Phase noise measurements in TRIUMF ISAC 2 cryomodule

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Talk outline

- Sources of phase noise in SCRF system
- Phase noise measurements
- Interpretation of results
- Conclusion

Self excited loop field equations

for self-excited

$$\begin{bmatrix} \delta V \\ \delta \omega \end{bmatrix} = \begin{bmatrix} \dfrac{1}{s\tau + 1} & 0 & 0 \\ \dfrac{-\tan\phi}{(s\tau+1)\tau V} & \dfrac{1}{\tau} & 1 \end{bmatrix} \begin{bmatrix} \delta v_a \\ \delta \phi \\ \delta \omega_c \end{bmatrix}$$

$$\tau(\omega - \omega_c) = \tan\phi \qquad \tau = \frac{\tau_o}{1+\beta} \qquad \tau_o = \frac{2Q_u}{\omega_c} = \frac{1}{\xi\omega_c} \qquad \beta = \frac{R}{r}$$

δv_a is the input amplitude noise

$\delta\phi$ is the input phase noise

$\delta\omega_c$ is the variation in resonance frequency due to microphonics

δV is the output amplitude noise

$\delta\omega$ is the output frequency noise

for perfect tune, $\tan\phi \approx 0$

$$\begin{bmatrix} \delta V \\ \delta \omega \end{bmatrix} = \begin{bmatrix} \dfrac{1}{s\tau + 1} & 0 & 0 \\ 0 & \dfrac{1}{\tau} & 1 \end{bmatrix} \begin{bmatrix} \delta v_a \\ \delta \phi \\ \delta \omega_c \end{bmatrix}$$

$$\begin{bmatrix} \delta V \\ \delta \omega \end{bmatrix} = \begin{bmatrix} \frac{1}{s\tau + 1} & 0 & 0 \\ 0 & \frac{1}{\tau} & 1 \end{bmatrix} \begin{bmatrix} \delta v_a \\ \delta \phi \\ \delta \omega_c \end{bmatrix}$$

Several observations can be drawn immediately from the above equation:

$\delta V = \frac{\gamma}{s\tau + 1} \delta v_a$, The output amplitude noise is a single pole response to the input amplitude noise only, independent of other factors,

$\partial \Phi = \frac{1}{s\tau} \partial \phi$ The output phase noise is proportional to input phase noise/noise modulation frequency, suppressed by the Q Of the cavity. For an input white phase noise, the output phase noise power spectrum will have a $1/f^2$ dependence, and

$\frac{\partial \omega}{\partial \omega_c} = 1$, The cavity self-excited frequency varies directly as the detuning caused by microphonics.

Therefore, output phase noise are due to microphonics and amplifier phase noise, while output amplitude noise are due to amplifier amplitude noise only.

Source of phase noise

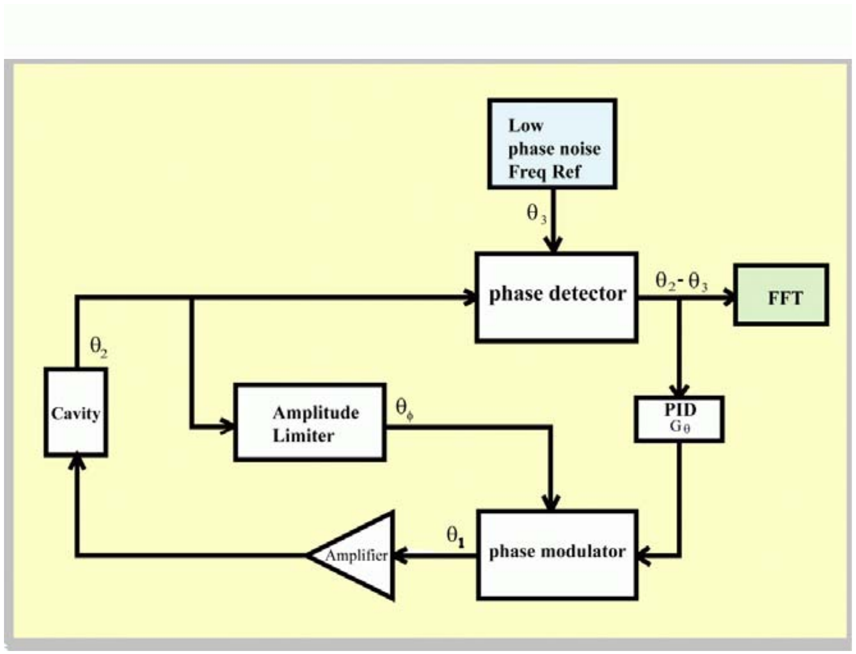
- Power-line induced phase shift in amplifier
  - DC Biases affect conduction angle.
- Microphonics in amplifier tuning circuits
  - Cooling fan vibration.
- Microphonics in cavity
  - Ambient vibration
    - Ground vibration
    - Pump vibration
  - He pressure fluctuations (significant in bulk niobium cavities)
    - Nucleated boiling (<2W/cm)
    - Refrigerator cycling
    - Exhaust back pressure fluctuation

