Zurich Instruments

Lock-in Amplifiers for Precision Measurements

Dr. Jim Phillips, Application Scientist, Zurich Instruments

MIT Research Laboratory of Electronics, Dec. 5, 2025

Zurich Instruments
Company profile

- Headquarters in Zurich, Switzerland
- Founded 2008; 200 people
- Offices in USA, China, France, Germany, Japan, Korea, India

→ Run by scientists for scientists

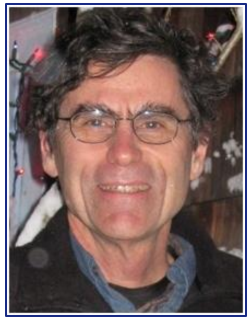
→ In 2021, Zurich Instruments became a Rohde & Schwarz company. Growth continues, modus operandi unchanged.

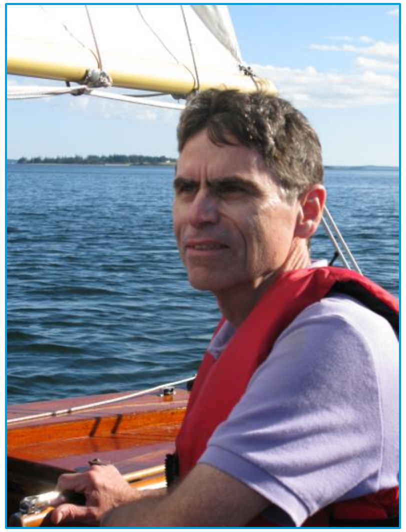
Zurich Instruments

Jim Phillips
Application Scientist

- 40-year career primarily in research: precision measurement, often using low-noise electronics.
- Searched for 1/3 e charges on levitated Nb spheres, discovered major systematic error.
- Designed a space-based astronomical interferometer.
- Studied a test of the gravitational equivalence principle to $1:10^{17}$.
- Developed most precise laser distance gauge: 0.25 m measured to 40 fm in 30 s.

→ … the diameter of a uranium nucleus.





Presentation Outline

→ Ask questions!

I am happy to answer them at any time.

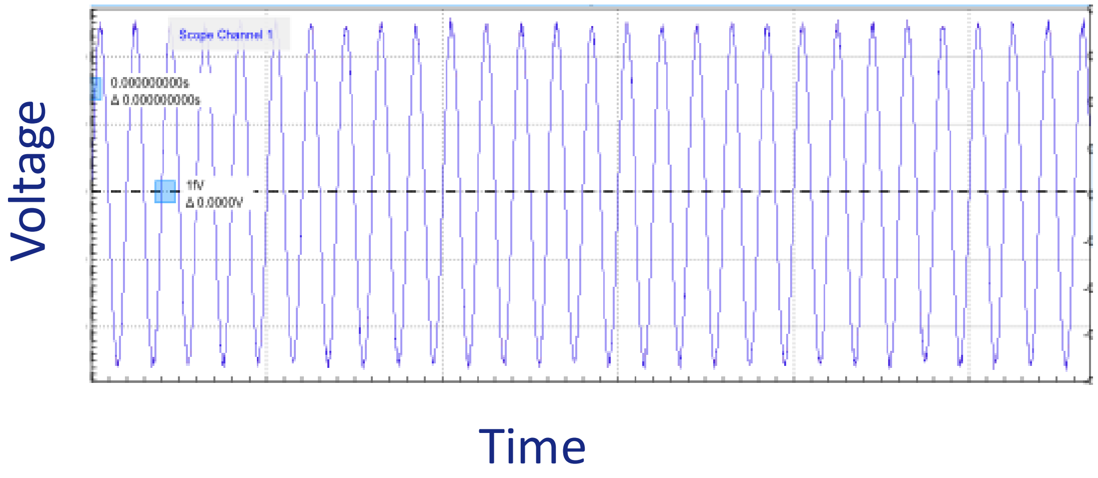
- Principles of Lock-In Detection
- Key Parameters for Lock-In Amplifiers
- Applications to Accurate Resonator Measurement

What kind of problems do we help to solve?
Detecting tiny periodic signals in noisy environments

Does **this** switch control **that** light?

Why use lock-in amplifiers?

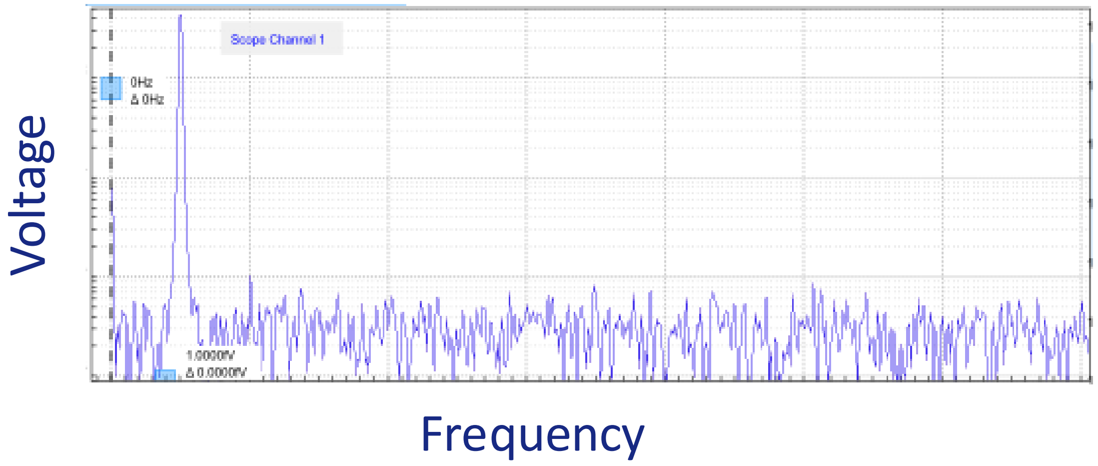
Time domain



SNR ~ 1000

... easy

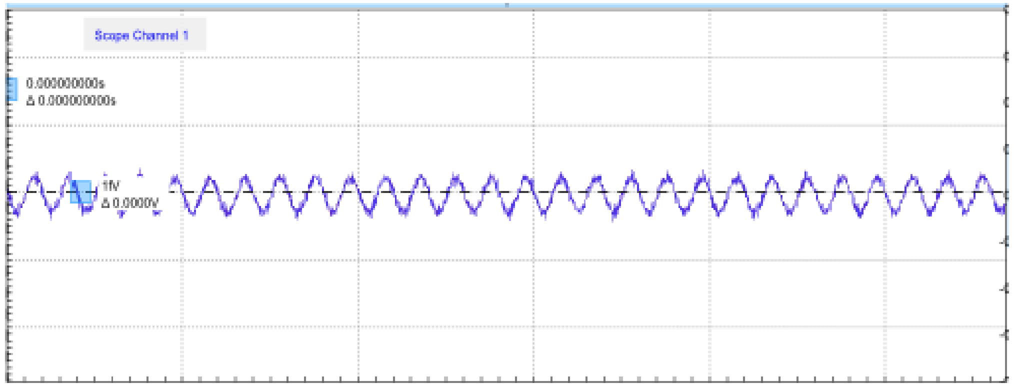
Frequency domain



Why use lock-in amplifiers?

Time domain

Voltage



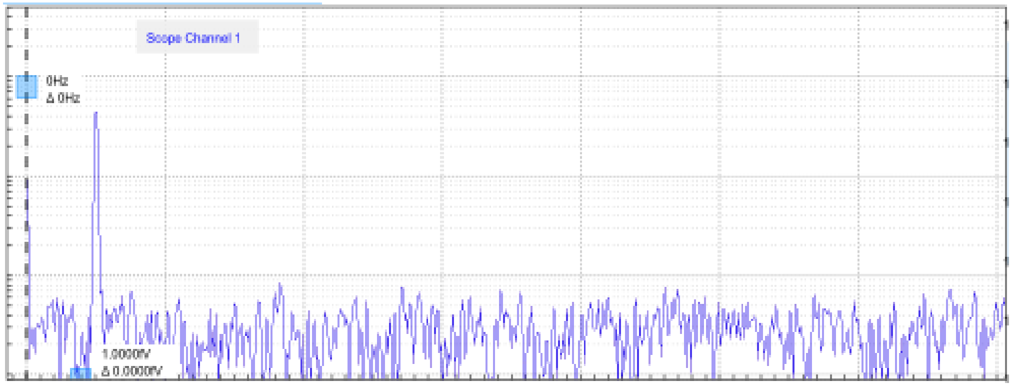
Time

SNR ~ 100

... Lock-in helps

Frequency domain

Voltage



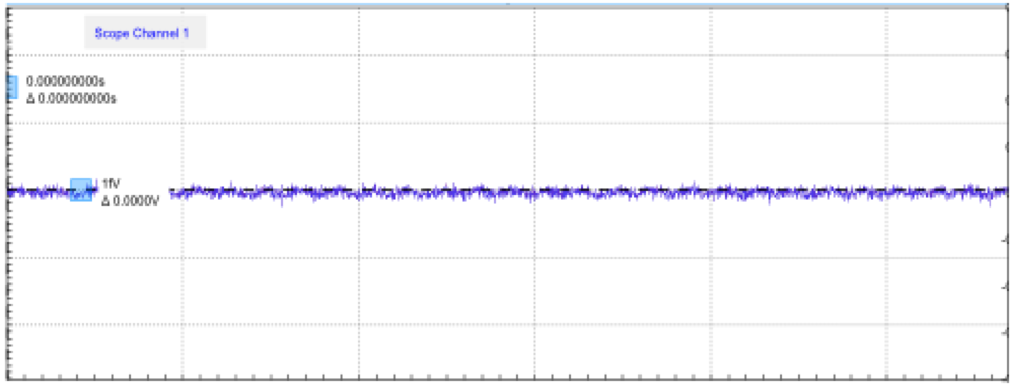
Frequency

Why use lock-in amplifiers?

