PI Loop Resonance Control For The Dark Photon Experiment at 2 K Using A 2.6 GHz SRF Cavity

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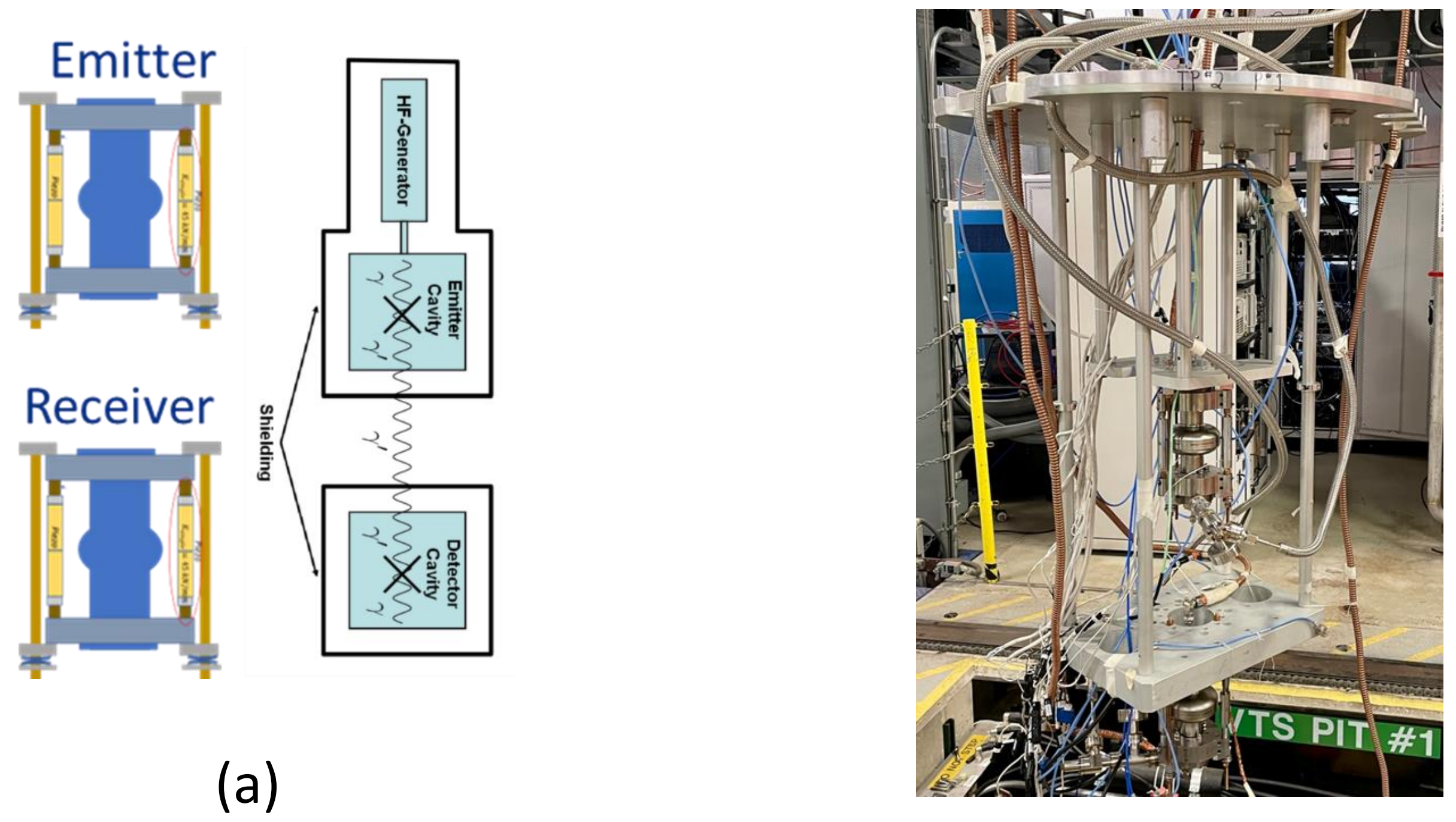
Introduction

- Two 2.6 GHz cavities are being used for dark photon search at VTS in FNAL.
- During testing at 2 K the cavities experience frequency detuning caused by microphonics and slow frequency drifts.
- These two cavities are equipped with frequency tuners consisting of three piezo actuators.
- A PI feedback loop was used to control the frequency of the emitter cavity
- The integration time was also calculated with a simulation

Setup



(a)

(b)

Figure 1: (a) : Left picture shows the setup of the experiment. The right picture shows a schematic of the process of dark photon production and detection (b) Actual cavity setup.