Measuring Phase noise

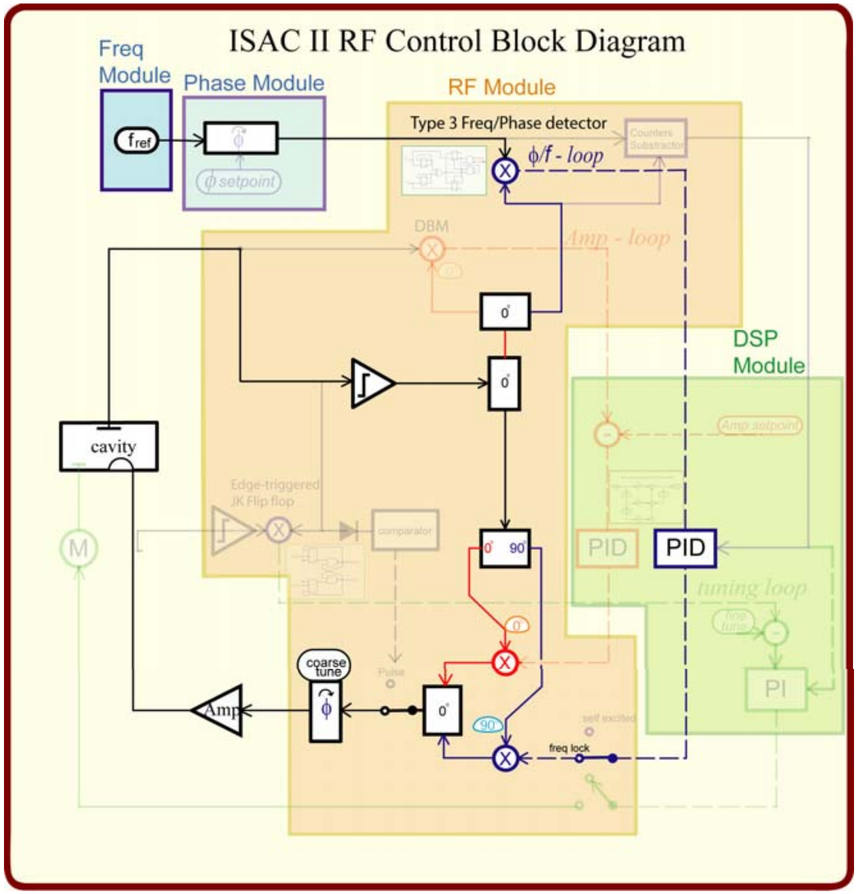
- Amplitude noise must be removed
  - Use amplitude limiter.
- Direct measurement using RF spectrum analyzer
  - Impractical due to
    - Phase/frequency stability of reference source in spectrum analyzer
    - Frequency resolution of spectrum analyzer.

