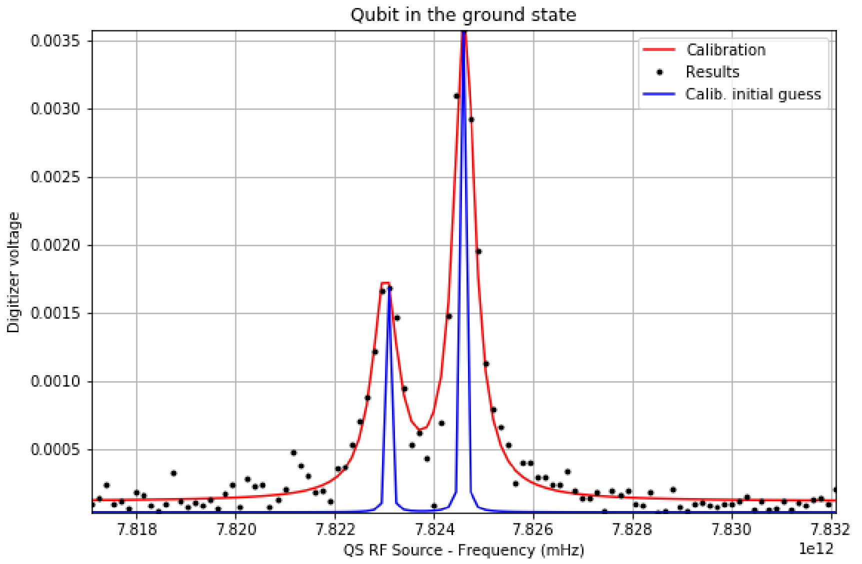
$$\frac{1}{T} = f_d - f_q$$

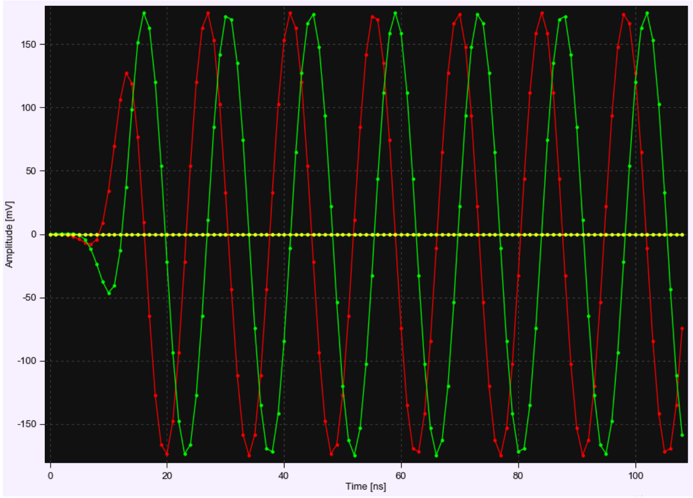
cal._QubitFreq = 4.8250361 GHz

Cavity Frequencies calibration

$$\frac{A_0}{(x-f_0)^2-\left(\kappa_0/_2\right)^2}+\frac{A_1}{(x-f_1)^2-\left(\kappa_1/_2\right)^2}+\mathrm{c}$$

cal.getResonatorFreq()

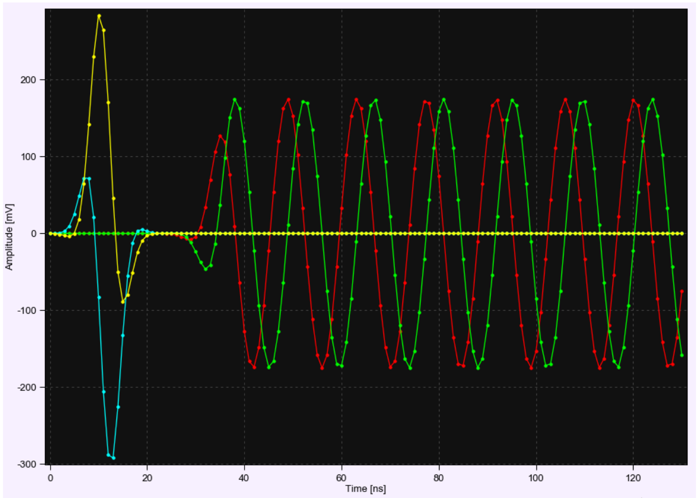


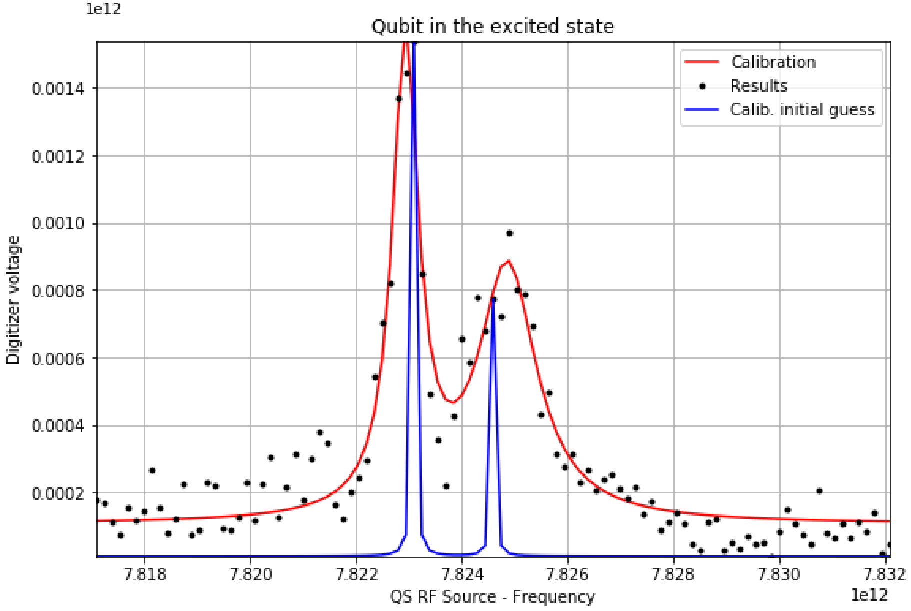


cal._ResonatorFreq0 = 7.75462 GHz

cal._ResonatorFreq1 = 7.75294 GHz

$X\pi$ - pulse





https://github.com/UB-Quantic/Qubit-Calibration

Qubit Calibration

Raquel García Bellés

IFAE Summer Fellowship @ Quantum Computing Technology Group

July – August 2020

Institut de Física d'Altes Energies
EXCELENCIA SEVERO OCHOA
BIST Barcelona Institute of Science and Technology

Outline

- Theoretical Background
- Technical Aspects
- Calibration Results
- DRAG scaling constant
- Reset Pulse

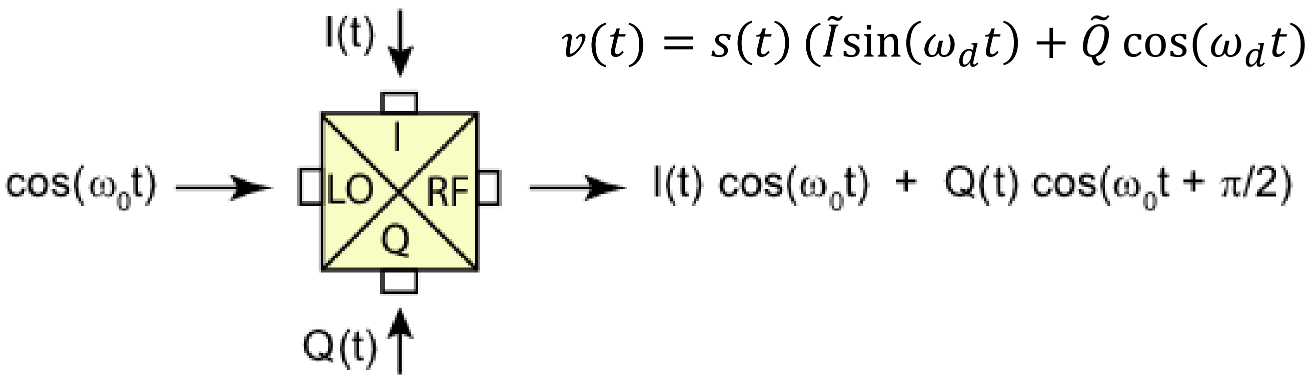
DRAG scaling constant

[1] - P. Krantz, M. Kjaergaard, F. Yan, T. P. Orlando, S. Gustavsson, and W. D. Oliver, A quantum engineer's guide to superconducting qubits, Appl. Phys. Rev. 6, 021318 (2019).
[5] - Matthias Baur. "Realizing quantum gates and algorithms with three superconducting qubits". PhD thesis. ETH Zurich, Mar. 2012.

Derivative Reduction by Adiabatic Gate (DRAG)

- **Leakage errors**: Excitations outside of the computational subspace

$$v(t) = s(t)\,(\tilde{I}\sin(\omega_d t) + \tilde{Q}\cos(\omega_d t))$$



- **Phase errors**: Accumulation of a phase

$$\boxed{s(t) \to s'(t) = \begin{cases} s(t) & \text{on} \quad \tilde{I} \\ \beta s'(t) & \text{on} \quad \tilde{Q} \end{cases}}$$

Labber generates: Mixer:

$$I(t) = s(t)\tilde{I}\cos(\omega_{SSB}t - \phi) - \beta s'(t)\tilde{Q}\cos\left(\omega_{SSB}t - \phi + {}^{\pi}/_{2}\right) \quad \times \cos(\omega_{LO}t)$$

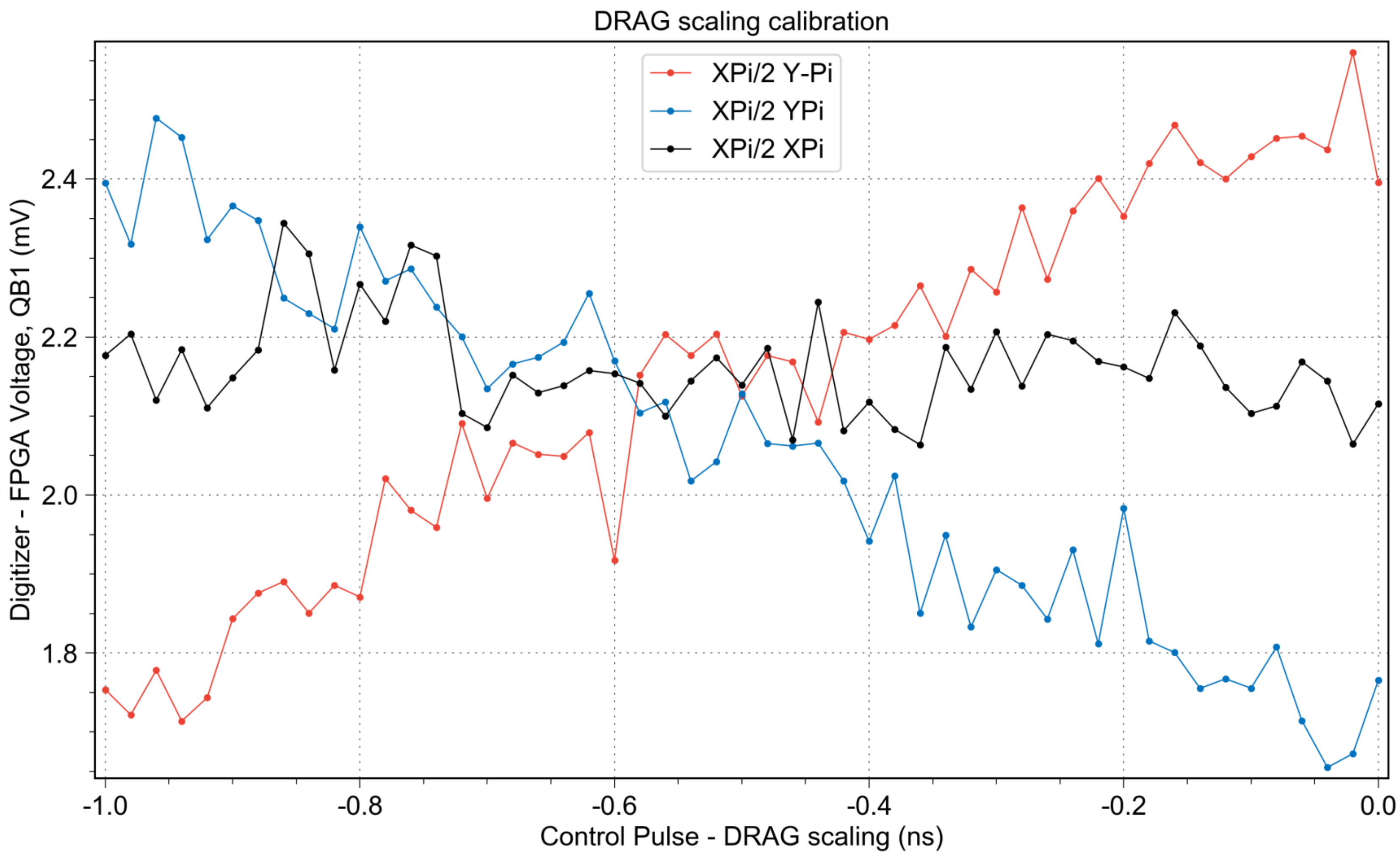
$$+$$

$$Q(t) = -s(t)\tilde{I}\sin(\omega_{SSB}t - \phi) + \beta s'(t)\tilde{Q}\sin(\omega_{SSB}t - \phi + {}^{\pi}/_{2}) \quad \times \cos\left(\omega_{LO}t + {}^{\pi}/_{2}\right)$$

$$s(t)\tilde{I}\cos\left((\omega_{LO} - \omega_{SSB})t + \phi\right) - \beta s'(t)\tilde{Q}\sin\left((\omega_{LO} - \omega_{SSB})t + \phi\right)$$