Small signals surrounded by noise are difficult to detect

Time domain

Voltage



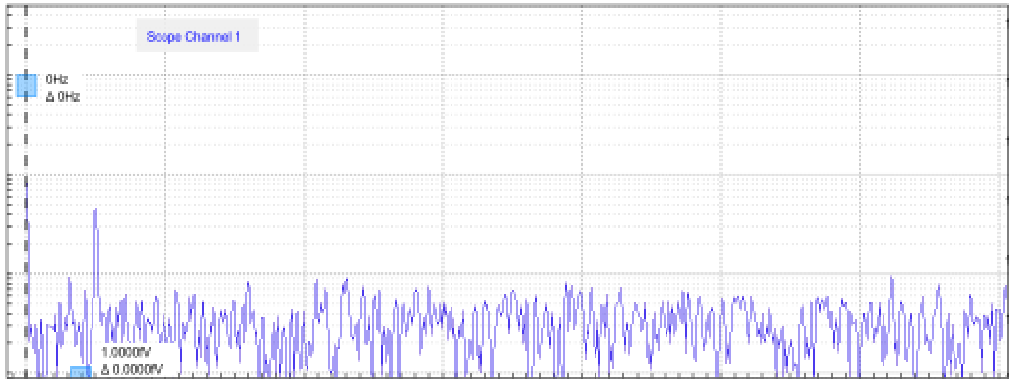
Time

SNR ~ 10

... where is that signal, anyway?

Frequency domain

Voltage



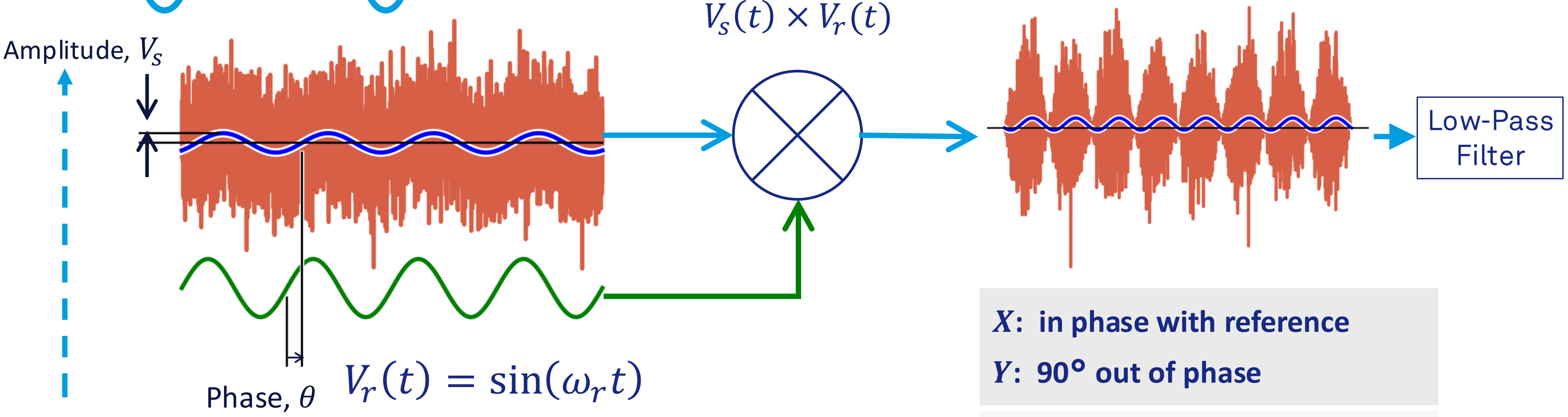
Frequency

How Does a Lock-in Amplifier Measure Such Tiny Signals?

$$x = \frac{1}{2}\{\cos[(\omega_s - \omega_r)t + \theta] - \cos[(\omega_s + \omega_r)t + \theta]\}$$

IF $\omega_s = \omega_r$, $\quad x = \frac{1}{2}\{\cos\theta - \cos[2\omega_s t + \theta]\}$

$$V_s(t) = V_s \sin(\omega_s t + \theta)$$



X: **in phase with reference**

Y: **90° out of phase**

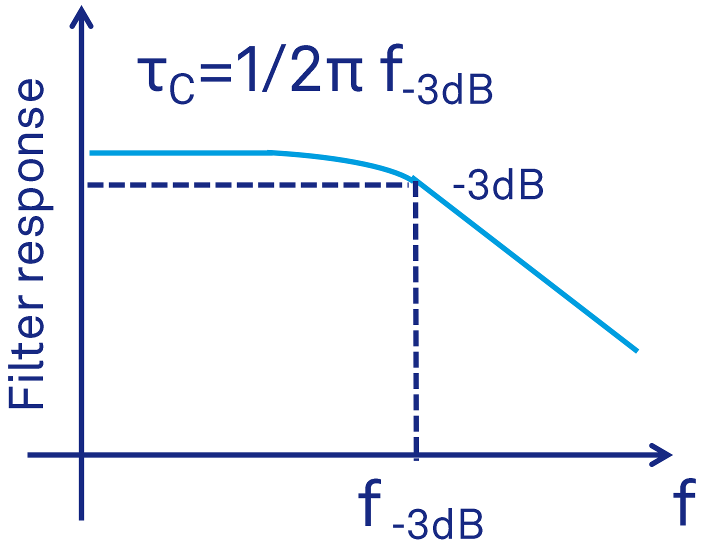
$$R = \sqrt{X^2 + Y^2}$$

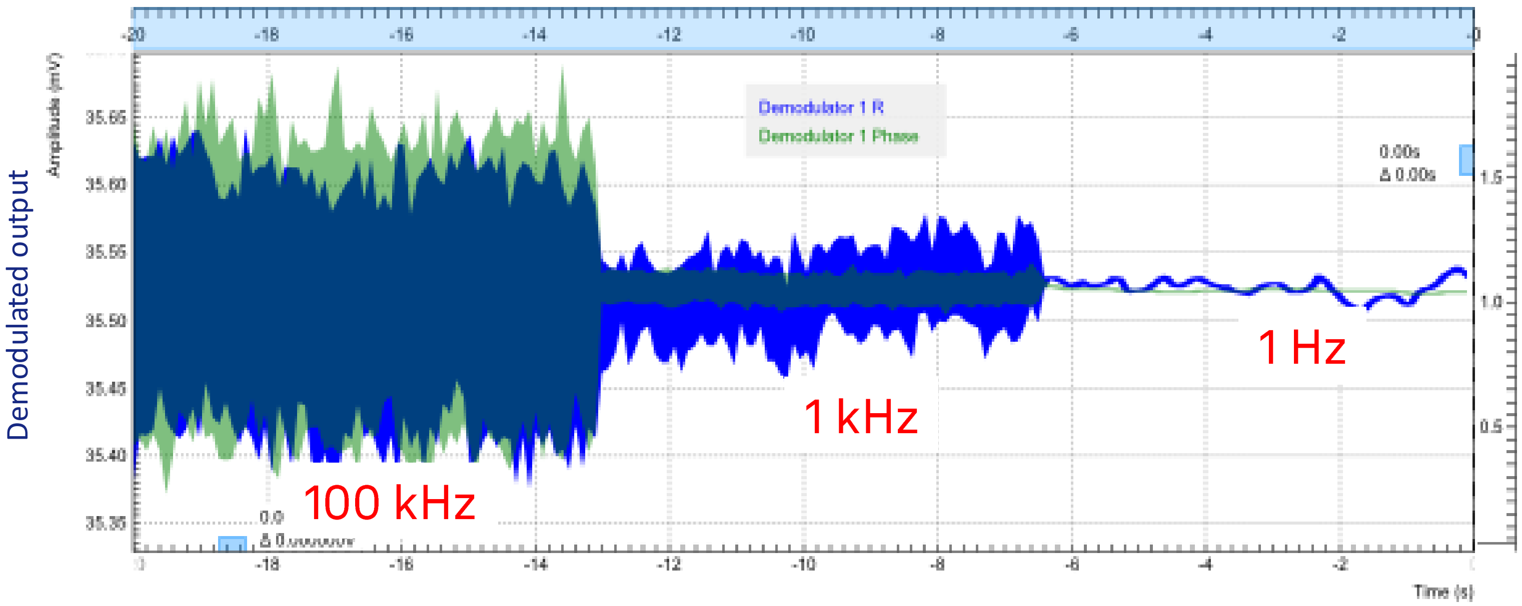
$$\theta = atan2(Y, X)$$

What does it measure?