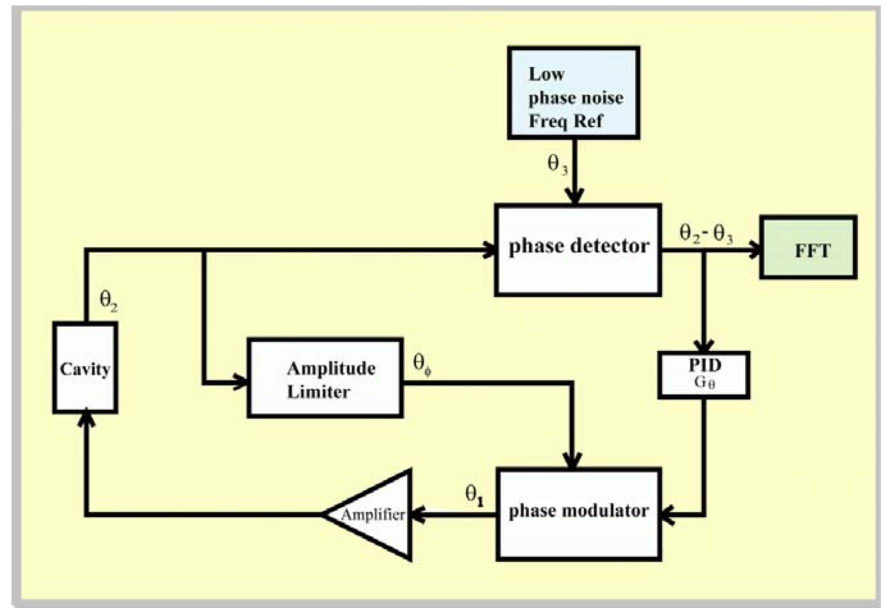
Measuring Phase noise

- Down-conversion into audio frequency
  - Requires low phase noise RF sources
    - Synthesized commercial unit – multi-frequencies, very expensive
    - crystal oscillator – single frequency, cheap.
  - At least 2 identical sources are required for self-calibration.
  - After mixing, phase noise will be converted into amplitude noise.
  - Typically a commercial FFT analyzer is used to record the detected phase noise.
  - Even if the 2 signals have the same frequency, the phase difference will exhibit random walk behavior, and eventually increase out of bound.
    - Frequency detection
      - IF Quadrature Detector + Differentiation
    - Phase detection with weak phase-locking (Single Channel Measurement Method)
      - Product detector
        - » Double balanced mixer – simple, non-linear, 0 -150 range, low noise
        - » Digital phase detector – more complex, linear but may have dead bands, 0 – 300 range.