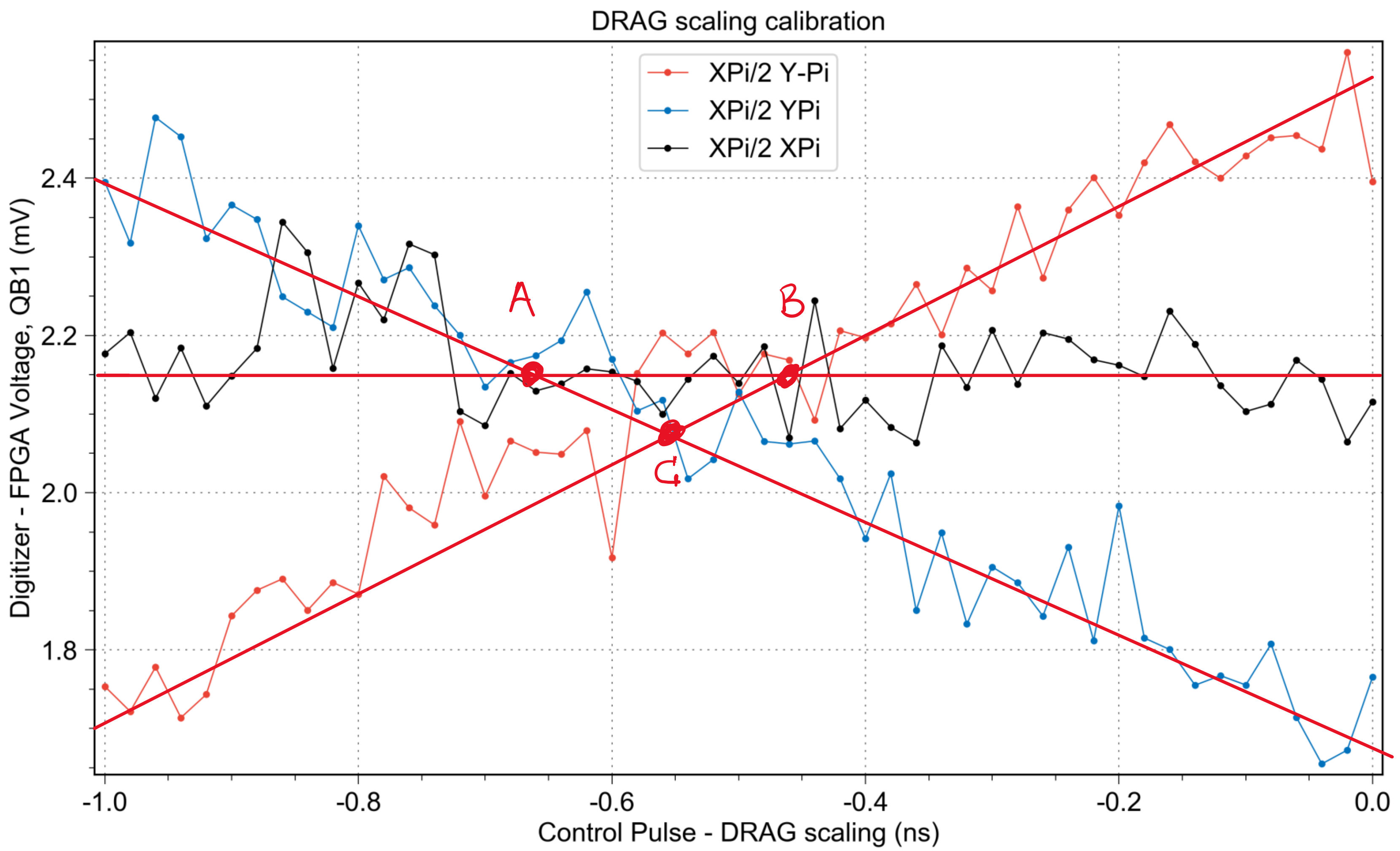
DRAG scaling constant

cal.getDRAG()



DRAG scaling constant

cal.getDRAG()