Importance of Filter Bandwidth and Time Constant

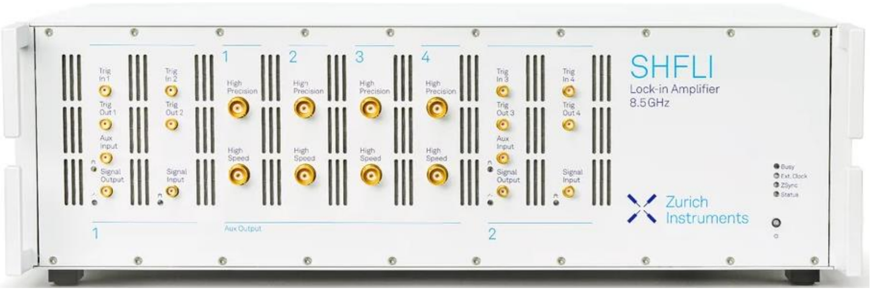
$$x = \frac{1}{2}\{\cos\theta - \cos[2\omega_s t + \theta]\}$$

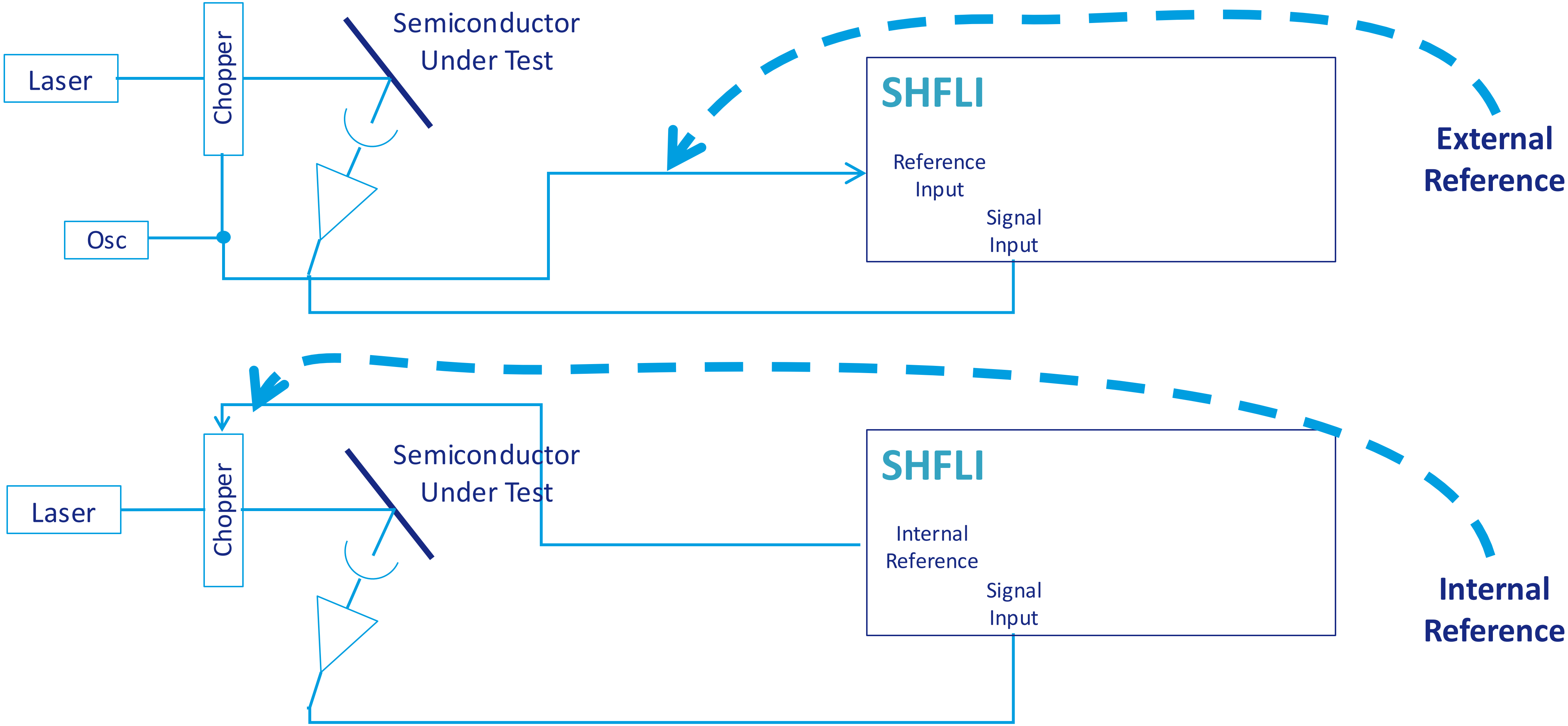




Reducing filter BW = increase time constant
Slower measurements but less noise

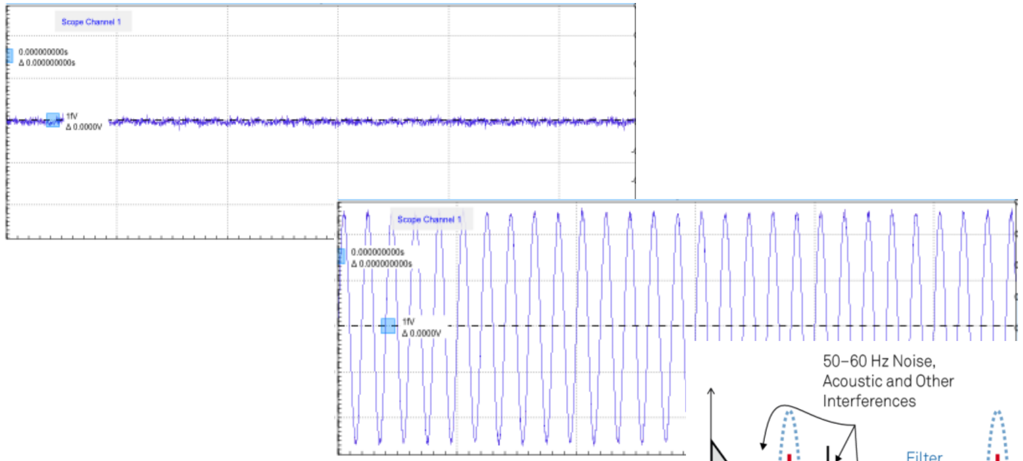
Typical Lock-In Amplifier Setup

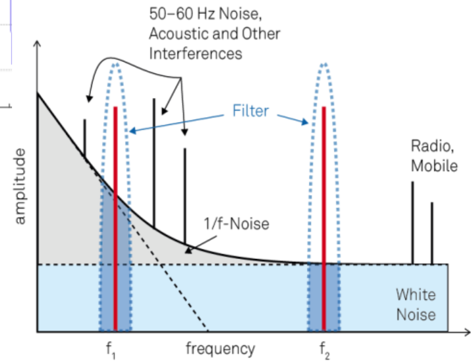


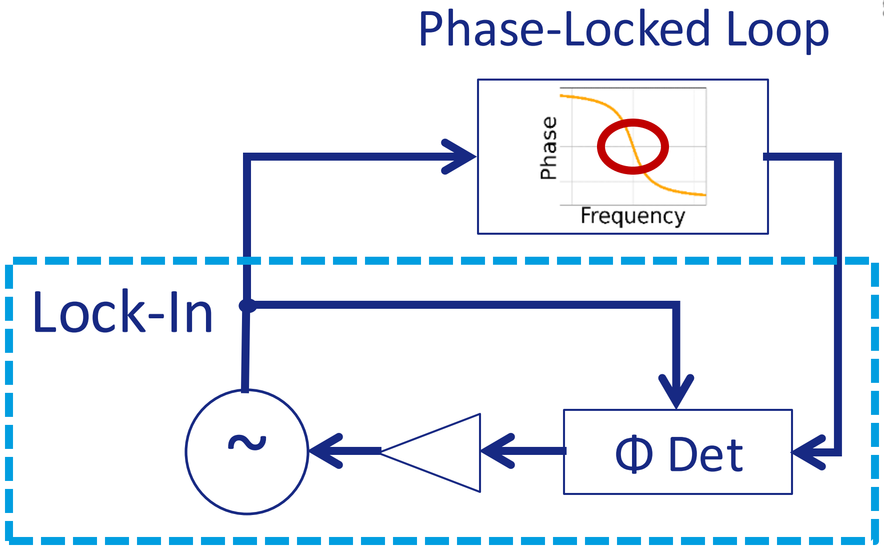


When does a lock-in amplifier really help?