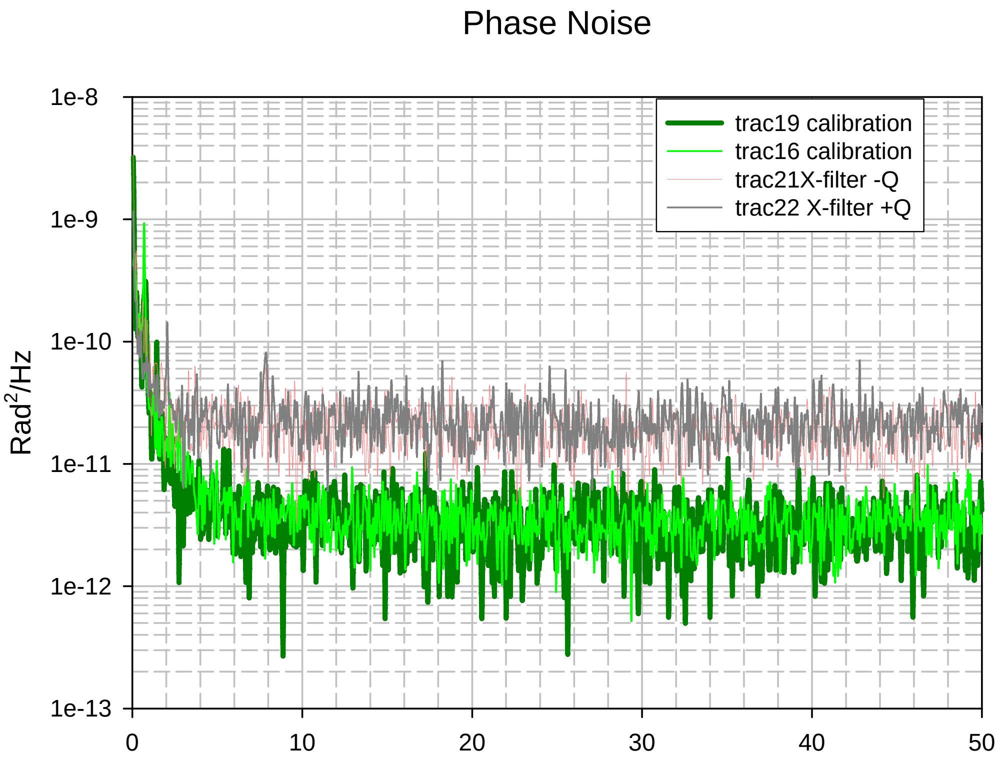


Phase noise measurement setup in ISAC 2





Calibration

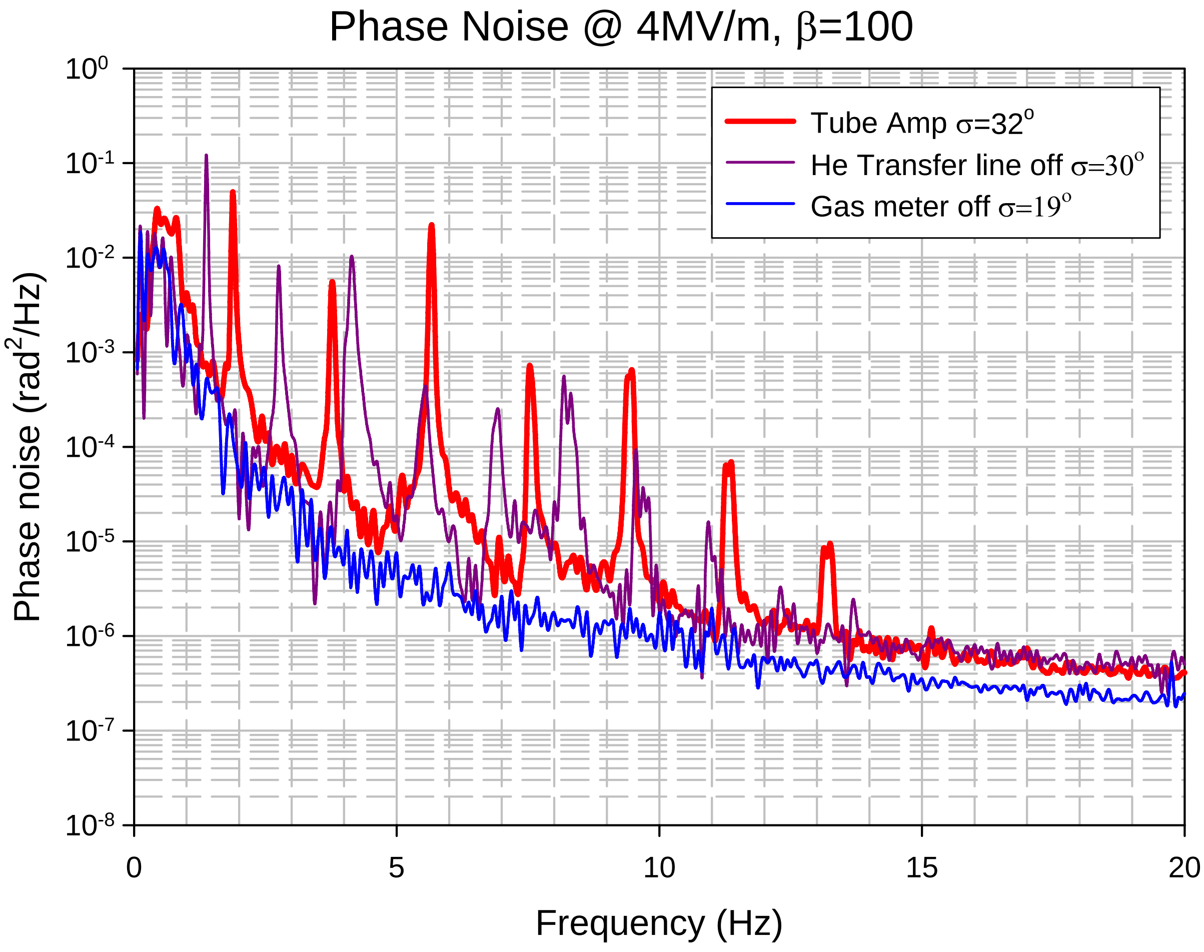


FFT noise floor=1e-14 Rad^2/Hz
PTT phase jitter=0.007 degree
DBM noise figure > 10 dB
Post detection filter – Johnson noise