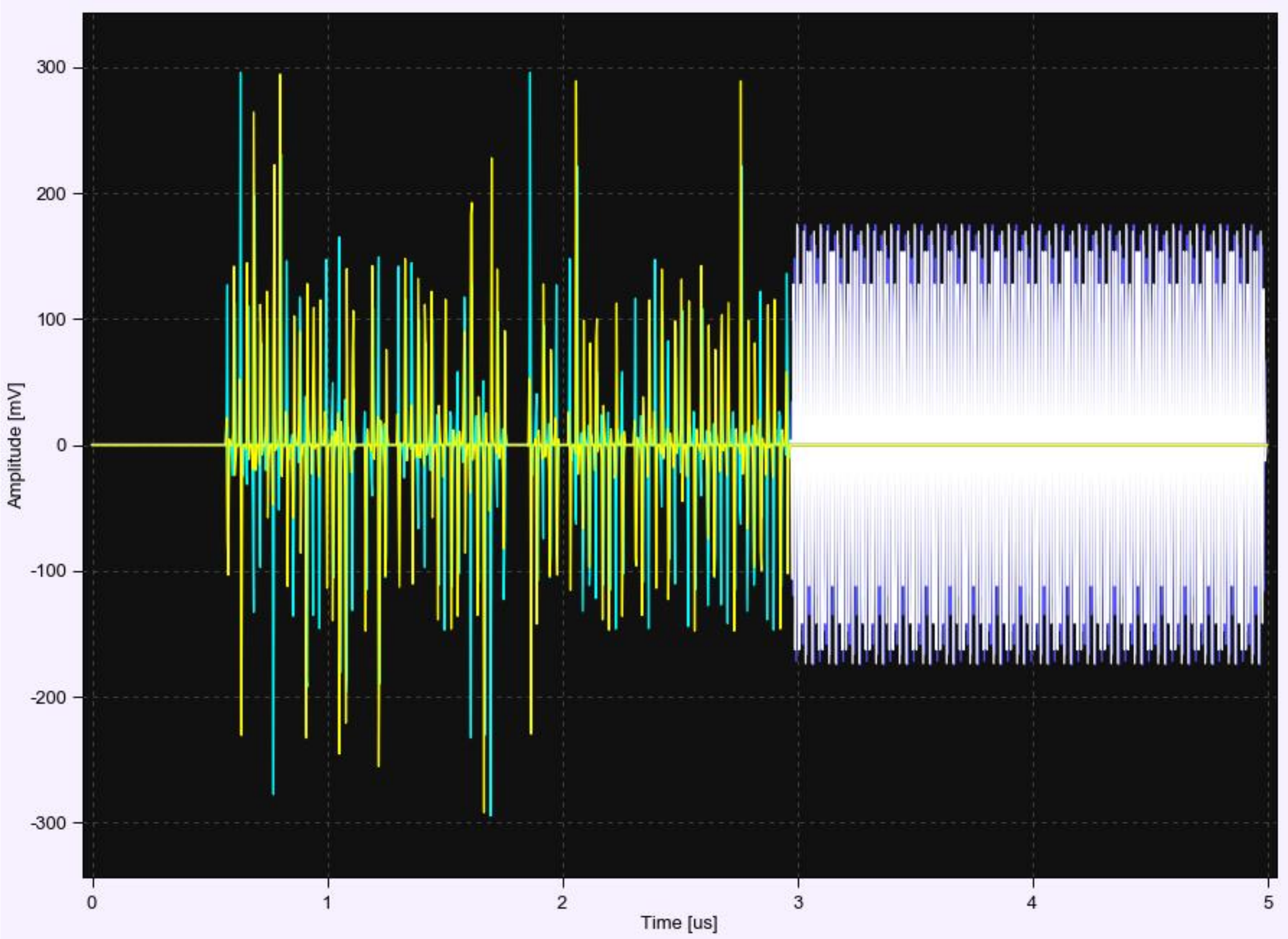


cal._DRAG = -598E-12 s

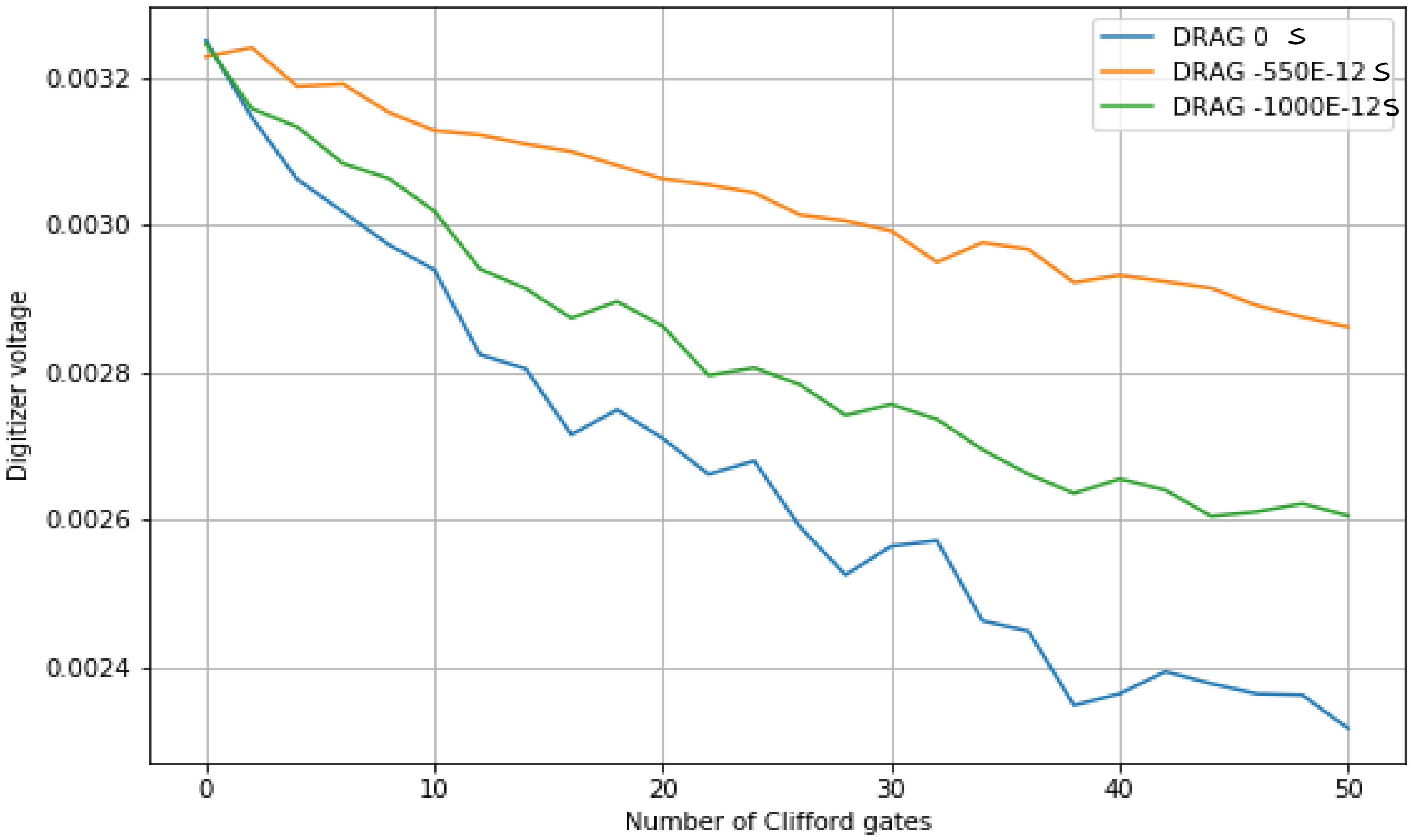
Randomized Benchmarking

- Apply N Clifford gates

- Last gate: Reverses all the other

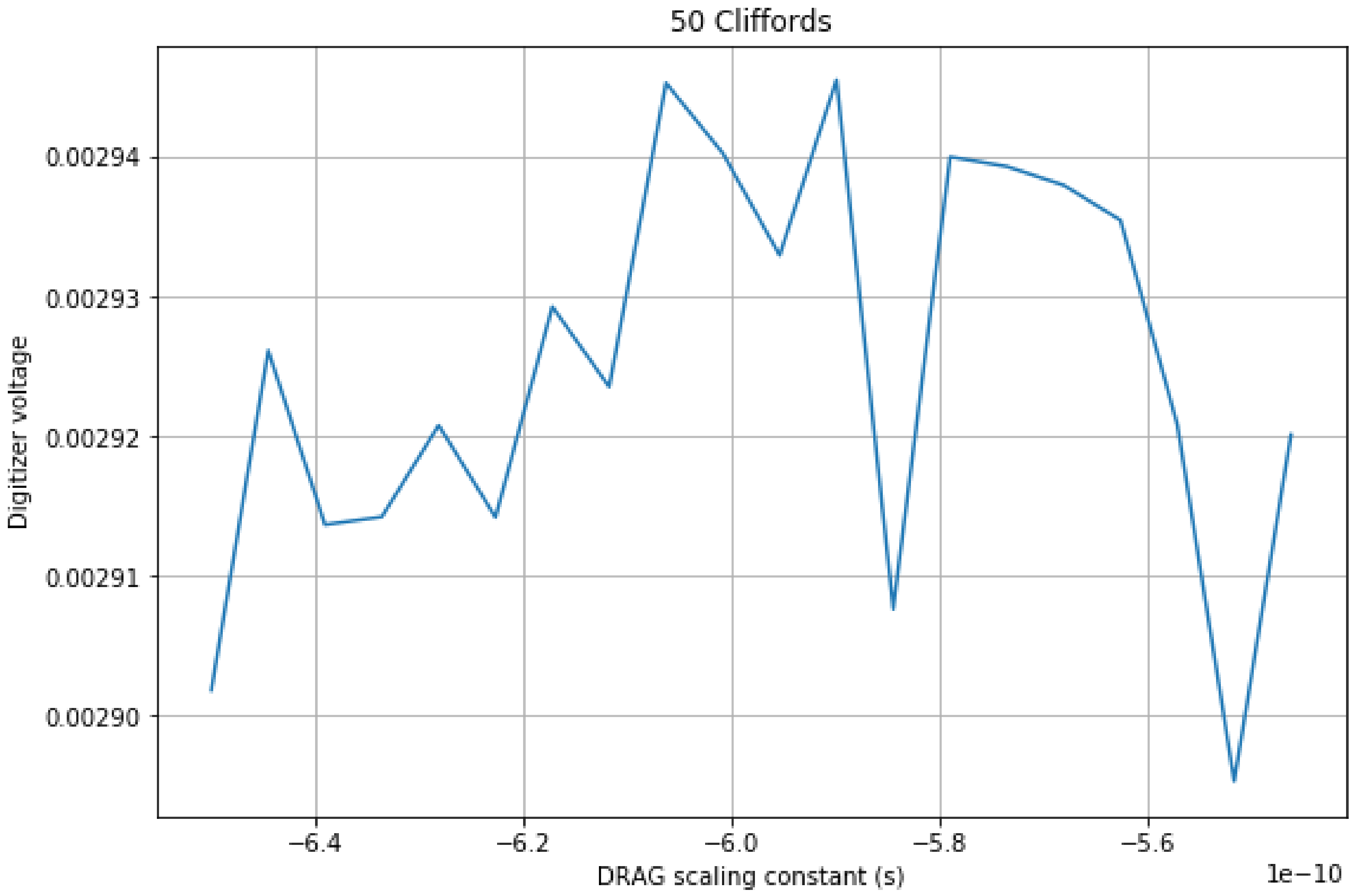


Randomized Benchmarking



Randomized Benchmarking

cal.getDRAG()

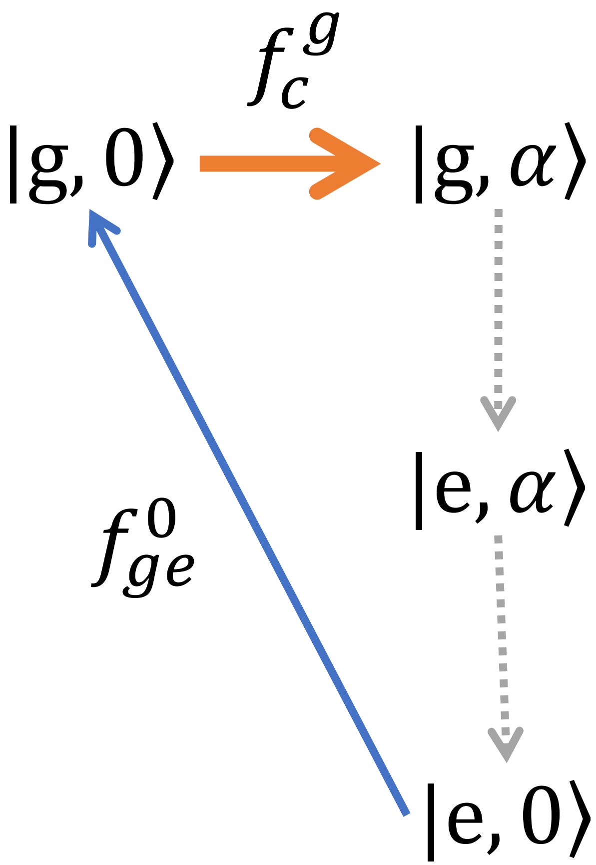


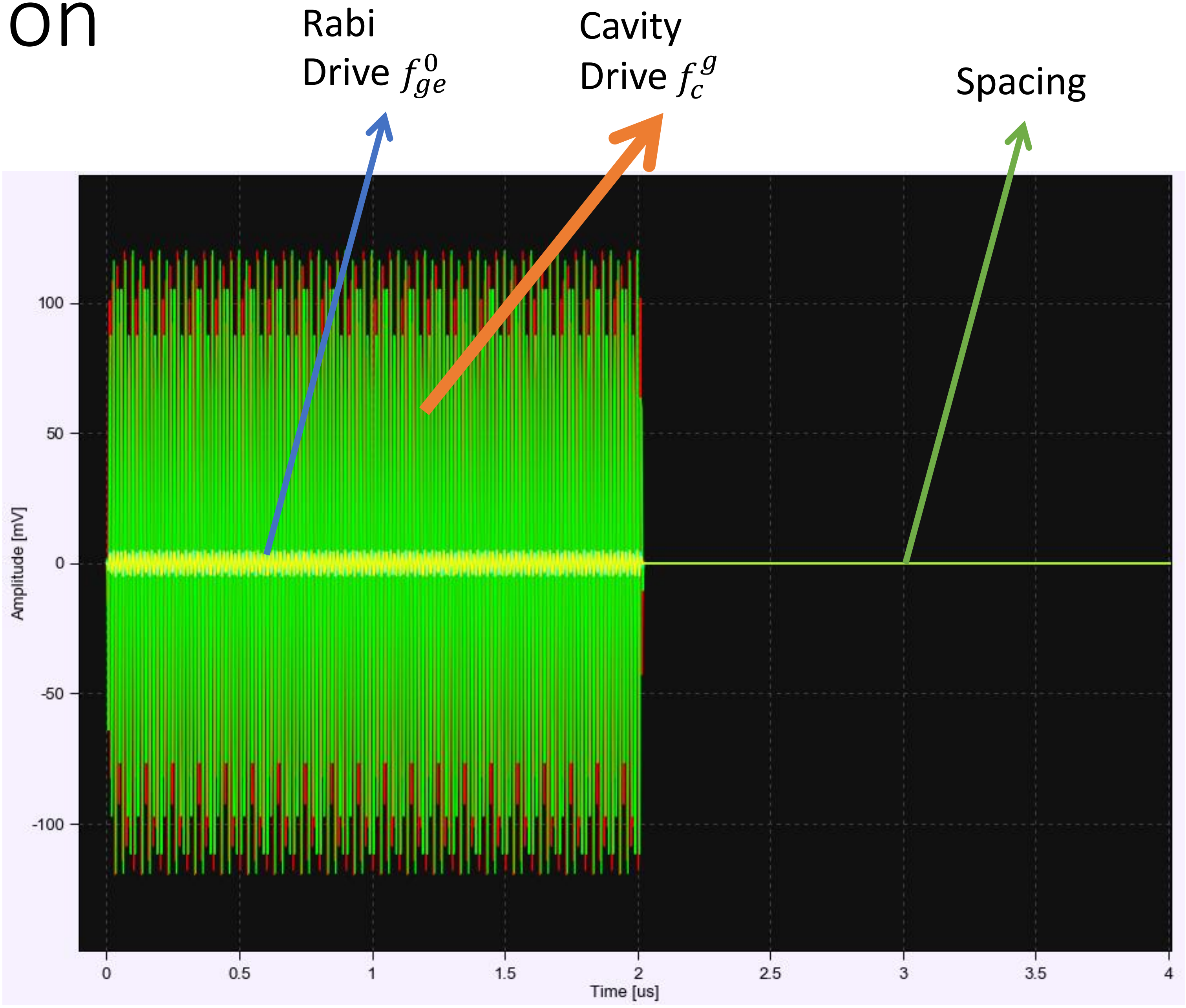
cal._DRAG = -590E-12 s

RESET calibration

[3] - Geerlings, K., Leghtas, Z., Pop, I. M., Shankar, S., Frunzio, L., Schoelkopf, R. J., ... & Devoret, M. H. (2013). Demonstrating a driven reset protocol for a superconducting qubit. Physical review letters, 110(12), 120501.
[4] - McClure, D. T., Paik, H., Bishop, L. S., Steffen, M., Chow, J. M., & Gambetta, J. M. (2016). Rapid driven reset of a qubit readout resonator. Physical Review Applied, 5(1), 011001.