- **Low SNR**
- **High SNR, require high accuracy.**
- **To increase operating frequency and escape low-frequency noise and drift**
- **More signal-processing tools: Scope, FFT, PLL, AWG (!)**







Questions?

- So far, we have covered how a lock-in amplifier works

→ Reference signal

→ Demodulation

→ Low-pass filtering

Conventional Lock-in Amplifiers

PAR 124A

SR830

SR7265

Zurich Instruments Lock-in Amplifiers

experience LabOne

MFLI
500 kHz/ 5 MHz

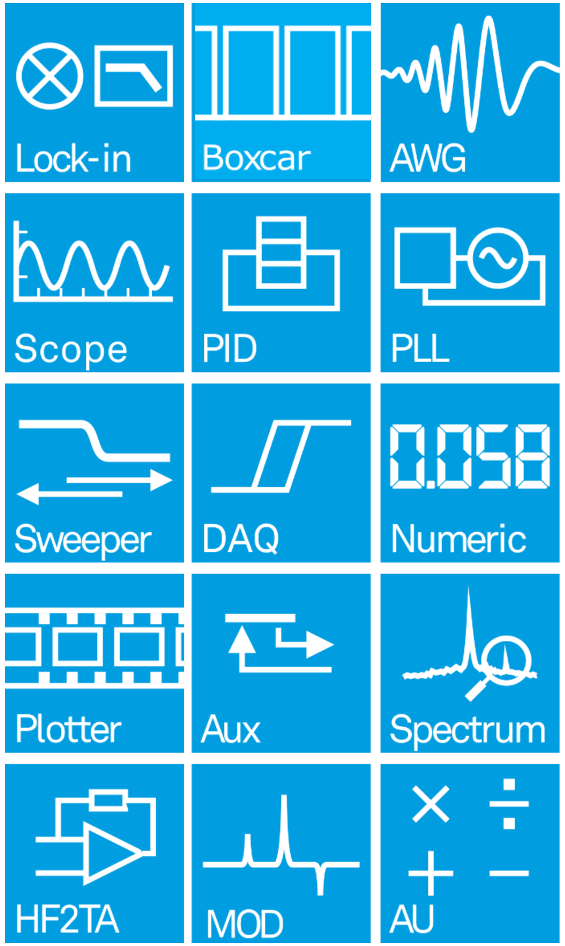
HF2LI
50 MHz

UHFLI
600 MHz

GHFLI *
1.8 GHz

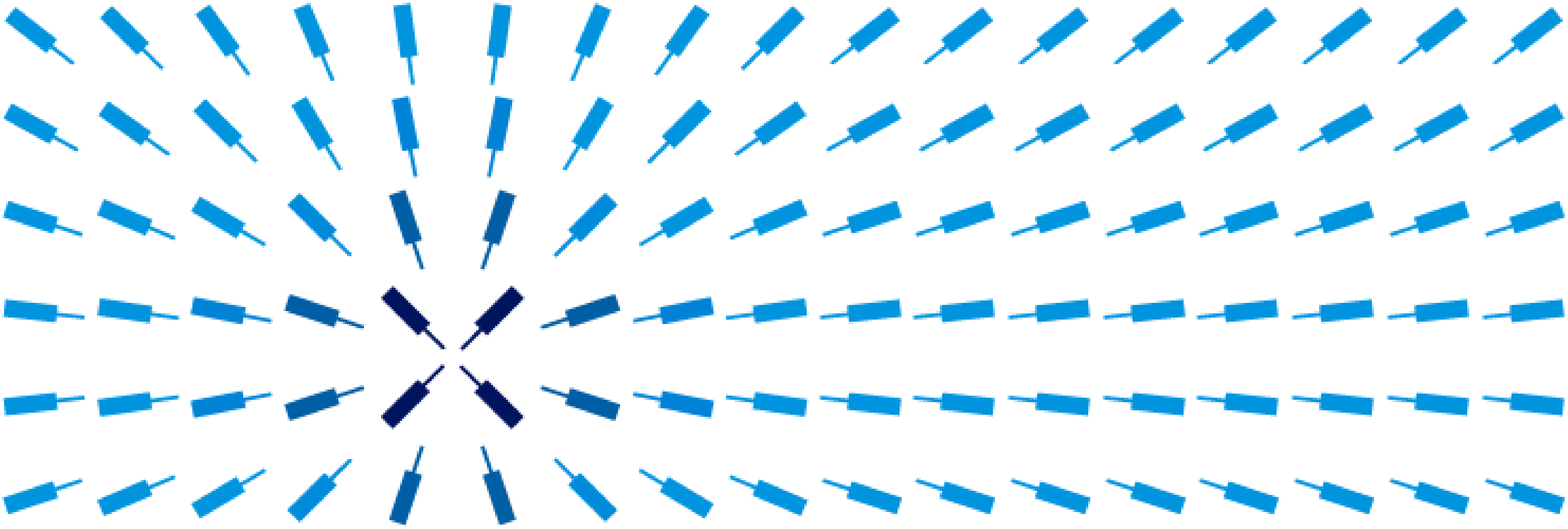
SHFLI *
8.5 GHz

* Launched 1 Sept. 2022



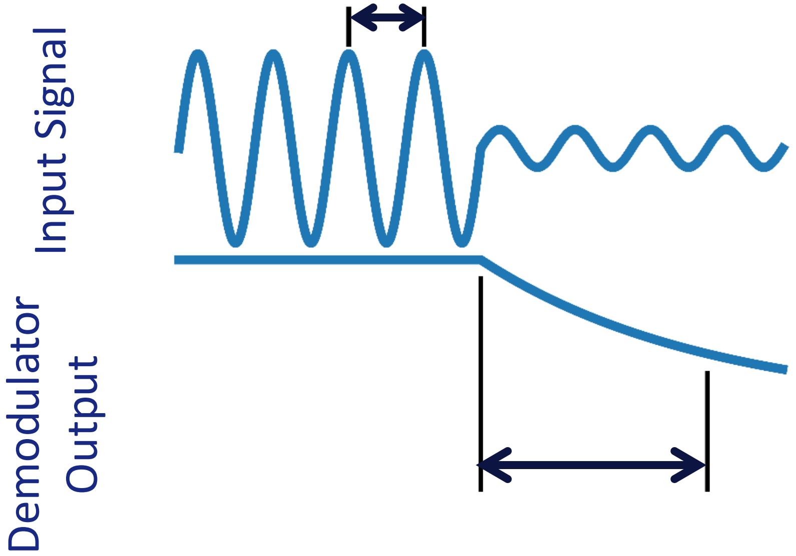
Zurich Instruments provides the best-in-class dynamic signal measurement devices for advanced R&D labs.

Lock-in Amplifier: Main characteristics



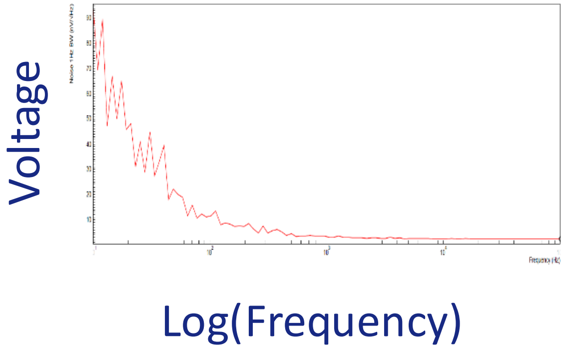
How to find the right instrument for the measurement?