Table 1: Figures of merit of both cavities, the bandwidth is calculated using the loaded Q_L

Cavity	R/Q [Ω]	Bandwidth [Hz]	Q_L
Emitter	104.7	5.84	4.42×10^8
Receiver	104.7	0.56	4.64×10^9

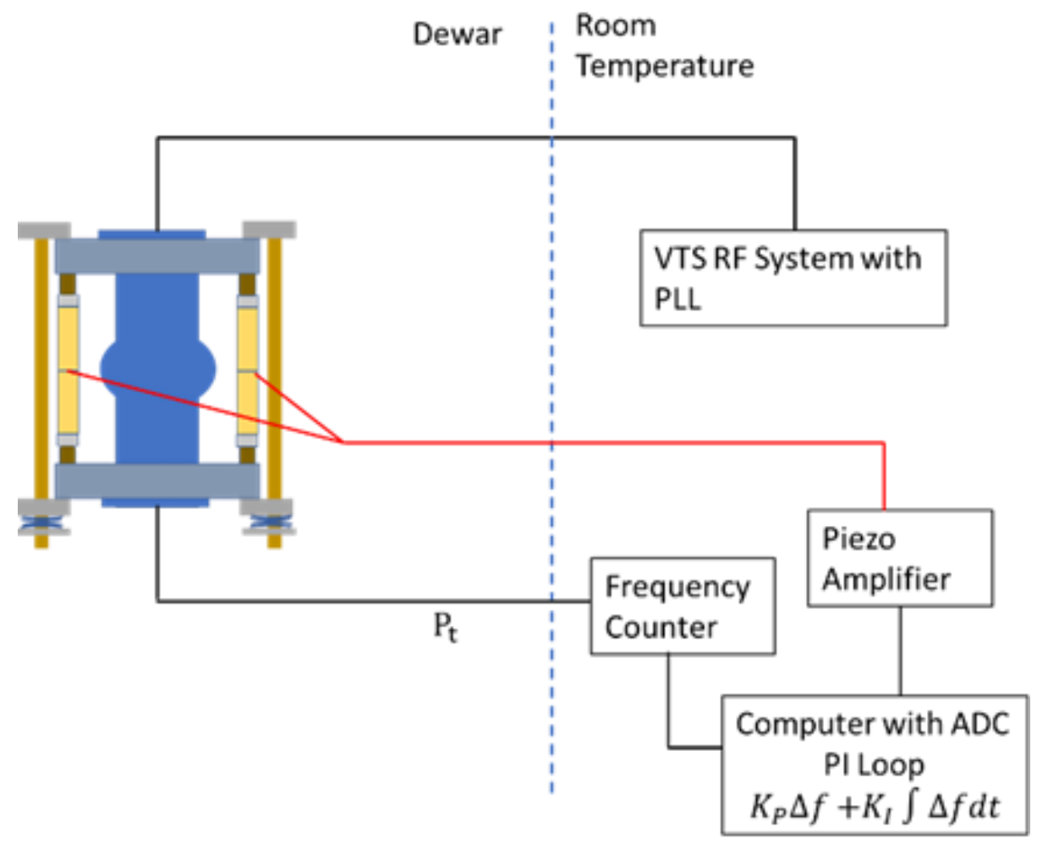
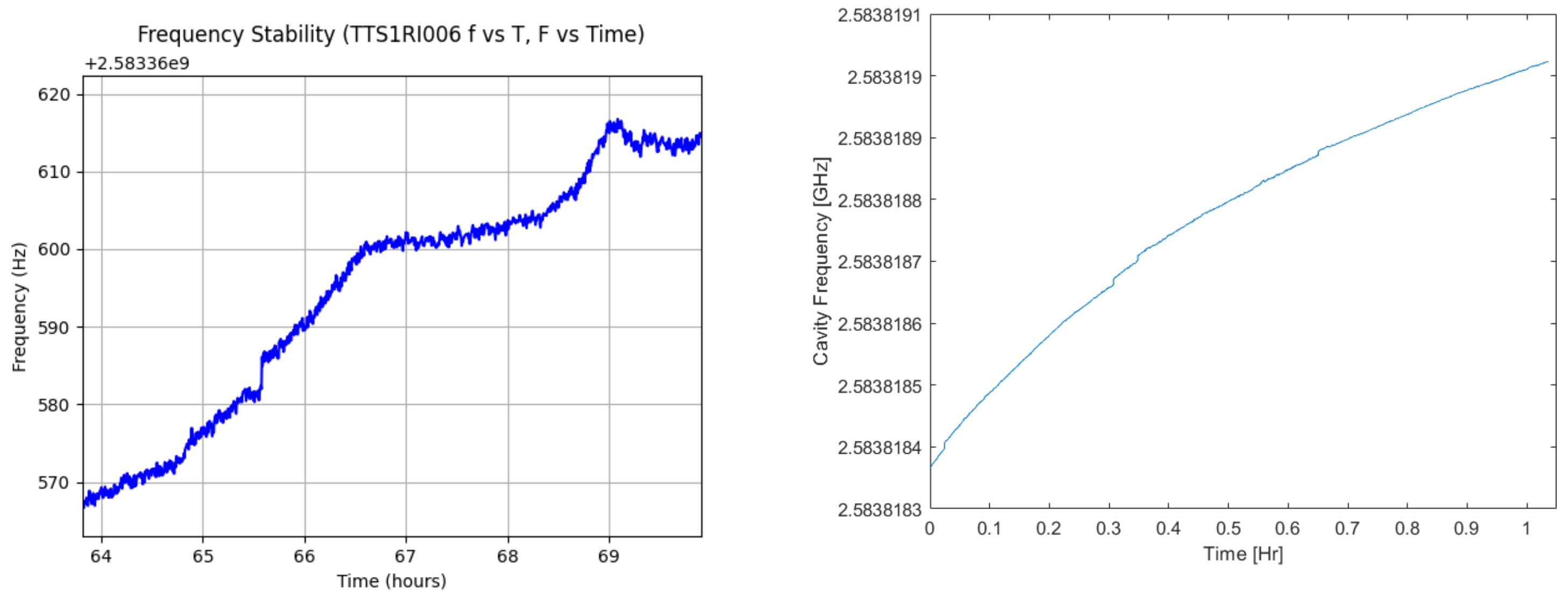