RESET calibration



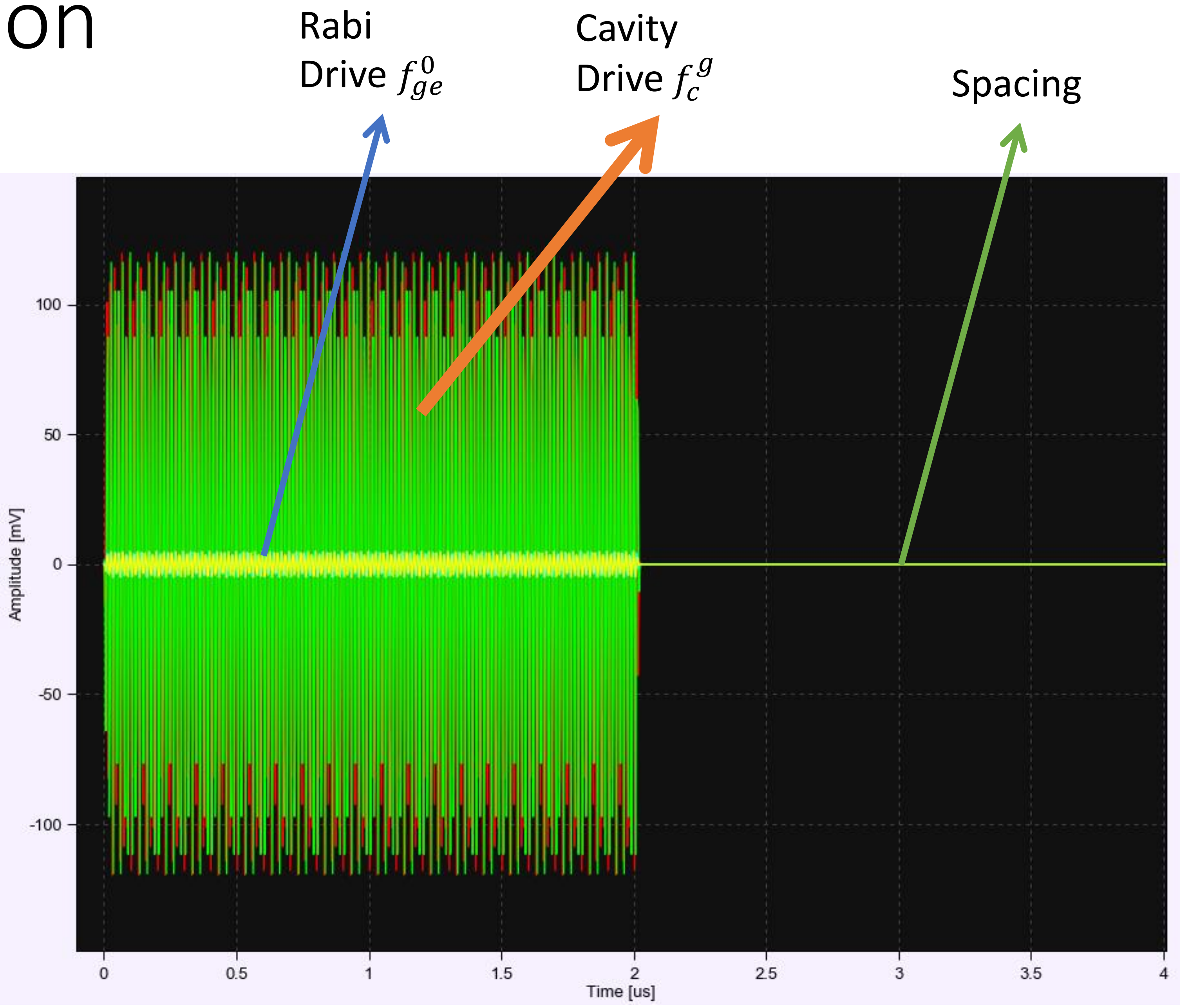


RESET calibration

$|g,0\rangle \leftarrow |g,\alpha\rangle$

$|e,\alpha\rangle$

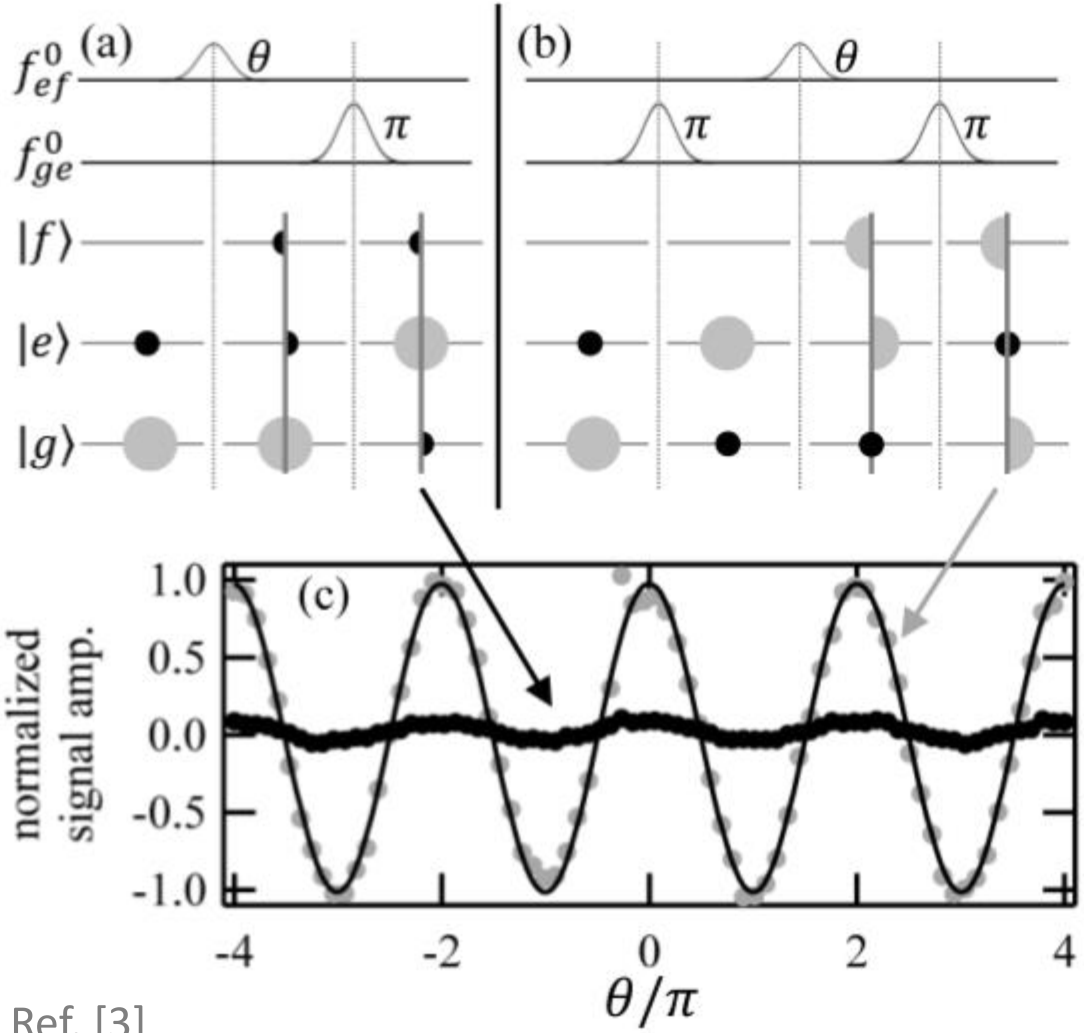
$|e,0\rangle$



RPM measurement

$|1\rangle \rightarrow |2\rangle$ transition

(a) Proportional to the **excited state** population

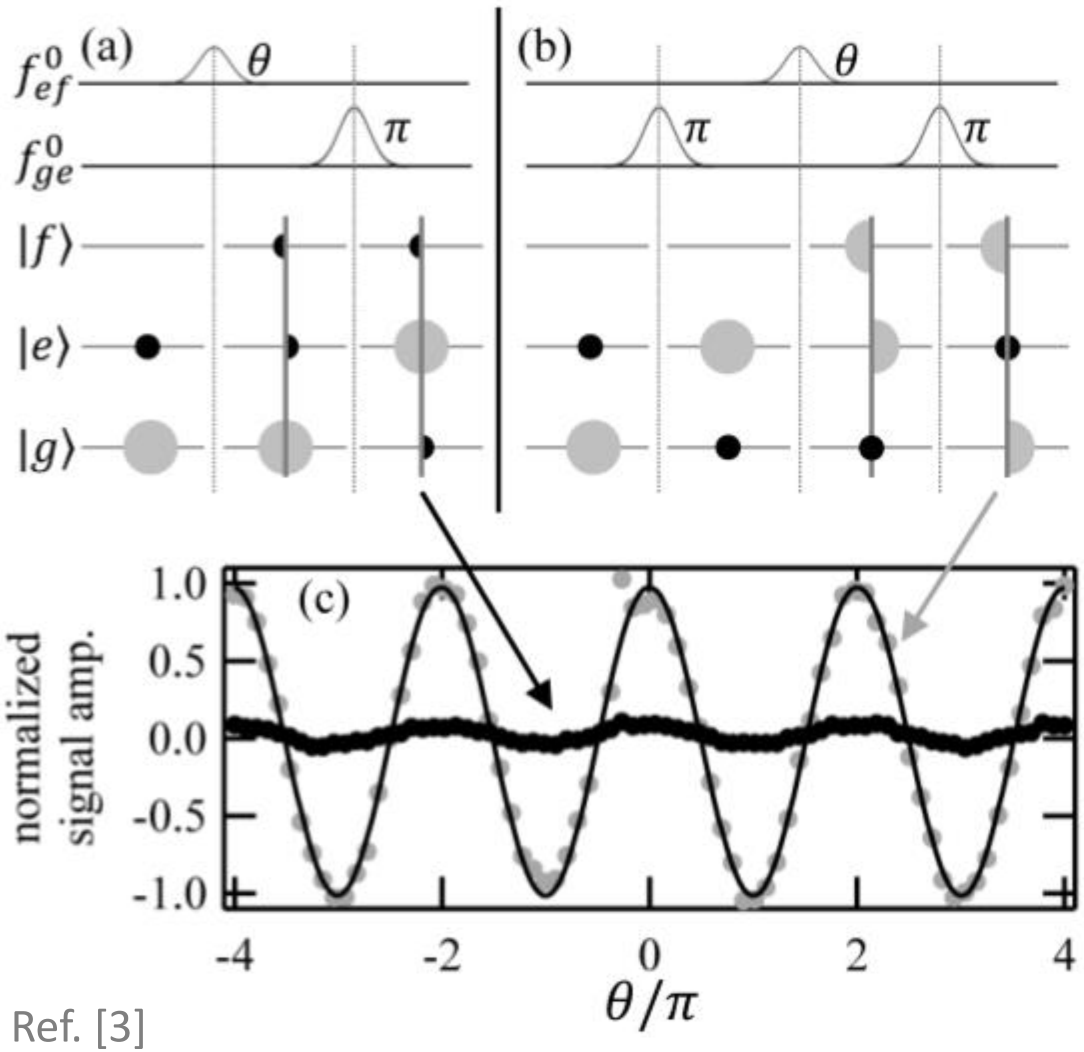


Ref. [3]

(b) Proportional to the **ground state** population

RPM measurement

$|1\rangle \rightarrow |2\rangle$ transition



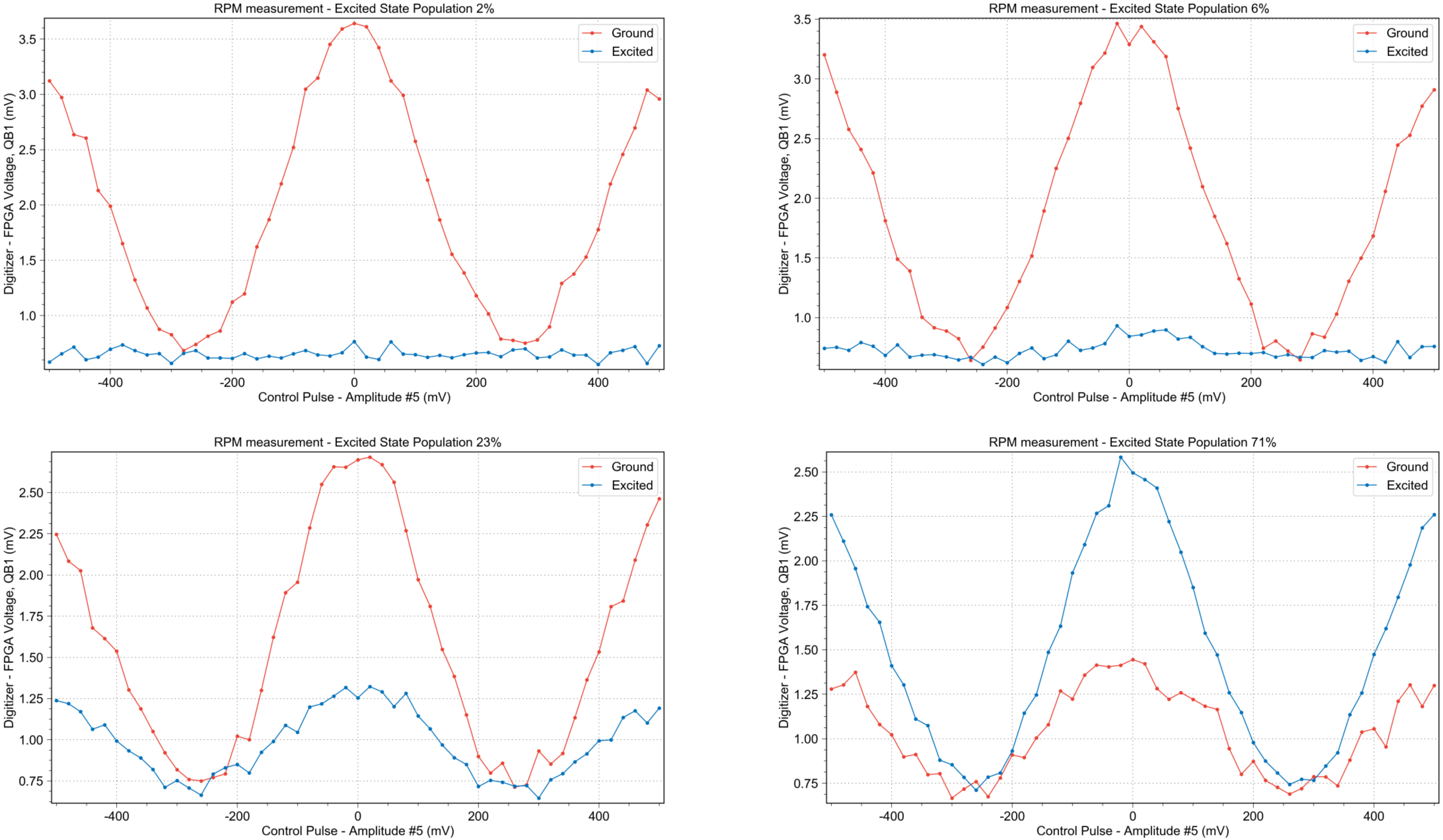
Ref. [3]

$$P_e = \frac{A_e}{A_e + A_g}$$

(a) Proportional to the **excited state** population

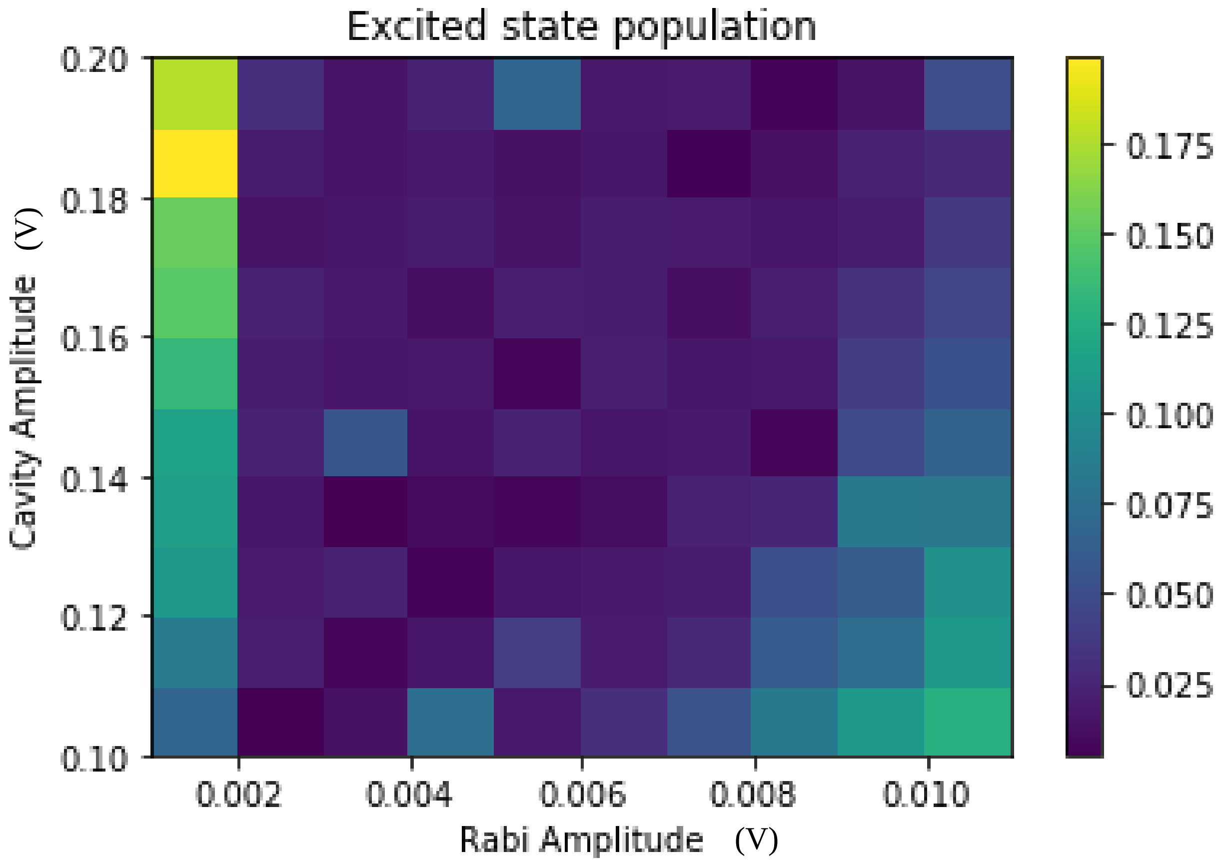
(b) Proportional to the **ground state** population