Modulation Frequency

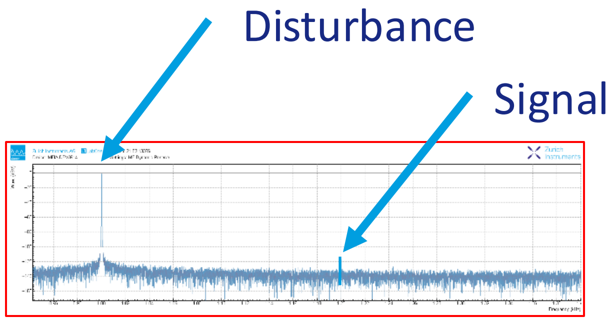


Shortest Demodulator Time Constant

Input Voltage Noise



Dynamic Reserve



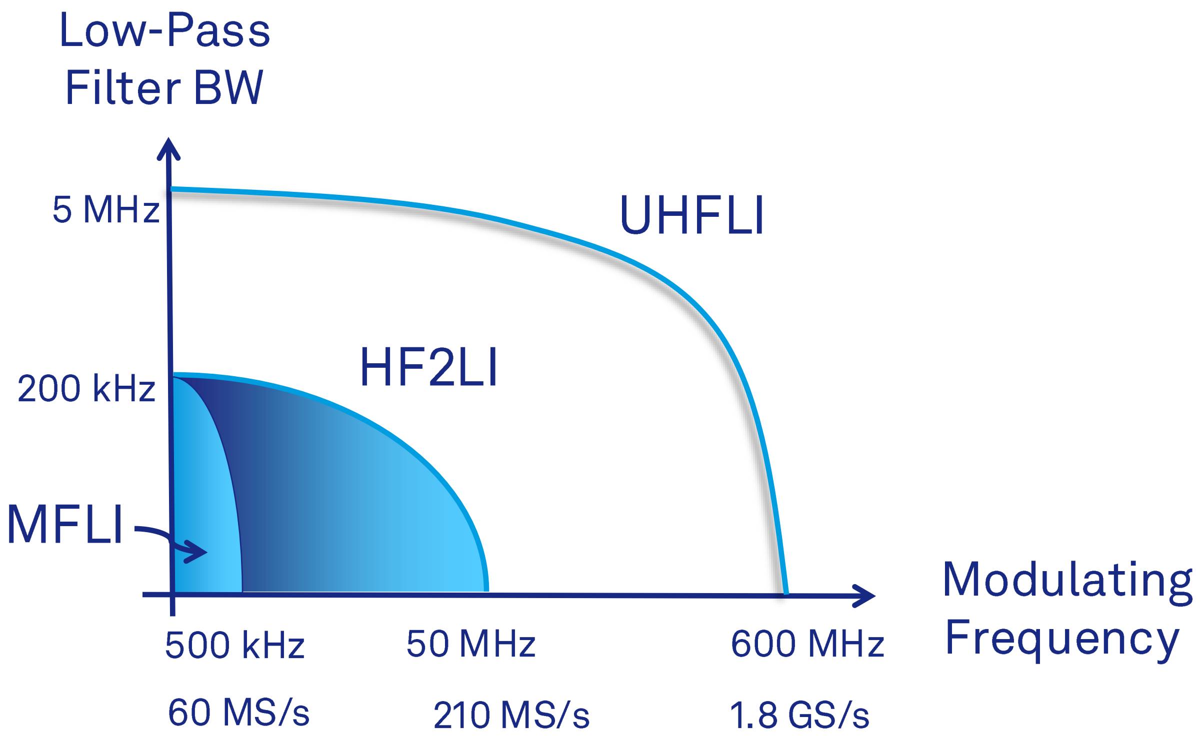
Demodulation Bandwidth and Time Constant