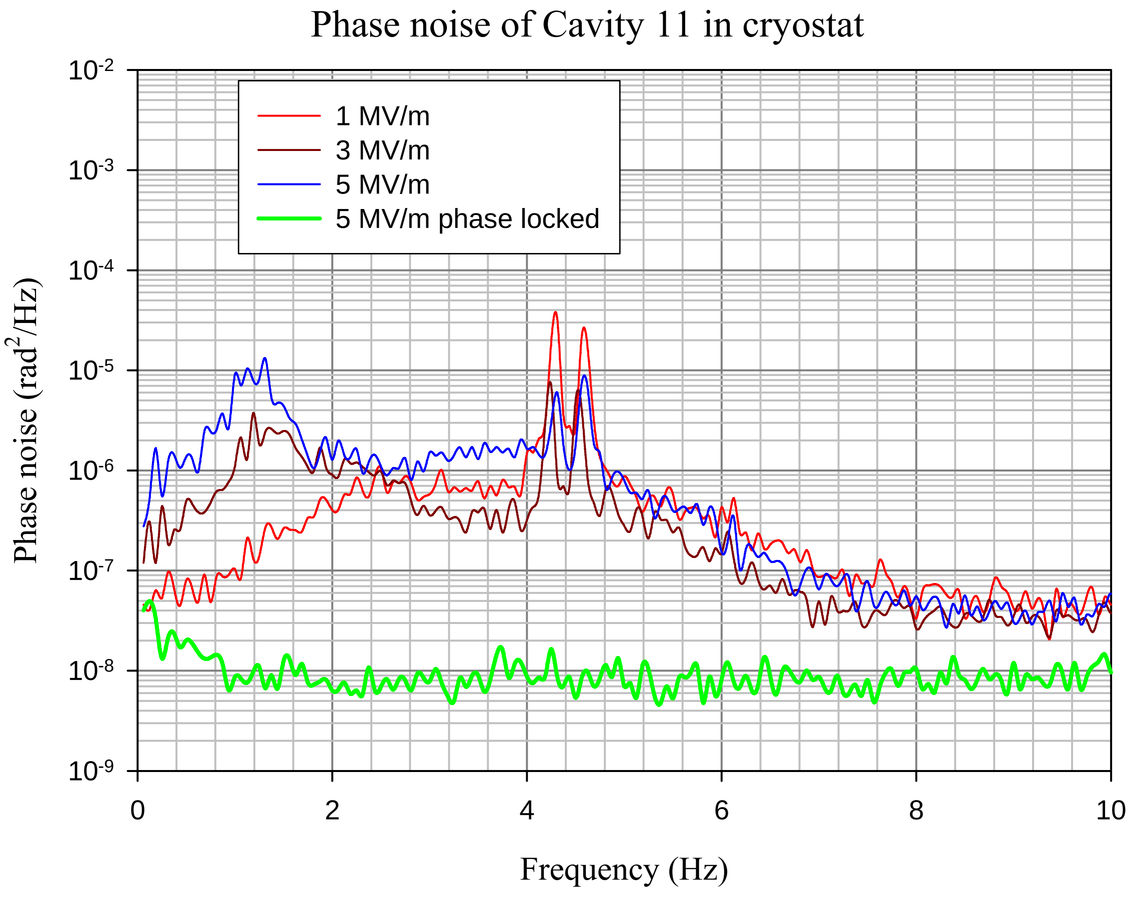
Phase jitter = 0.01 degree

Things to look out

- Injection locking
  - Parasitic coupling through power supplies, through the air, through mixer.
- Insufficient averaging
  - Close-in phase noise measurement requires long sampling time.
- Power line noise
  - Subharmonics and harmonics of power line frequency.
  - Ground loops, conductive and radiative interference.
  - Amplitude depends on time of day.
- Reference noise
- System noise
  - Phase detector, resistors, opamps…
- AM to PM conversion, Residual AM
  - Use low phase shift amplitude limiter.
- PLL bias data close to the reference
  - Avoid using charge pump phase detector.
- Broadband OK, $1/f$ region too high
  - Input and reference phase not in quadrature.
- Nonlinearity in phase detector.
- Large phase noise will cause the PLL to unlock.
  - Adjustable feedback loop gain
- PLL bandwidth suppressing phase noise close to carrier
  - Reduce feedback loop gain
- …