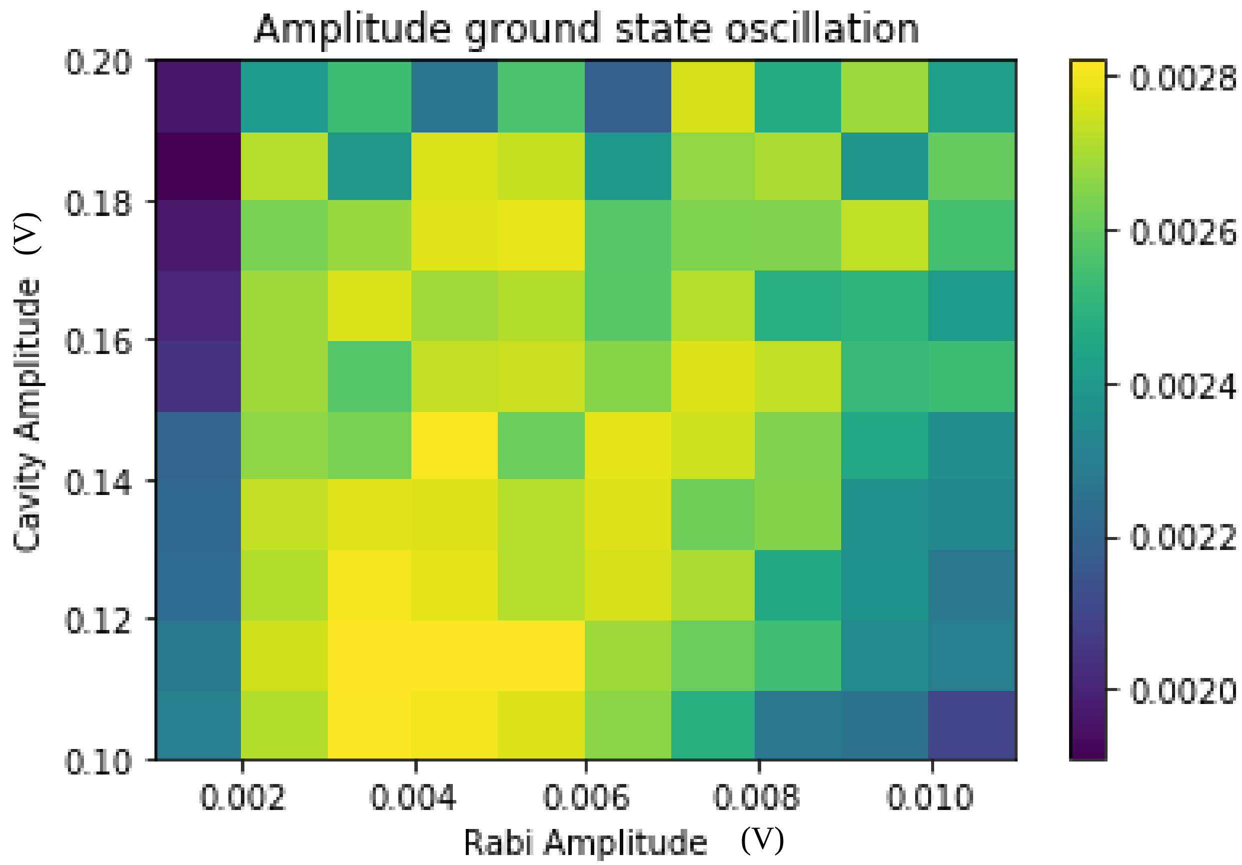
RPM measurement



Amplitudes calibration

cal.getReset(
Amplitudes = True)



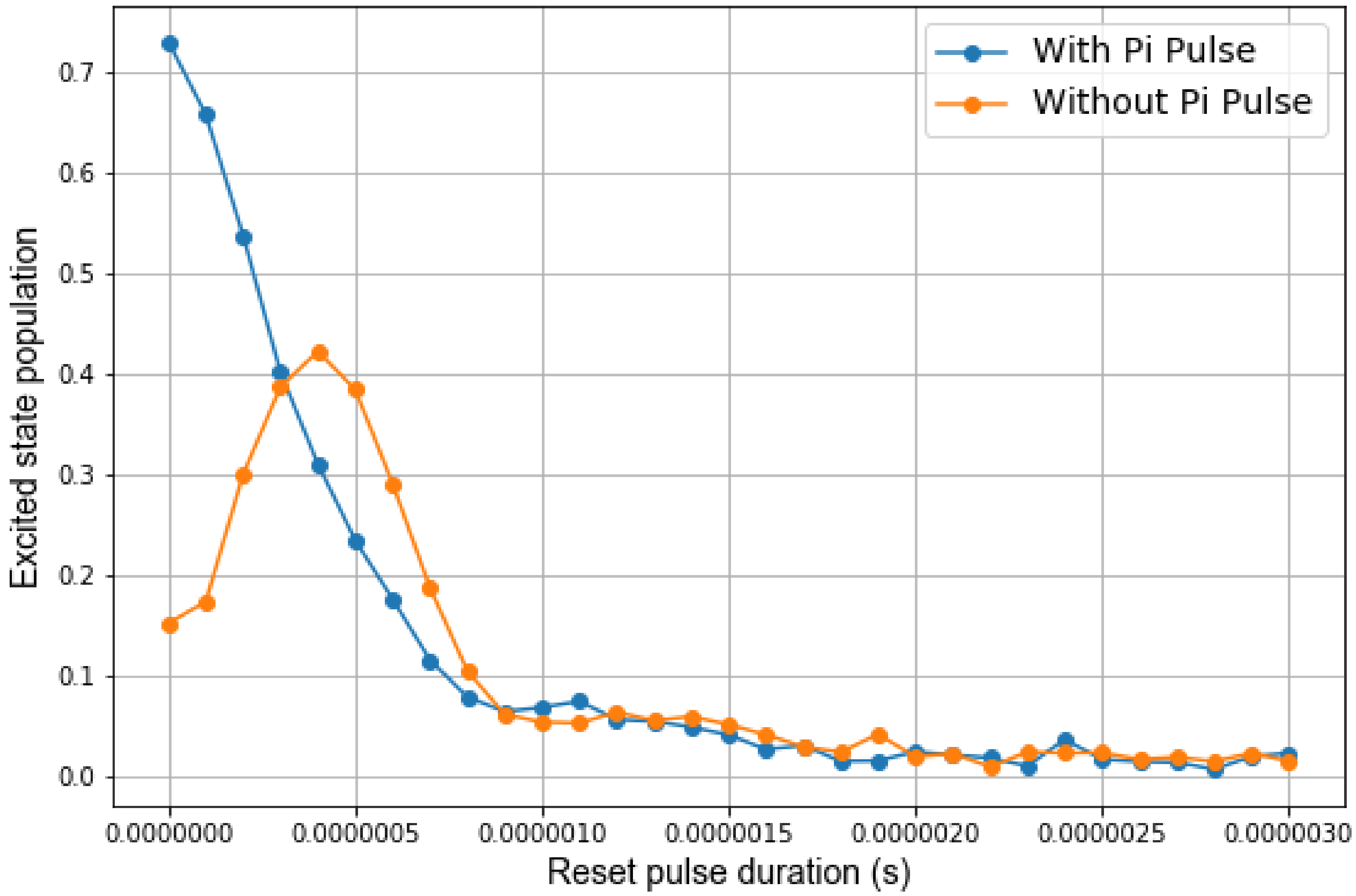


cal._ResetRabiAmplitude = 4 mV

cal._ResetCavityAmplitude = 110 mV

Duration calibration

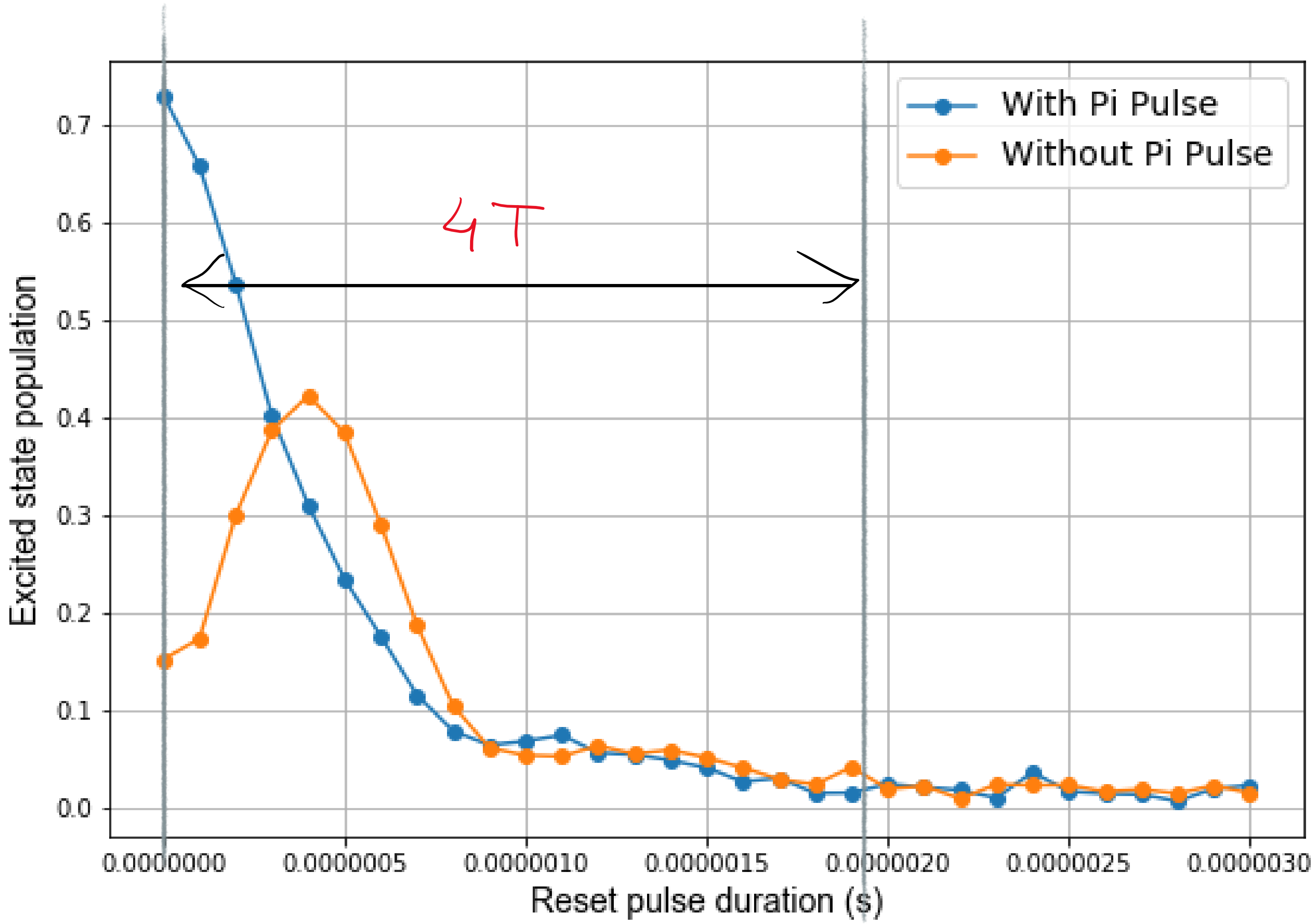
cal.getReset(
Length = True)