$\tau_C = 1/2\pi\, f_{-3dB}$

MFLI 500 kHz, 5 MHz
Min T_C = 330 ns

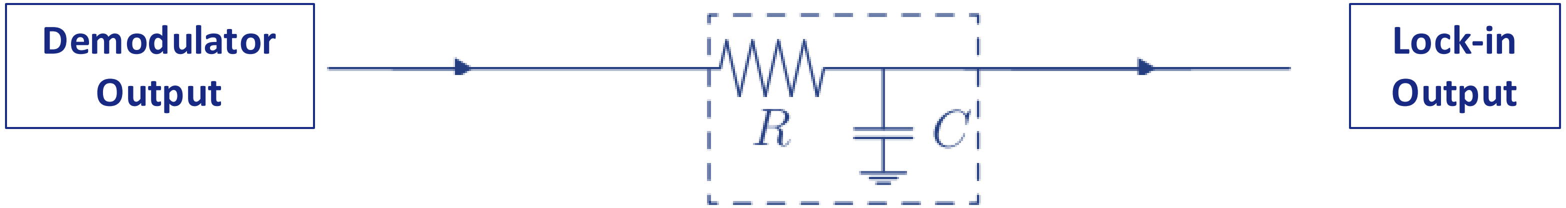
HF2LI 50 MHz
Min T_C = 780 ns

UHFLI 600 MHz
Min T_C = 30 ns



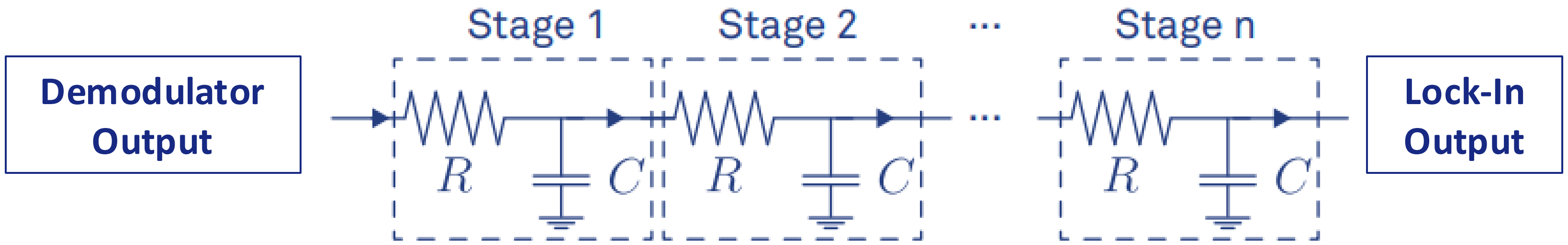
Low Pass Filter Order, or Rolloff

1st Order filter

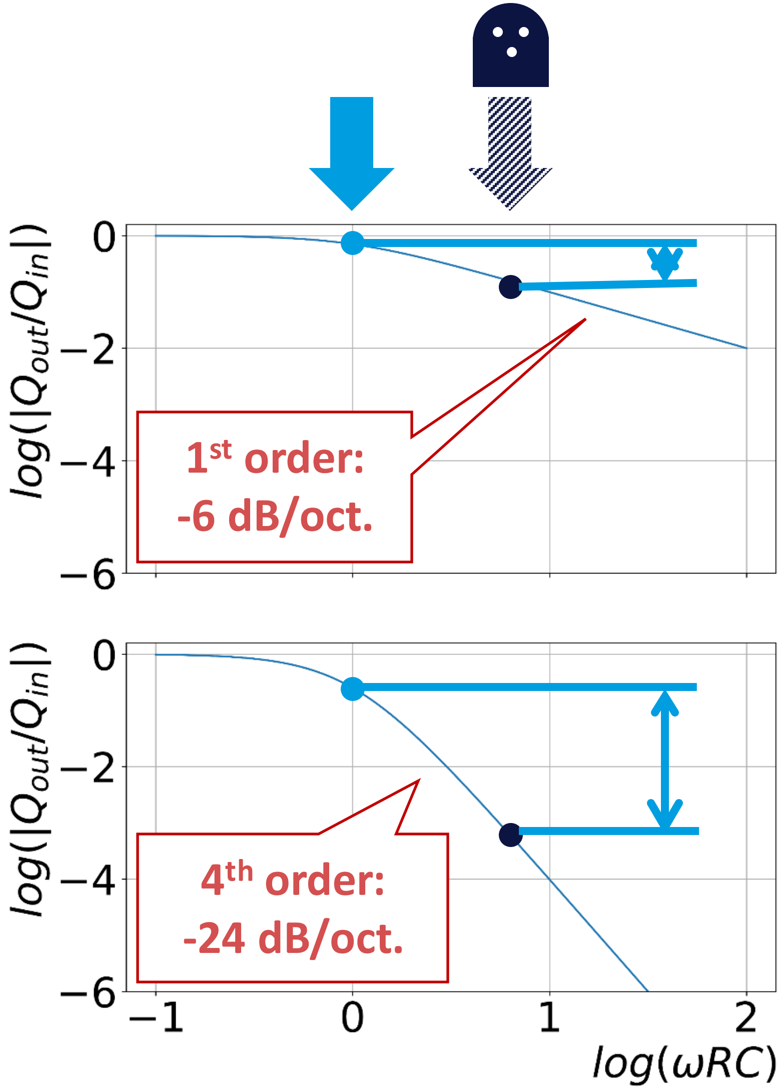


$$H(\omega) = \frac{1}{1 + i\omega RC}$$

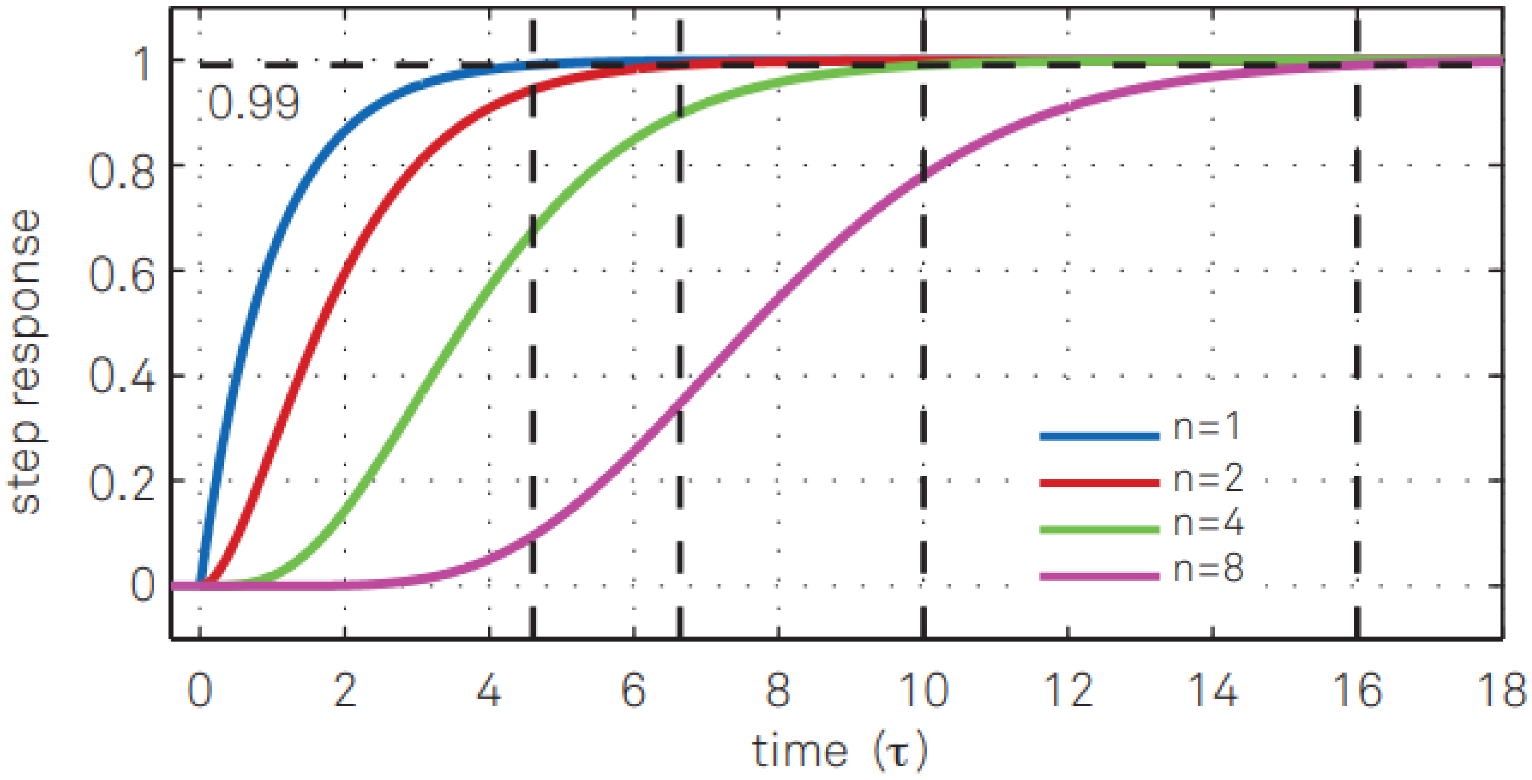
nth Order filter



$$H(\omega) = \left(\frac{1}{1 + i\omega RC} \right)^n$$



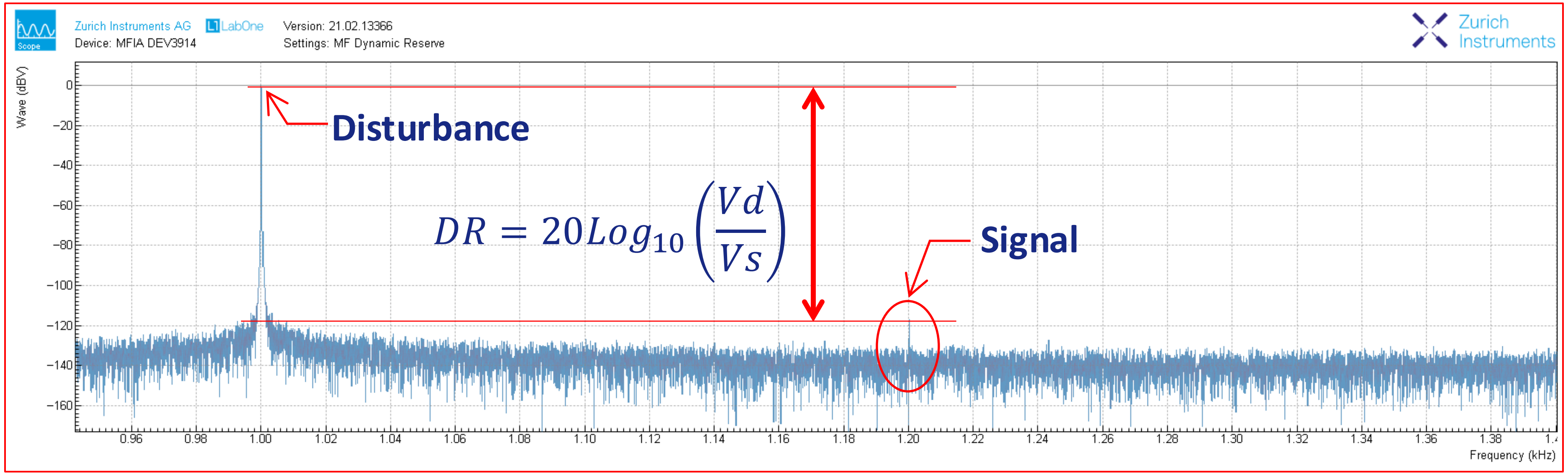
Filter Settling Time



The higher the filter order, the longer it takes for the filter to settle
Early data sampling would lead to erroneous results

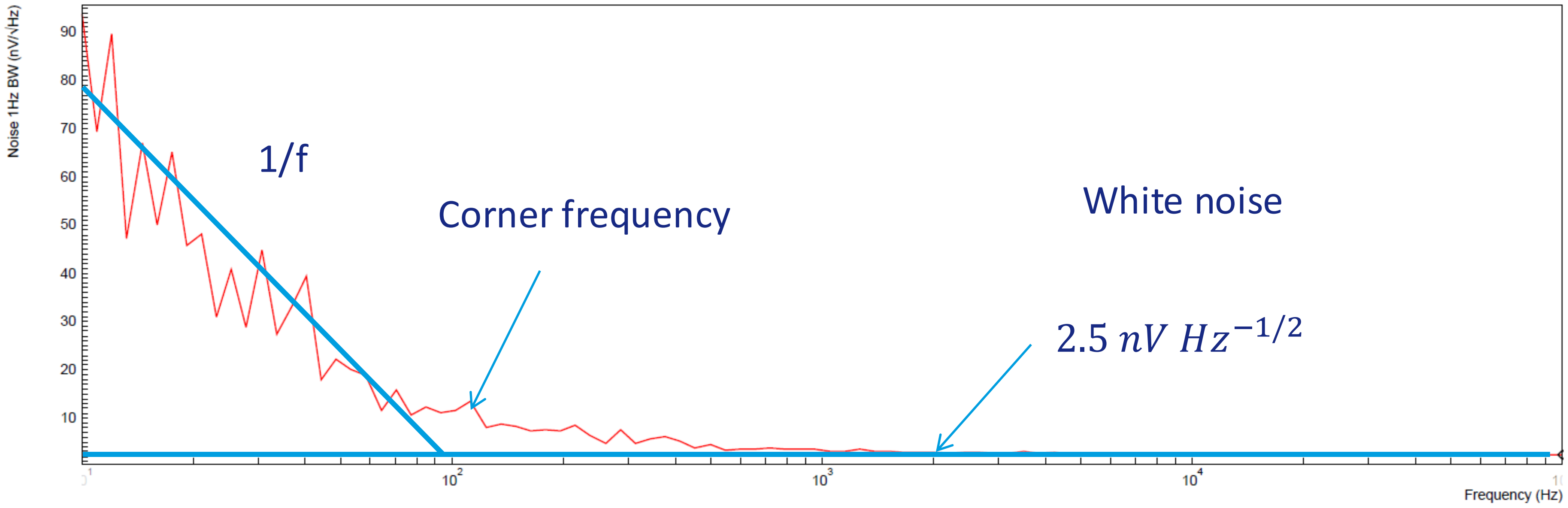
Dynamic Reserve

- Measures the instrument's capability to withstand disturbing signals and noise away from the reference frequency
- Maintain the specified measurement accuracy within the signal bandwidth
- Expressed in dB