Figure 2: Setup of the PI loop for the emitter cavity.

- The experiment consists of two cavities, one which will be called the emitter cavity and the other the receiver cavity
- The emitter will be powered on and create electromagnetic field inside the cavity, the field from this emitter cavity will then create dark photons which can be emitted outside the cavity
- Resonant enhancement of the receiver signal is achieved when the frequency of the SM photons, that result from the conversion of the dark photons from the emitter cavity, matches the frequency of the receiver cavity.

PI Loop Resonance Control

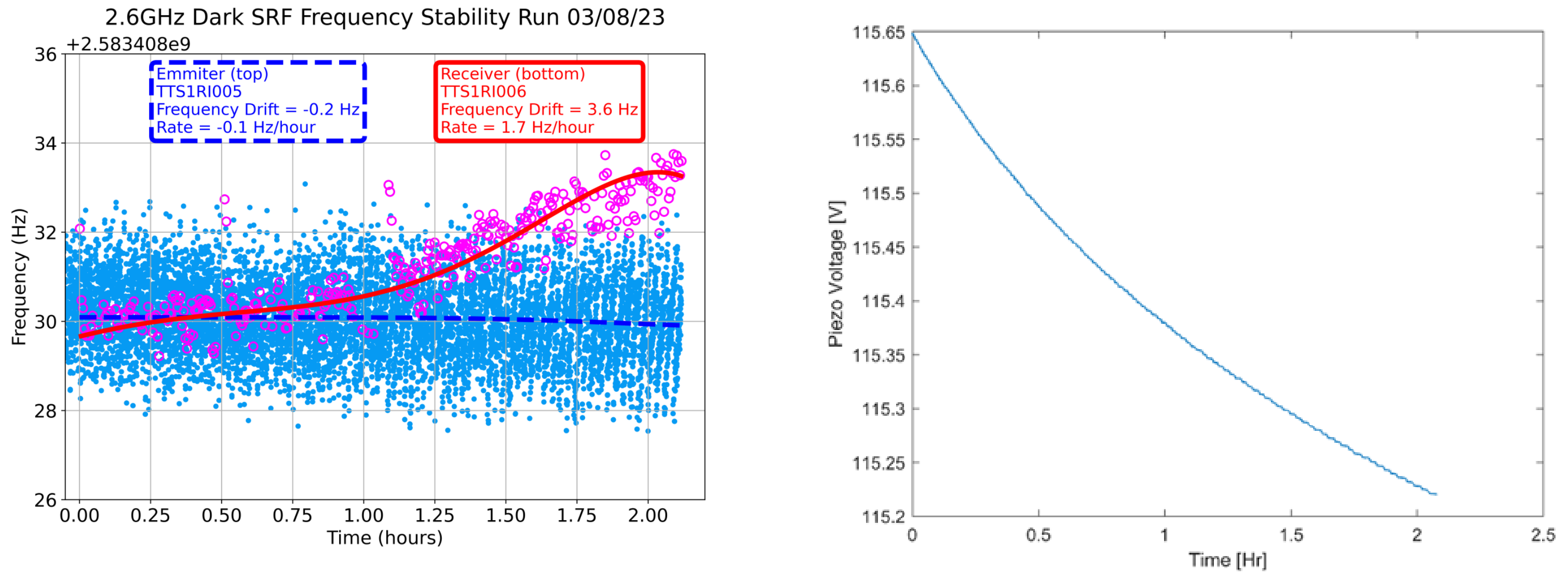


(a)

(b)

Figure 3: (a) Frequency stability of the receiver cavity using a network analyzer. The cavity frequency drift can be linear or can plateau. (b) Frequency stability of the emitter cavity with a gradient of 15 MV/m and piezo DC voltage of 108 V.

- During testing microphonics and slow frequency drifts can be observed
- The cavity frequency is recorded using the VTS system that utilizes a frequency counter and a network analyzer (see Fig. 2)
- Fig 3a show the frequency shift of the receiver cavity, the rate of change is ~ 10 Hz/hr , both cavities exhibit this behavior at low field
- At 15 MV/m the shift is 657 Hz in an hour for the emitter cavity
- A PI loop on the emitter was implemented to reduce the drift, a schematic of the setup is shown in Fig 2
- The PI loop implementation reduced the frequency drift from 657 Hz/hr to 0.1 Hz, see Fig 4a
- The piezo voltage during this period changed by 0.428V which is equivalent to 314 Hz (see Fig. 4b)



(a)

(b)