Duration calibration

$$A + Be^{-t/T}$$

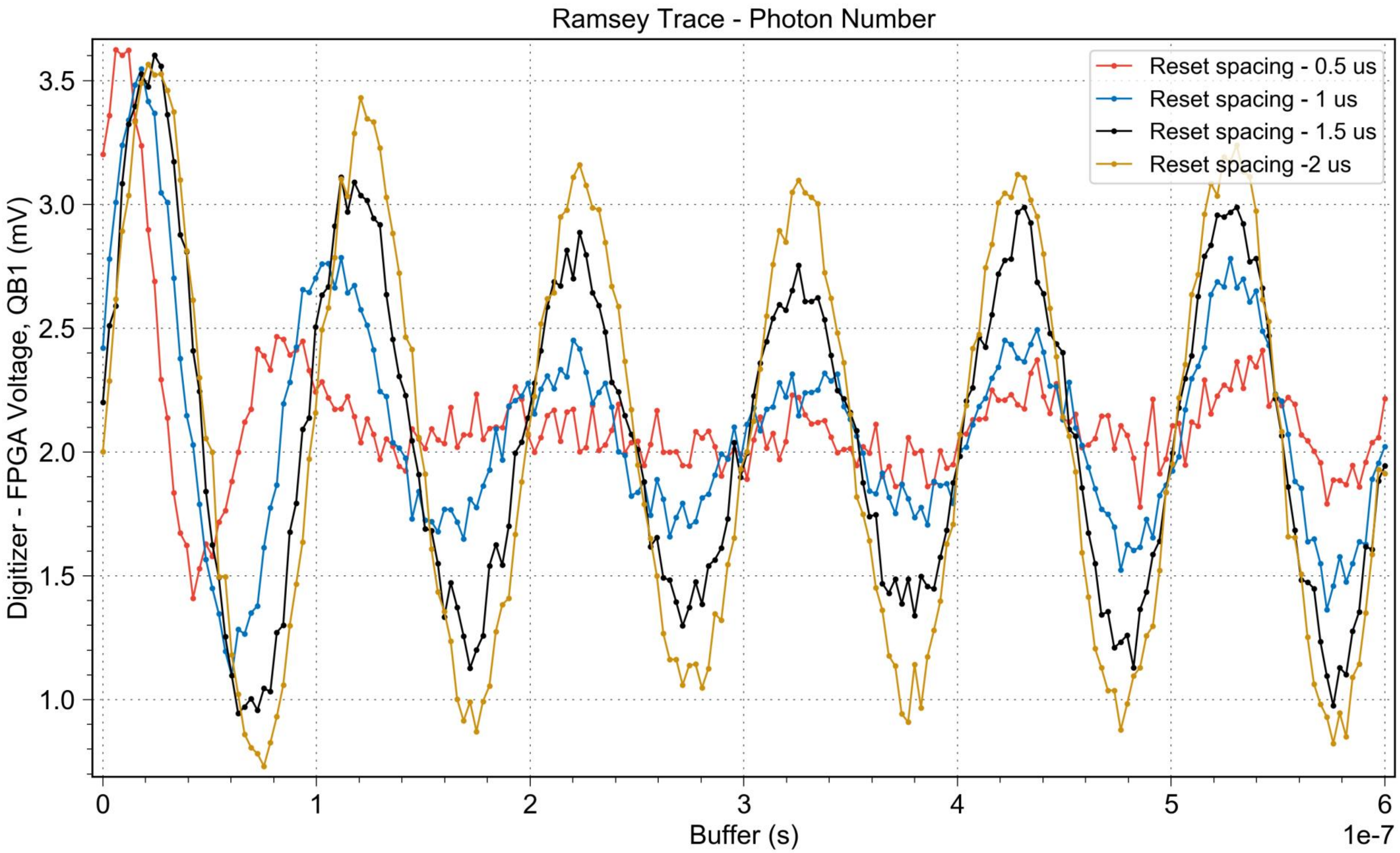
cal.getReset(
Length = True)



cal._ResetLength = 2 us

Spacing calibration

$$\frac{1}{2}\left[1 - \mathrm{Im}(\exp(-\left({}^{1}/_{T_{2Echo}} + \Delta i\right) t_R + (\phi_0 - 2n_0\chi\tau)i))\right]$$



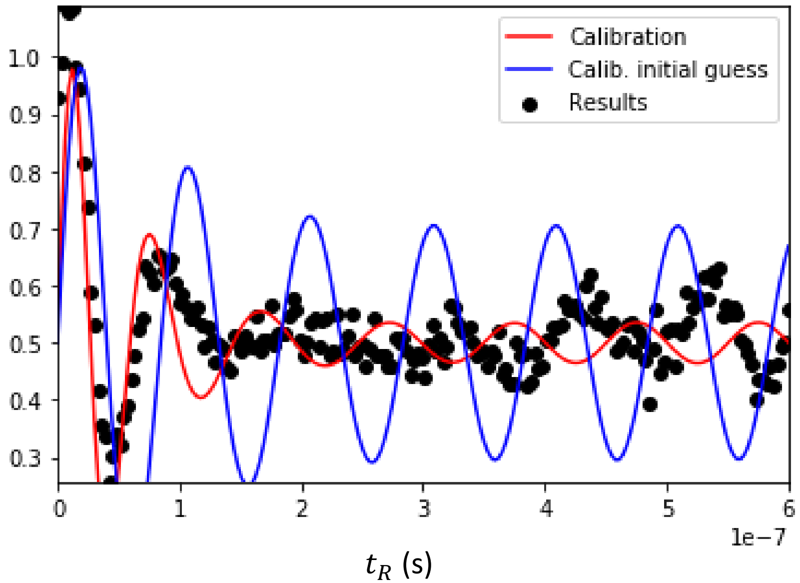
$$\tau = \frac{1 - e^{-(\kappa + 2\chi i)t_R}}{\kappa + 2\chi i}$$

Ref. [4]

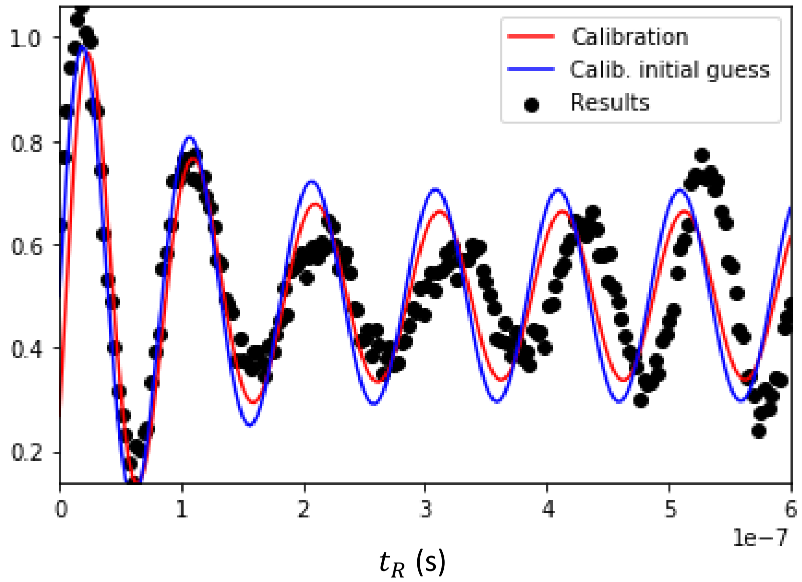
Number of photons

$$\frac{1}{2}\left[1-\mathrm{Im}\left(\exp\left(-\left({}^{1}/_{T_{2Echo}}+\Delta i\right)t_R+(\phi_0-2n_0\chi\tau)i\right)\right)\right]$$