Input Noise

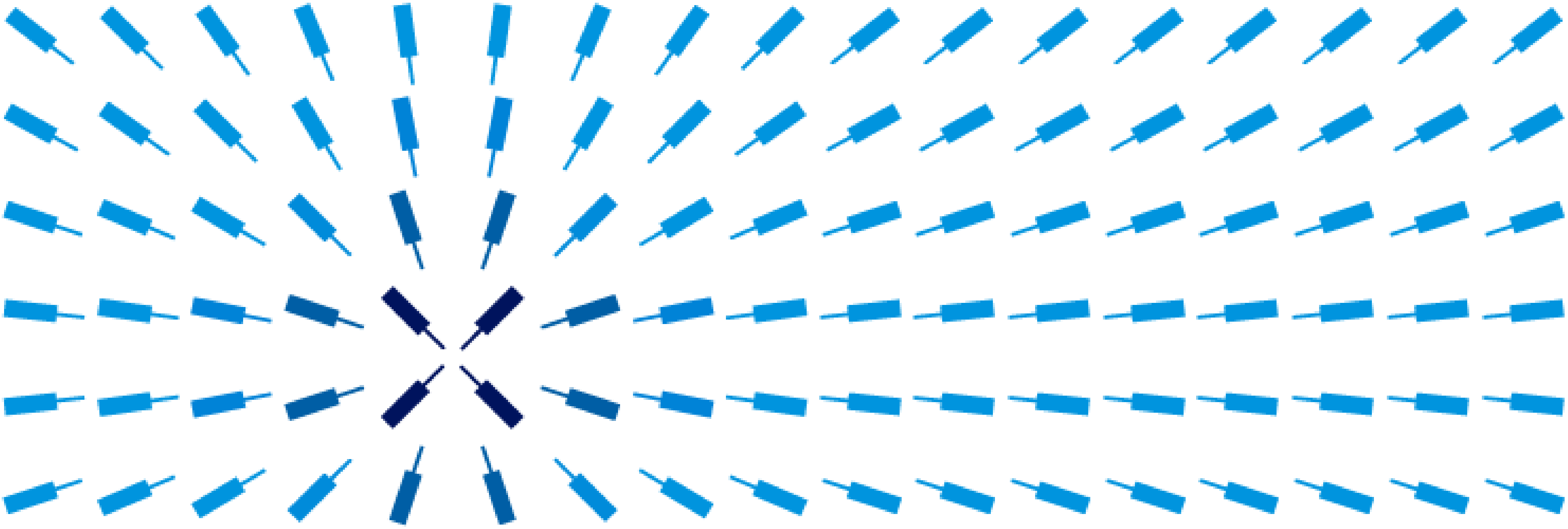
- Total noise internal to the instrument.
- Referenced to the signal input
- For random noise, use power spectral density (noise power per unit frequency), V^2/Hz .
  - More typically, voltage spectral density, $V/\sqrt{Hz}$.



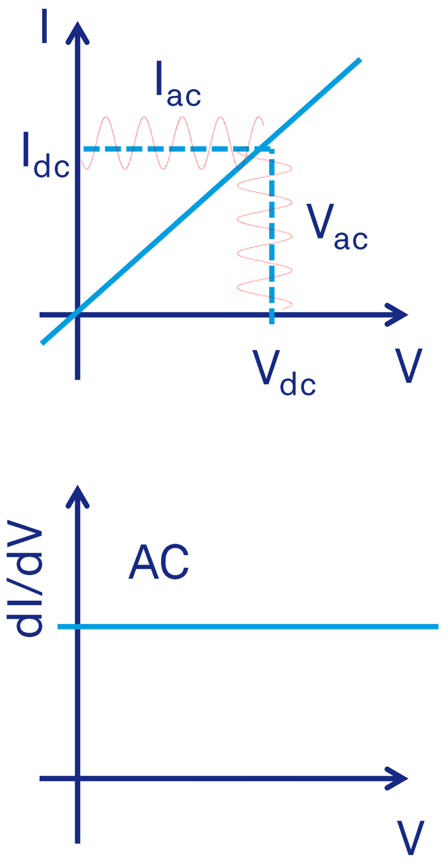
Questions?

- So far, we have covered how a lock-in amplifier works
→ Reference signal
→ Demodulation
→ Low-pass filtering
- Key Lock-In parameters
→ Modulation frequency
→ Demodulator time constant
→ Dynamic range
→ Input noise voltage

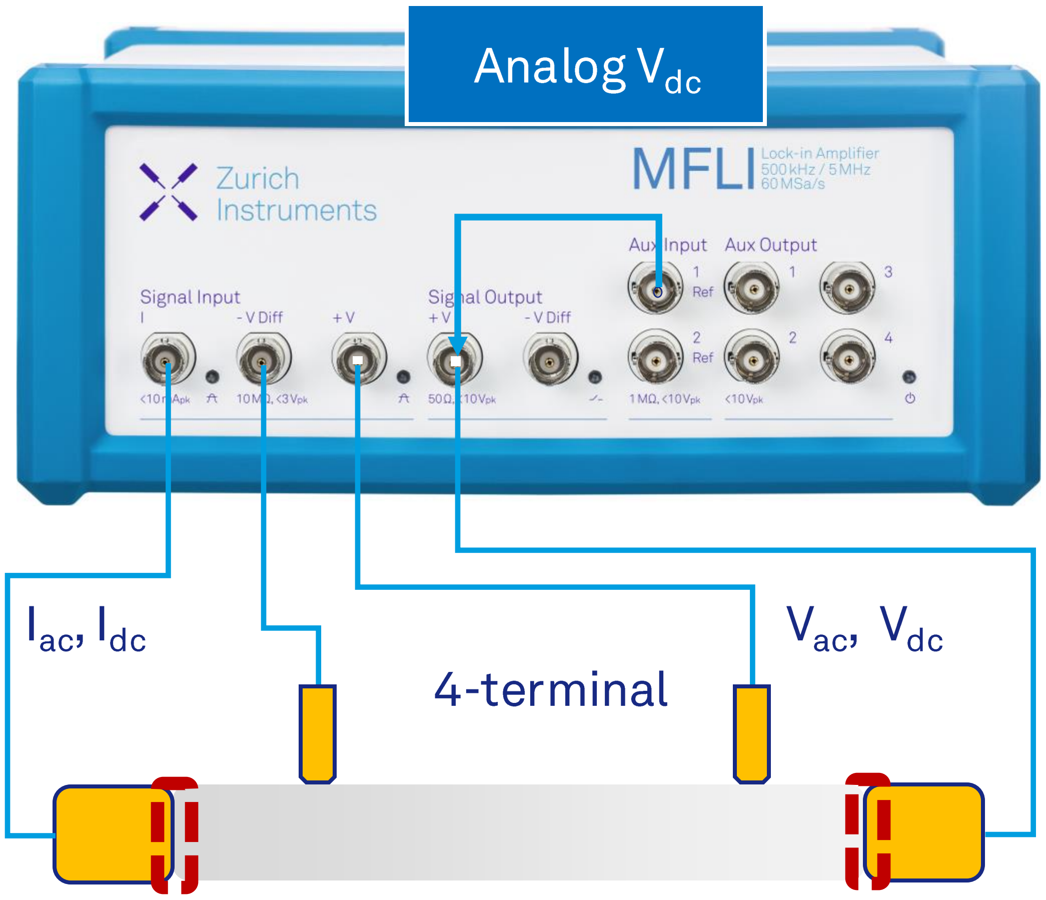
Applications

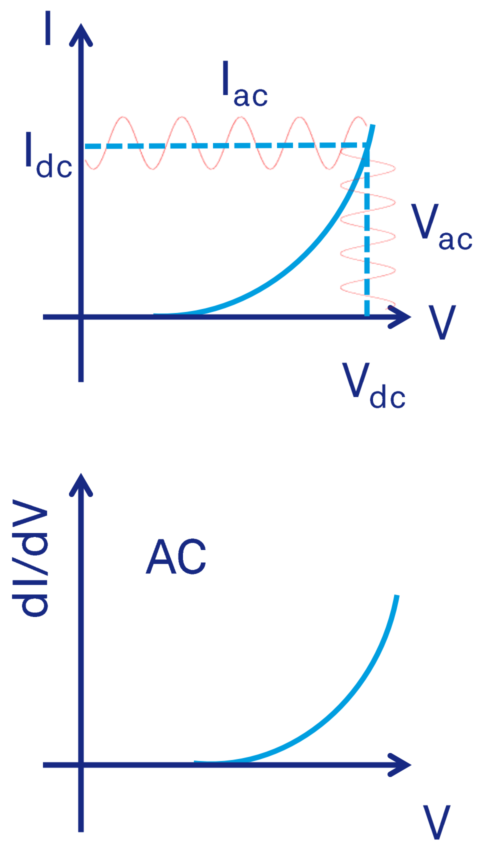


2- and 4-terminal measurements using MFLI



Linear





Non-Linear

Quantum Dots

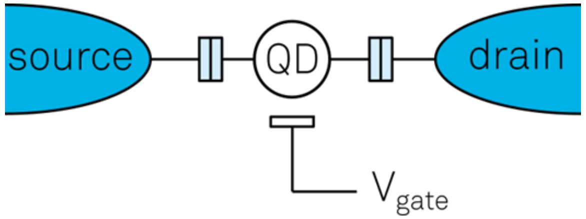
Charge carriers confined in all 3 directions