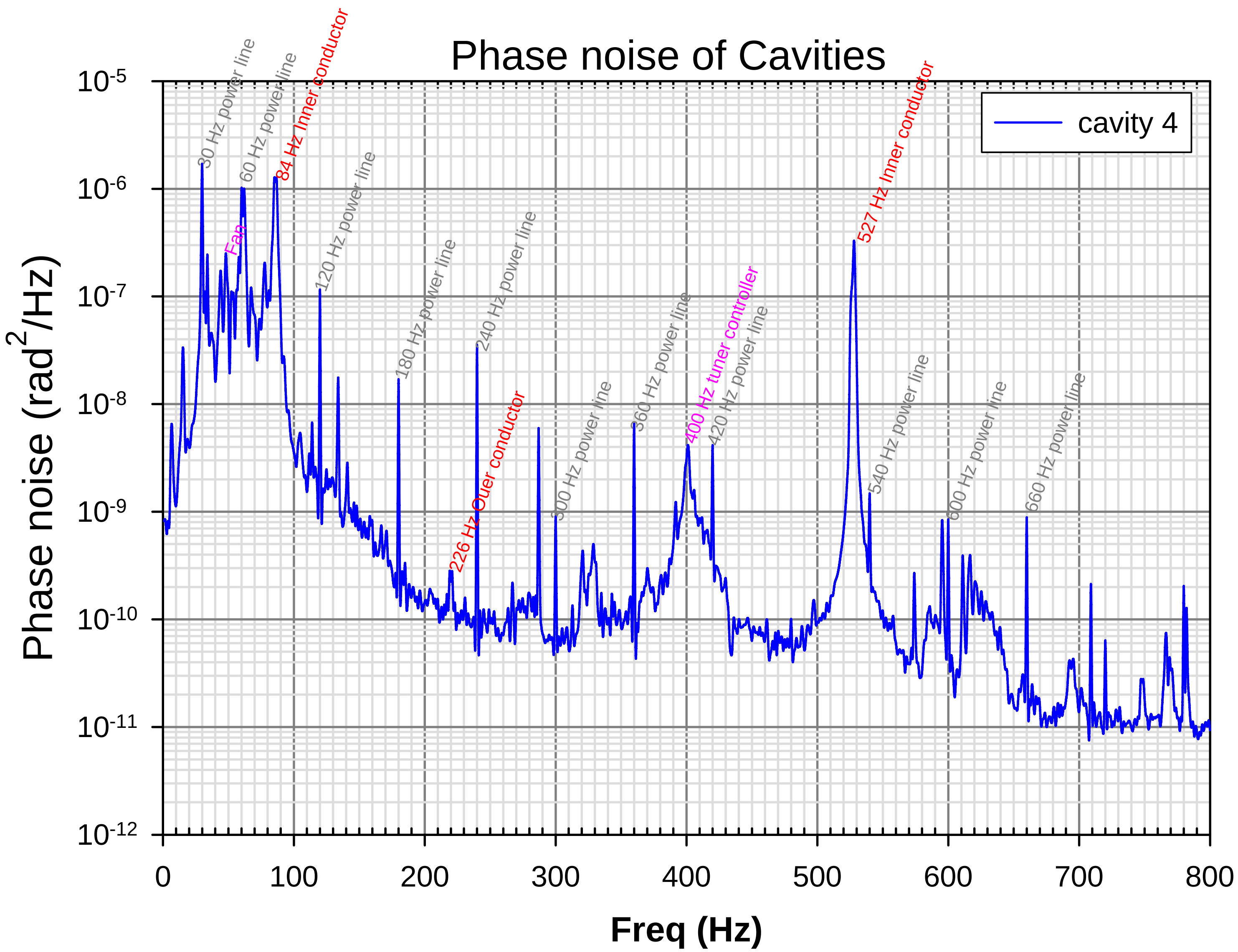

Phase Noise @ 4MV/m, β=100
Phase noise (rad²/Hz)
Frequency (Hz)
Tube Amp σ=32°
He Transfer line off σ=30°
Gas meter off σ=19°
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
0
5
10
15
20