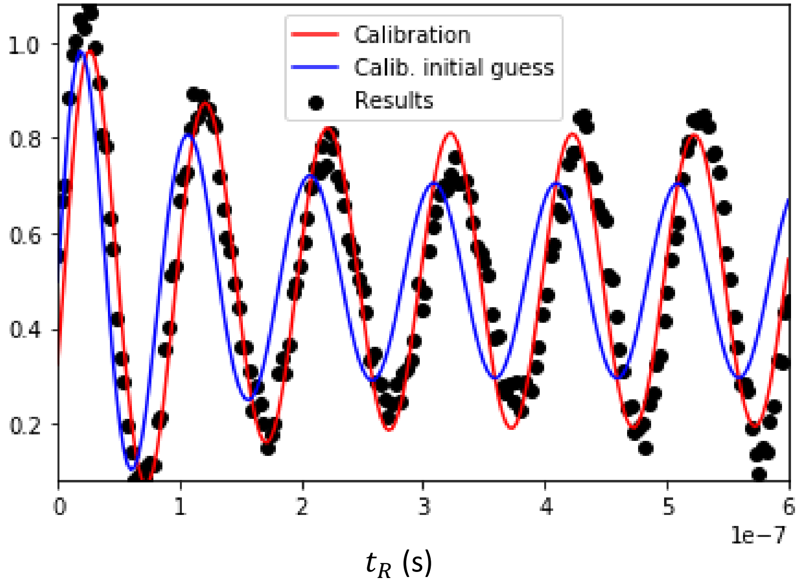
$n_0 = 6.19$



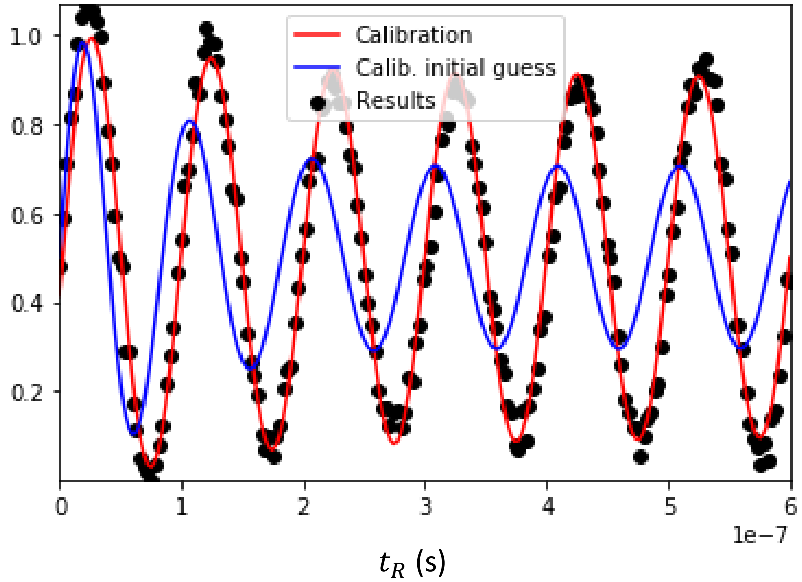
$n_0 = 2.53$



$n_0 = 1.03$

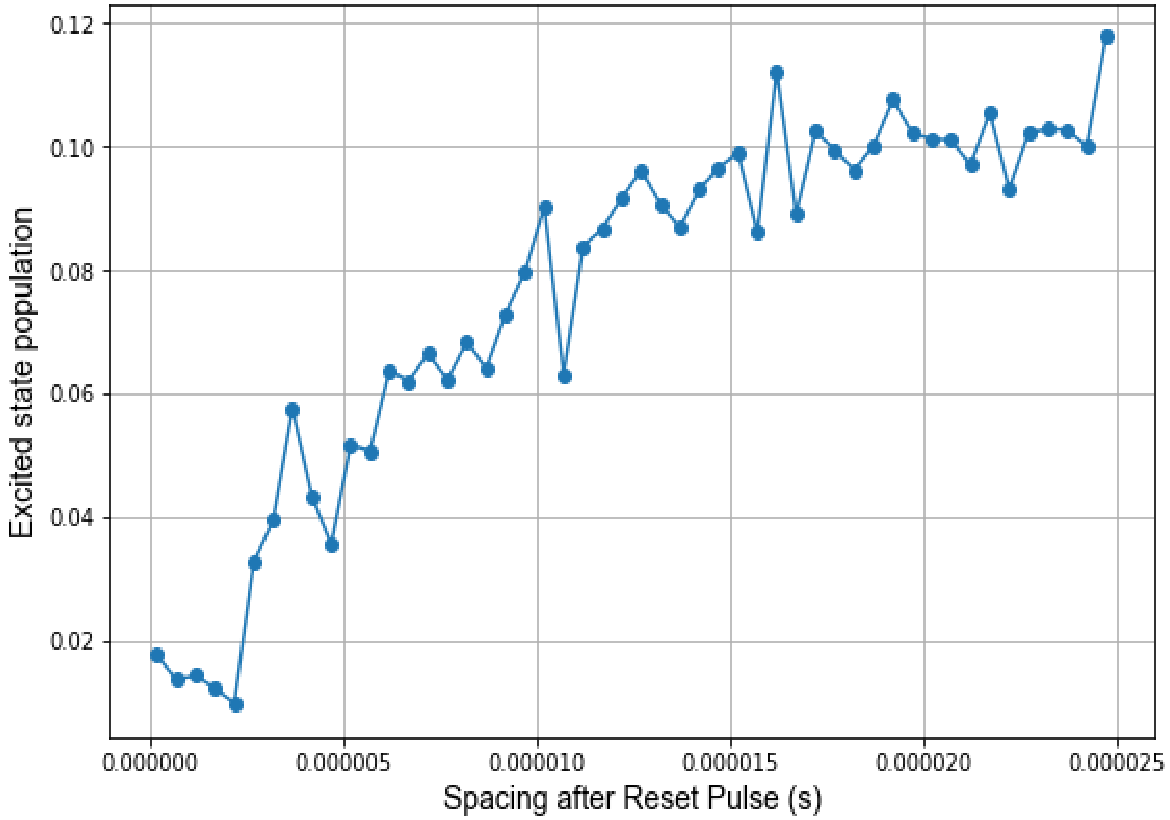


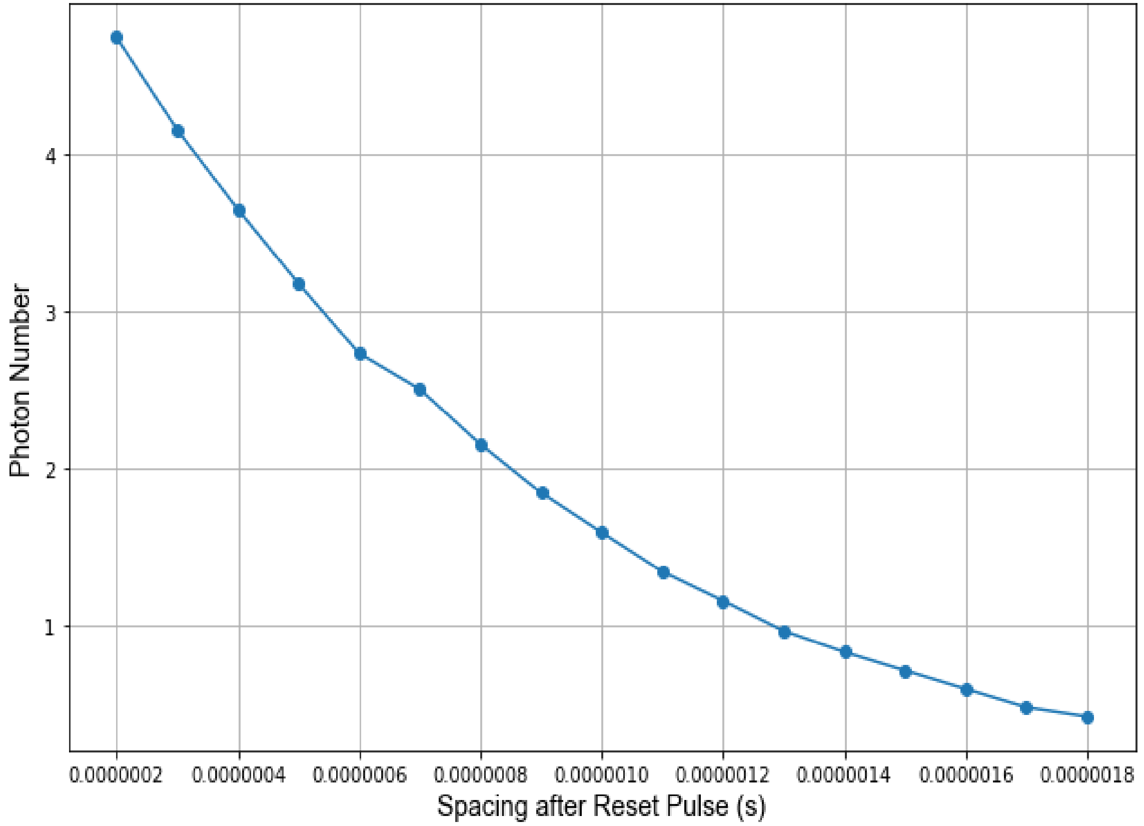
$n_0 = 0.35$



Spacing calibration

```
cal.getReset(
Spacing = True)
```

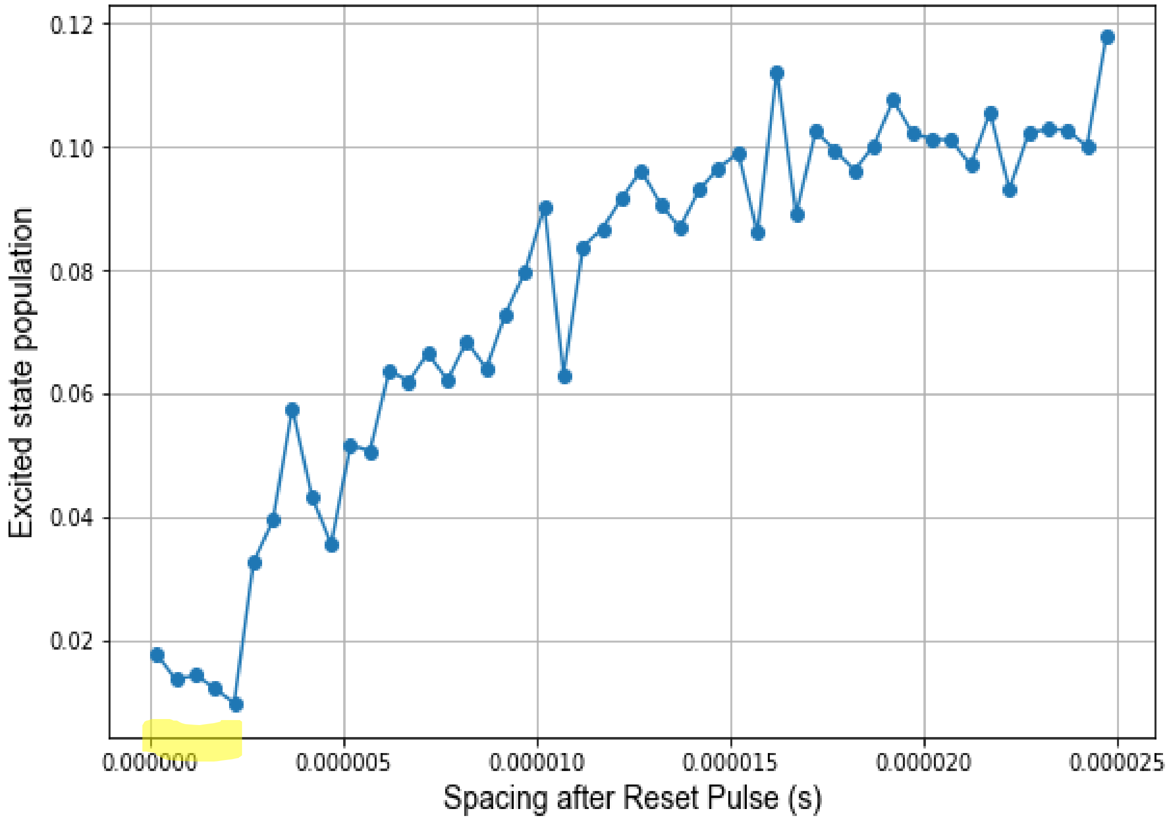


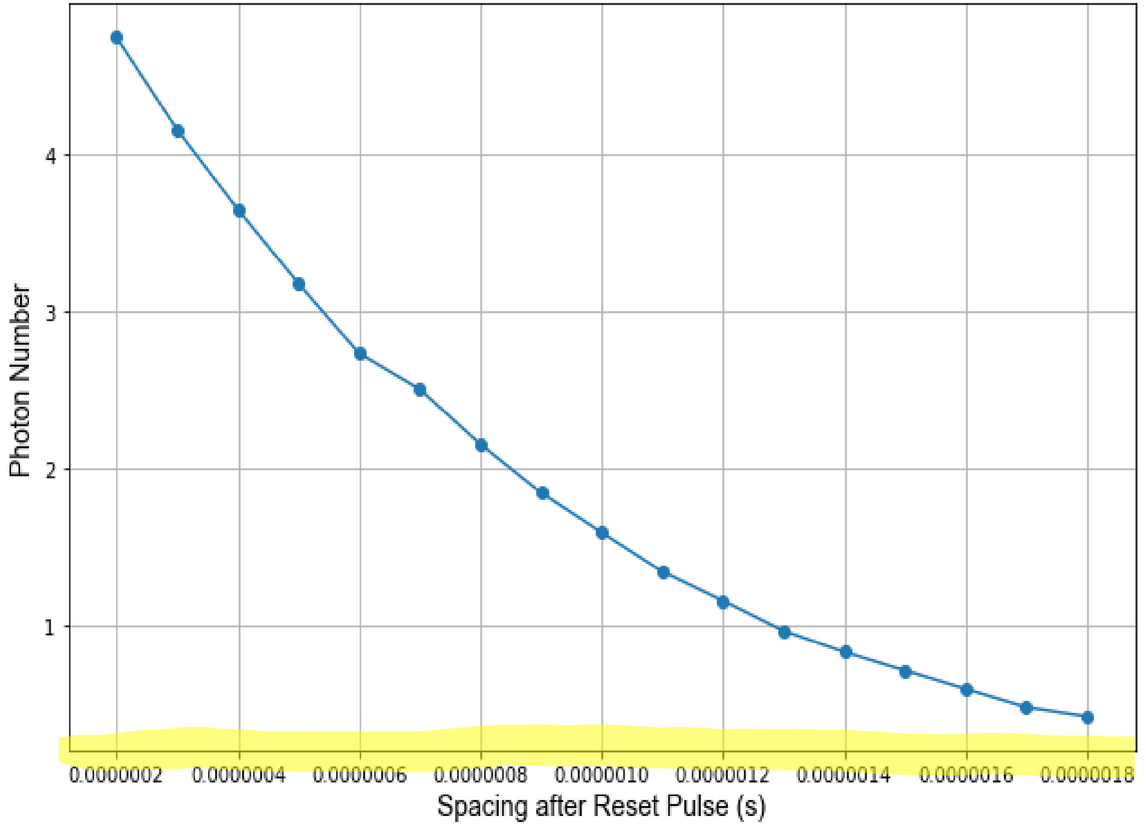


cal._ResetSpacing = 2 us

Spacing calibration

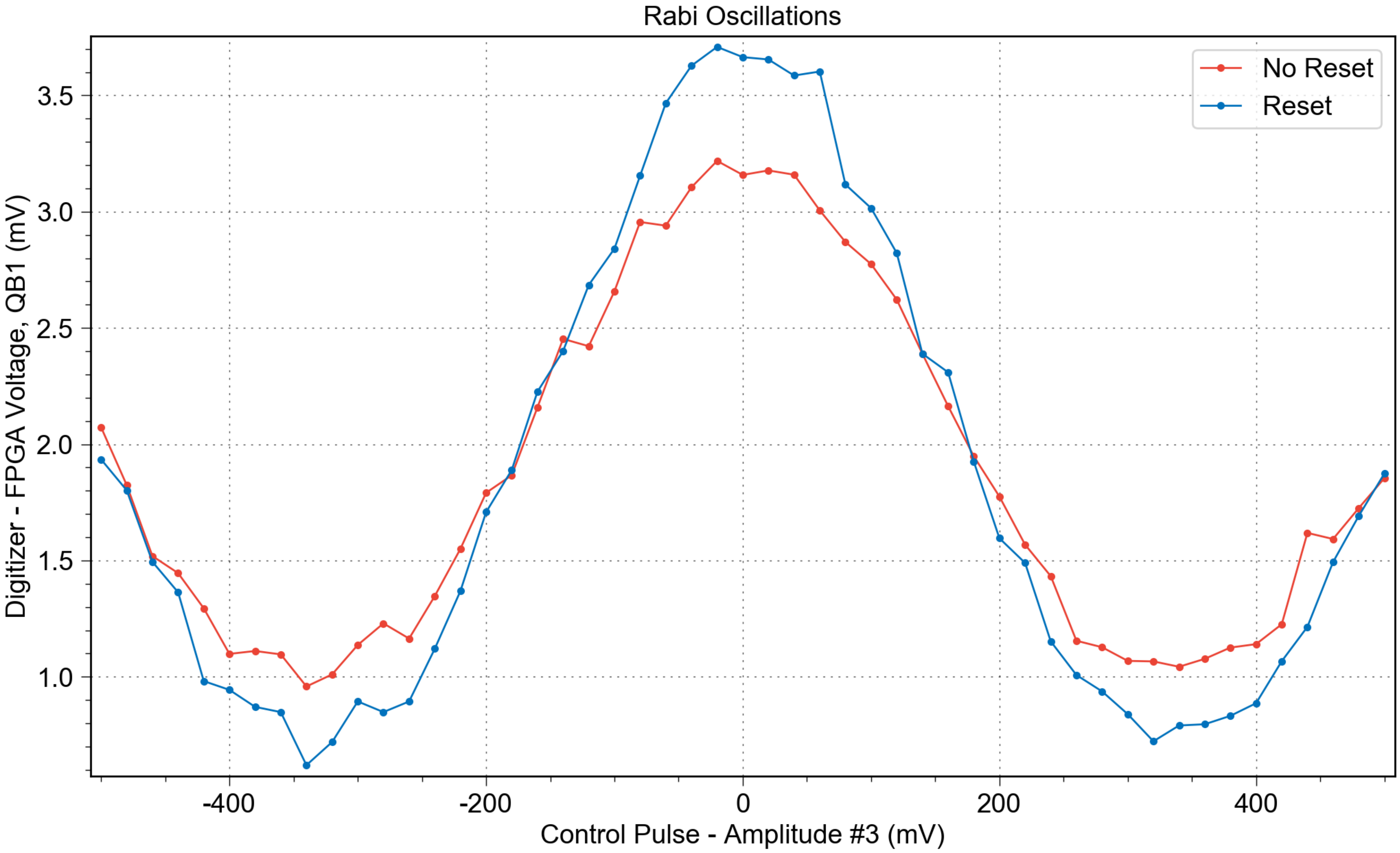
```
cal.getReset(
Spacing = True)
```



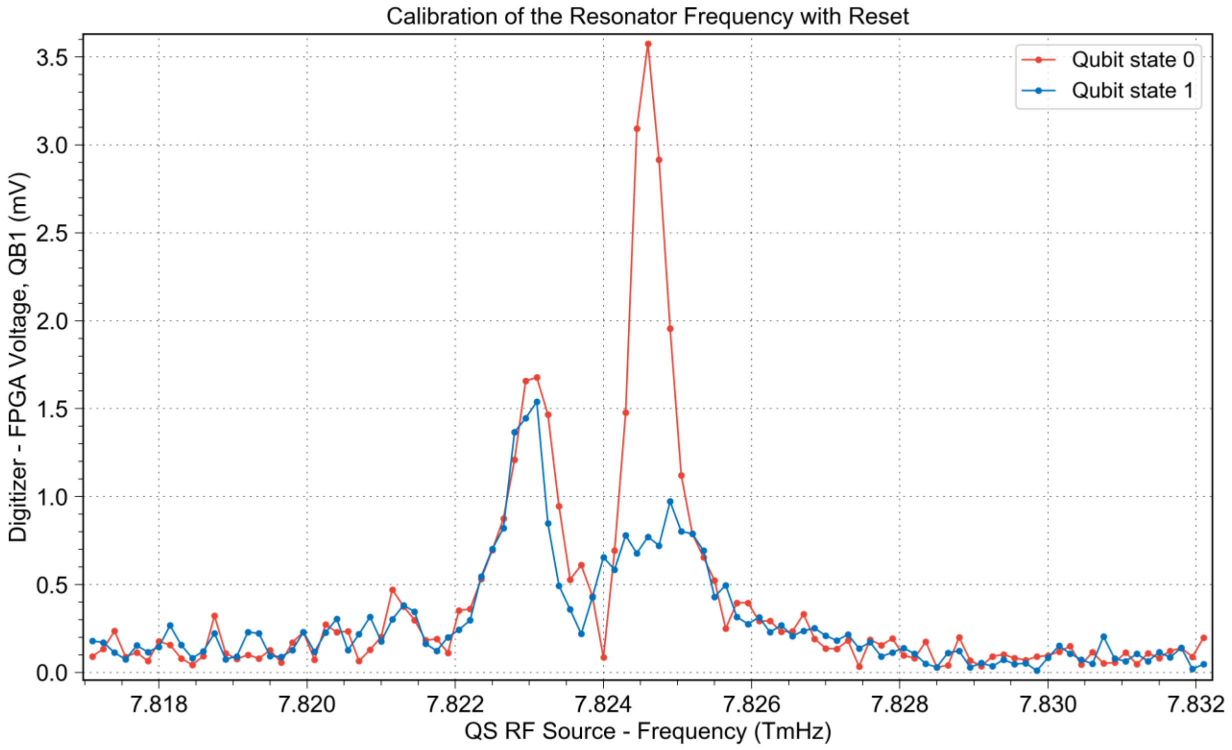


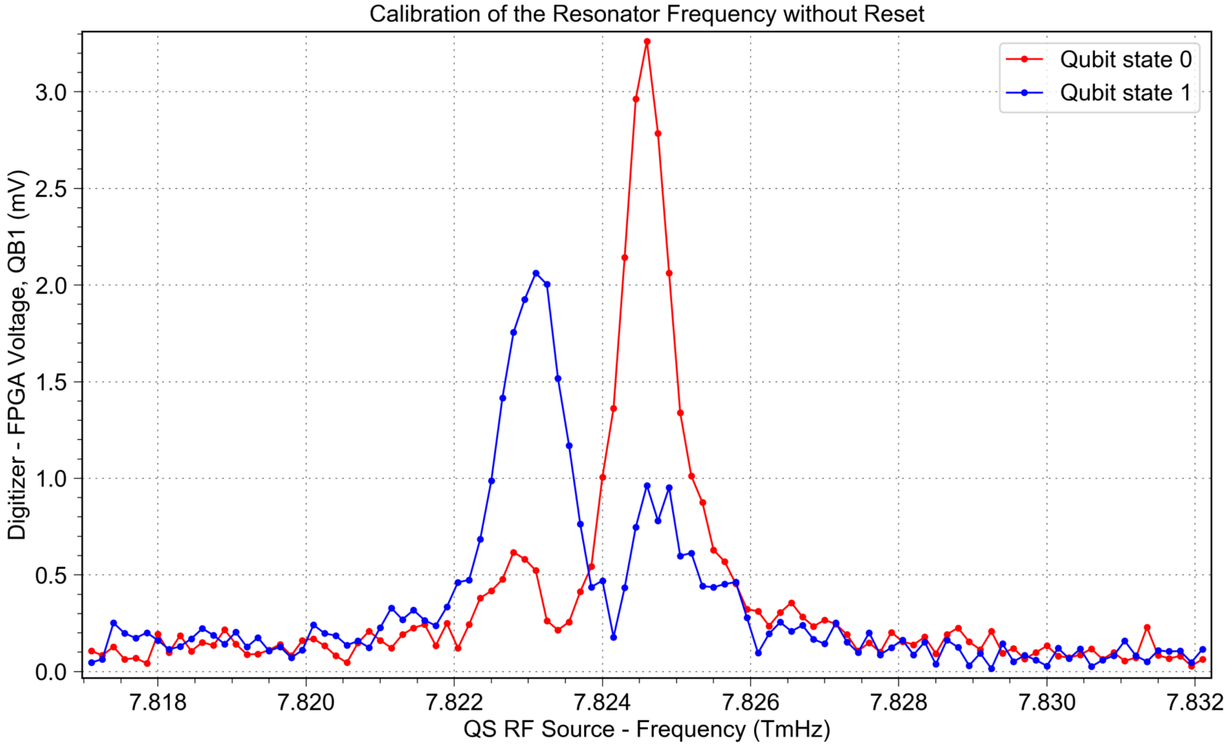
cal._ResetSpacing = 2 us

Reset vs. No Reset