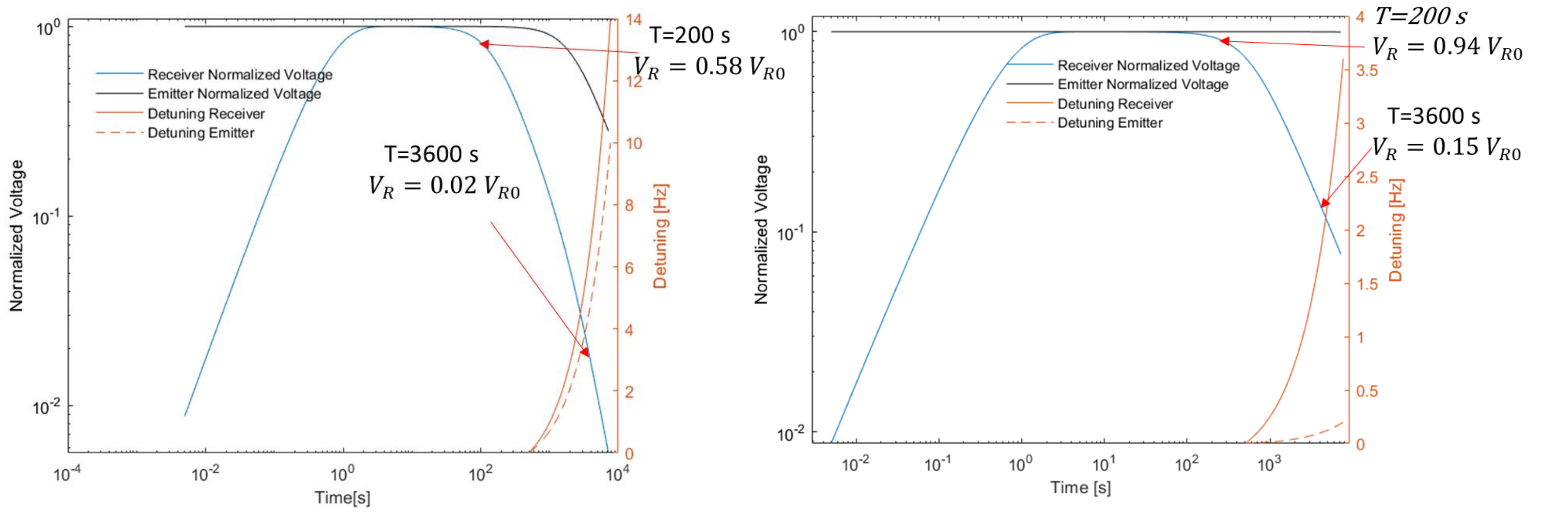
Figure 4: (a) Frequency drift of the emitter cavity is shown in blue and for the receiver it is shown in red. A frequency counter is used to record the frequency on the emitter and NA for the receiver. b) Voltage of the piezos on the emitter cavity with PI algorithm.

Integration Time Simulation

- The purpose of this simulation is to estimate the field inside the receiver cavity considering the slow frequency drift
- The cavity behavior was modeled by using an LCR circuit, note that the same behavior can be arrived at by using the cavity field and expanding in the cavity eigen modes

$$\frac{d\boldsymbol{V_E}}{dt} + \left(\omega_{1/2} - i\Delta\omega_E\right)\boldsymbol{V_E} = R_L\omega_{1/2}\left(\boldsymbol{I_{RF}}\right) \text{ (Eq. 1.1)}$$

$$\boldsymbol{V_E} = \frac{R_L\omega_{1/2}I_{RF}}{\omega_{1/2} - i\Delta\omega_E}\left[1 - e^{-(\omega_{1/2} - i\Delta\omega_E)t}\right] \text{ (Eq. 1.2)}$$



(a)

(b)

Figure 5: (a) The simulations are done with no PI loop and linear cavity frequency drift. For the emitter frequency change rate is 5Hz/hr and for the receiver it is 2 Hz/hr. (b) PI loop on the emitter, Emitter frequency change rate is 0.1 Hz/hr and for receiver it is 1.7 Hz/hr

- For the receiver, the same equation 1.1 is used except the driving term is

$$\boldsymbol{I_E} \propto \frac{\omega_{\frac{1}{2}}}{\omega_{\frac{1}{2}} - i\Delta\omega_E(t)}\left[1 - e^{-\left(\omega_{\frac{1}{2}} - i\Delta\omega_E(t)\right)t}\right] \text{ (Eq. 1.3)}$$

- Eq. 1.1 for the behavior of the emitter is solved using Runge-Kutta 4
- The frequency shift of the emitter is given by $\Delta\omega_E = \delta\omega_{slow,E}$ and for the receiver cavity $\Delta\omega_R = \Delta\omega_E + \delta\omega_{slow,R}$
- With no PI loop on the emitter the field on the receiver drops to 58 % after 200 s and to 2 % at 1 hour

Conclusion

- Result with PI resonance control on the emitter reduce the slow drift from 657 Hz/hr to 0.1 Hz/hr
- This improvement in frequency stabilization improved the frequency matching capability which will greatly help increase the dark photon search sensitivity.
- Simulation results show that even with a PI loop after 1 hour the field of the receiver drops to 15 % of its initial value
- A constrain of integration time is calculated to be about ~200 s

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