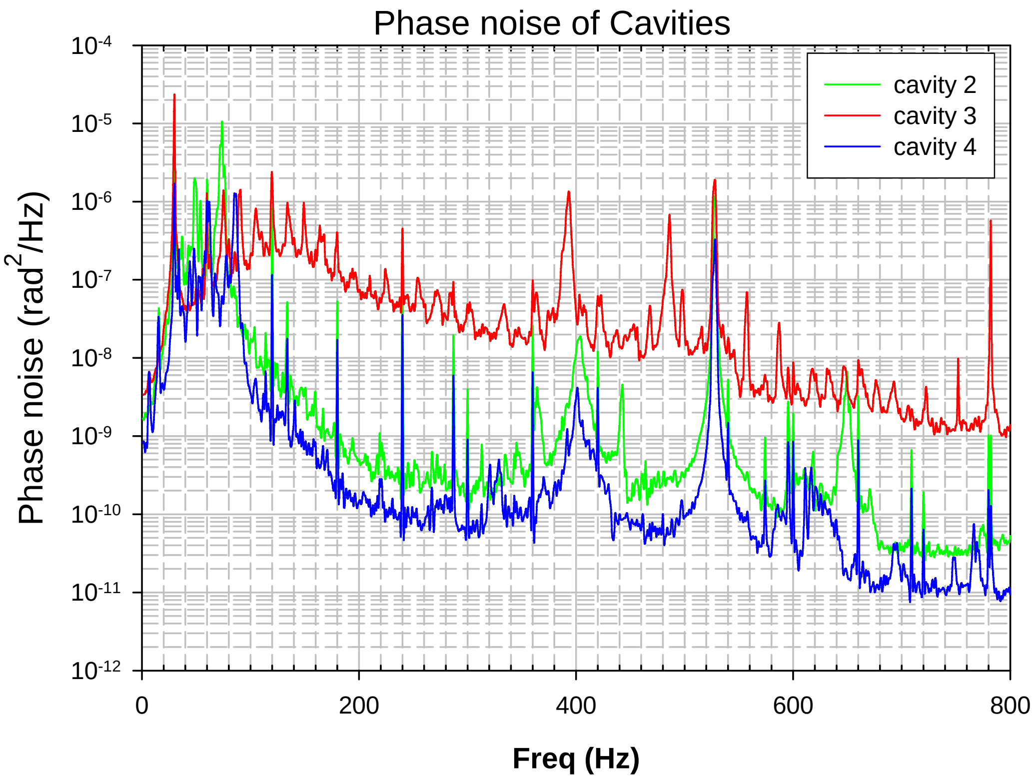
Effect of RF Power on phase noise due to boiling



Nucleated Boiling

- He II , <2.17 K – superfluid, evaporation
- LHe (He I) > 2W/cm film boiling, <2 W/cm nucleated boiling.
- The noise spectra generated by bubbles are very complicated
  - Bubble oscillate inside LHe
  - Pressure spike when a bubble pops.
  - All together there is characteristic noise spectrum
  - In MEBT cavities, this is a broadband noise centered at around 2 Hz
  - Frequency and amplitude depends on rate of boiling →RF power.
    - High RF power results in lower frequency and larger amplitude


Phase noise of Cavities
cavity 4
30 Hz power line
60 Hz power line
84 Hz Inner conductor
Fan
120 Hz power line
180 Hz power line
240 Hz power line
226 Hz Ouer conductor
300 Hz power line
360 Hz power line
400 Hz tuner controller
420 Hz power line
527 Hz Inner conductor
540 Hz power line
600 Hz power line
660 Hz power line
Phase noise (rad^2/Hz)
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
0
100
200
300
400
500
600
700
800
Freq (Hz)



Something wrong with Amplifier #3!

Conclusion

- Phase noise measurement in self-excited phase locked mode does not require any addition hardware.
- To measure low, close-in phase noise accurately is a very complicated task, in an uncontrolled environment such as an accelerator, the results are usually not reproducible. To get a reasonable result, the entire measurement system must be calibrated at the same time as the measurement.
- The phase noise spectrum is a useful diagnostics tool on the entire RF system.
- Each noise contributor has its own signature.
- To get their signatures, one must be able to replace every component in the measurement loop by some other functionally similar component but with different design.
- Major contributors of phase noise are
  - He boiling,
    - Strong low frequency component
    - But easily suppressed through phase feedback
  - Amplifier, narrow band noises
    - Cooling fans
    - Power line interference