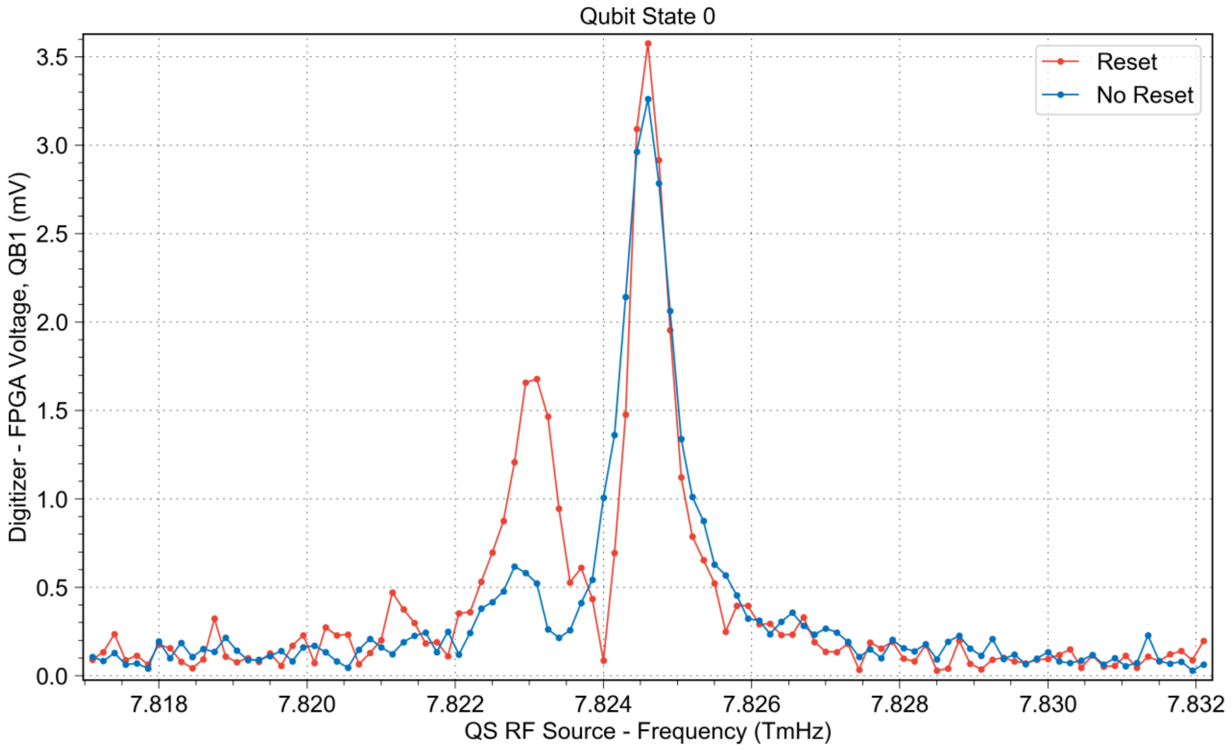


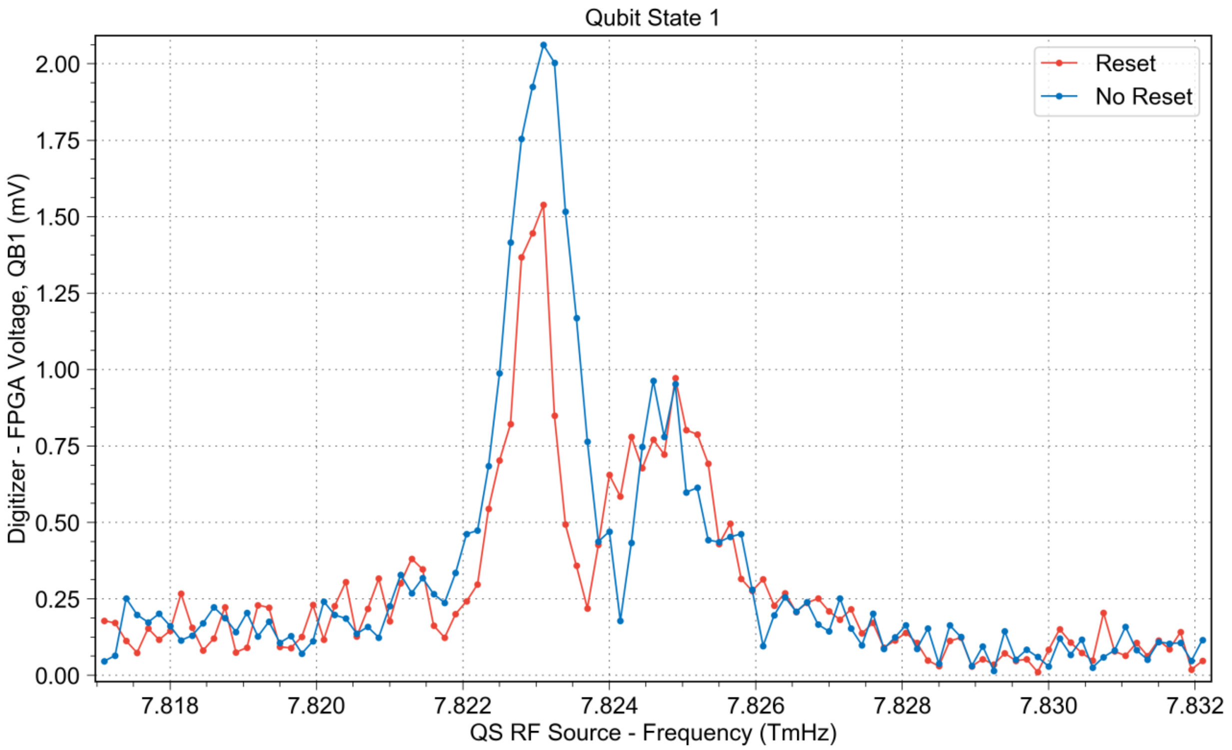
Reset vs. No Reset





Reset vs. No Reset





Reset vs. No Reset

	Reset: Result	Reset: Runtime	No Reset: Result	No Reset: Runtime
π pulse	0.338 V		0.337 V	
Amax	0.0036 V	15 s	0.0032 V	30 s
Amin	0.0007 V		0.0010 V	
T_1	14.67 us	15 s	14.56 us	30 s
T_2	6.77 us	2 min	8.65 us	3 min
$T_{\varphi,G}$	9.35 us		11.75 us	
T_{2Echo}	8.24 us	30 s	9.92 us	1 min
Qubit Frequency	4.8250361 GHz	1 min	4.8250351 GHz	2 min
Cavity Frequency $\|0\rangle$	7.75462 GHz	1 min	7.75460 GHz	2 min
Cavity Frequency $\|1\rangle$	7.75294 GHz		7.75305 GHz	