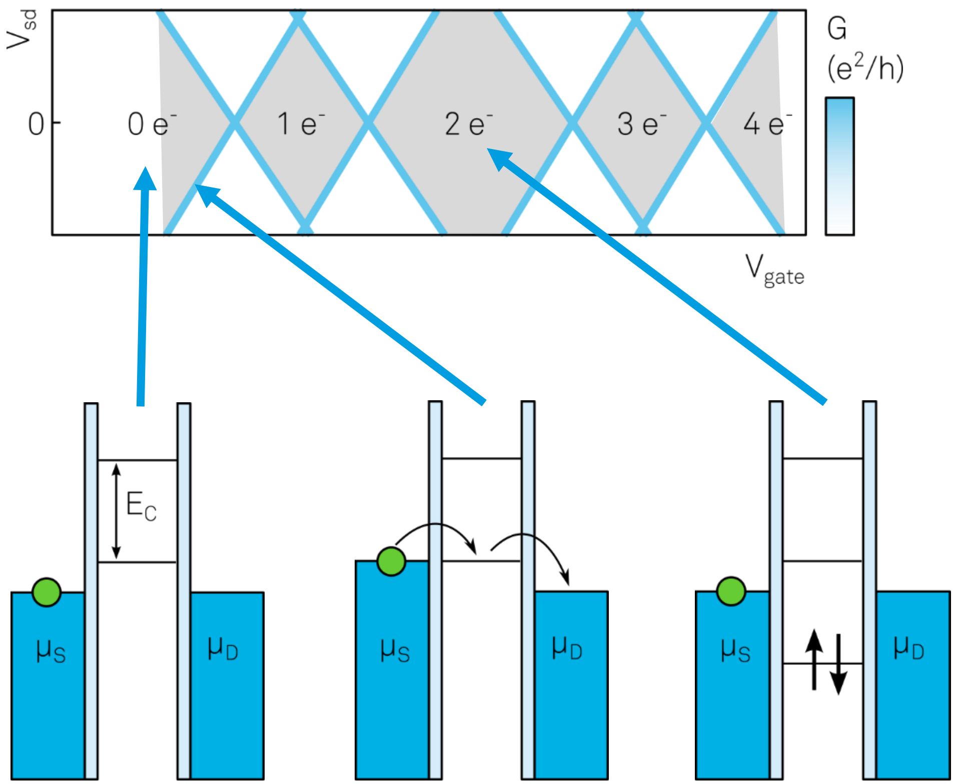
- Discrete energy levels

→ Source-drain conductance depends on energy levels in dot vs. S and D potential

- Coulomb blockade

→ Coulomb diamonds





Characterizing QDs

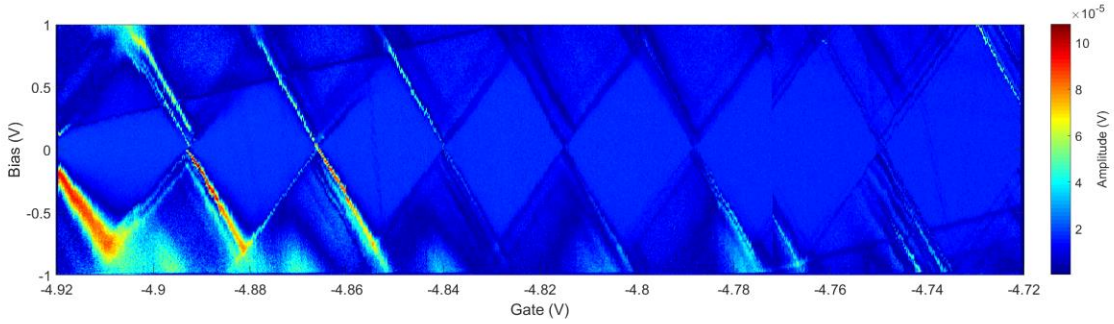
RF Reflectometry

Measure reflected RF wave

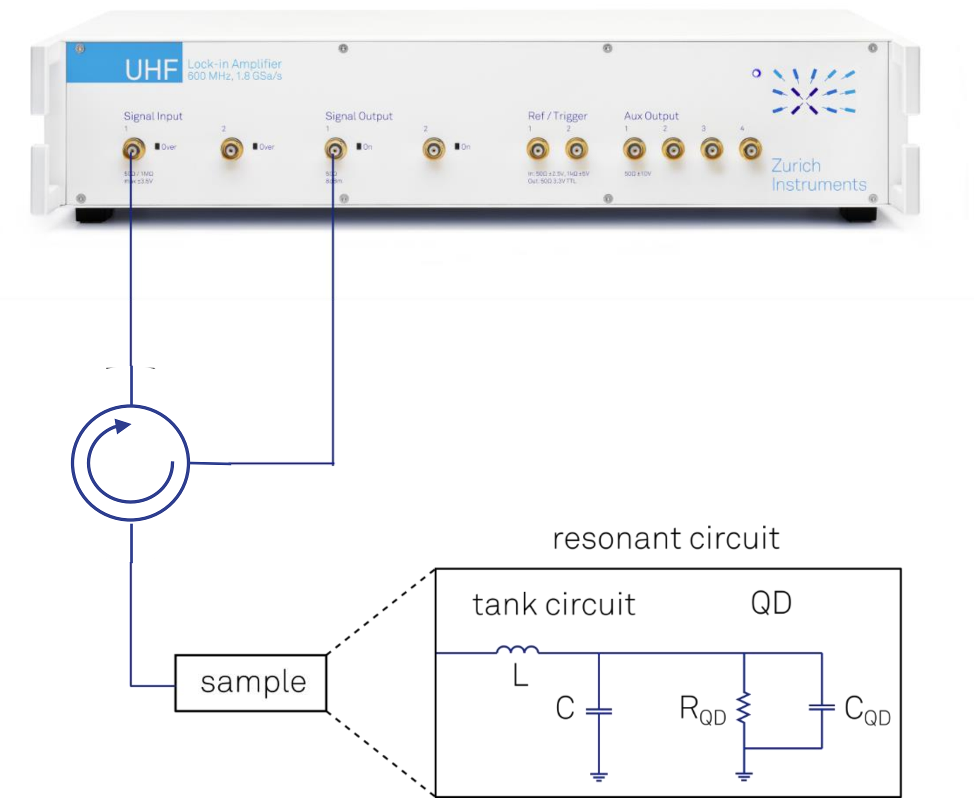
- Add LC matching circuit to the QD
- Drive at resonance

→ Change of QD state slightly changes the impedance and resonant frequency

→ Reflected signal indicates the QD state



Recorded in 1s



The Challenge

Superconducting Microwave Resonators

Fluctuations of resonance frequency, f_0

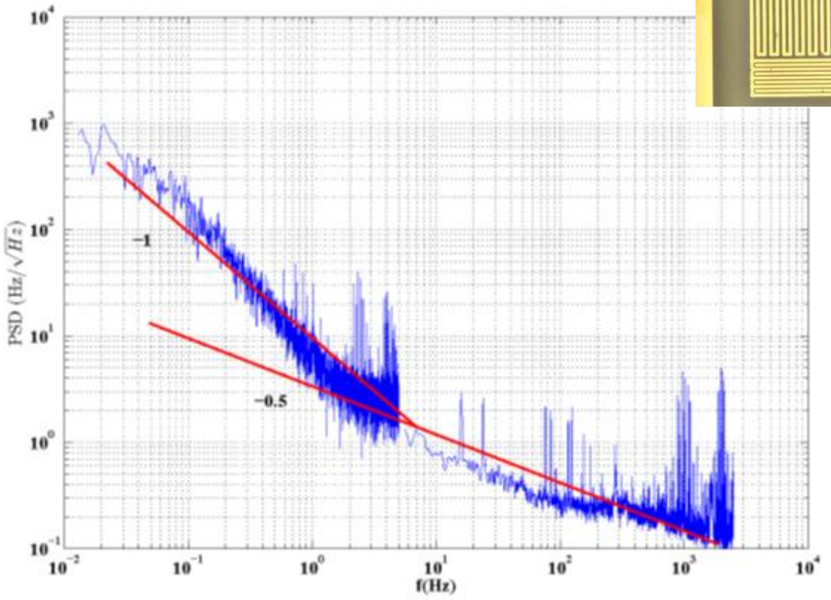
- **Low** excitation power

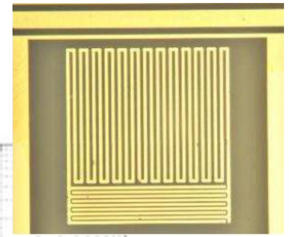
Measure quality factor, Q, directly

- **Pound-Drever-Hall method does this**
- **With a Vector Network Analyzer, frequency fluctuations look like increased linewidth, decreased Q**

Spectrum of fluctuations of f_0

$S_f(f_0), Hz/\sqrt{Hz}$





Frequency, Hz

Tzalenchuk et al., Rev. Sci. Instrum **82** (2011)

Four common strategies

	Vector Network Analyzer	Phase-Locked Loop	Dual-Frequency Resonance Tracking	Pound-Drever-Hall
Inject	Many tones	Single tone	Two tones	Frequency modulated tone

Zurich Instruments lock-ins can do all 4. PDH wins: fastest f_0, measures Q.

Measuring a resonator more accurately

When parasitics confound a PLL

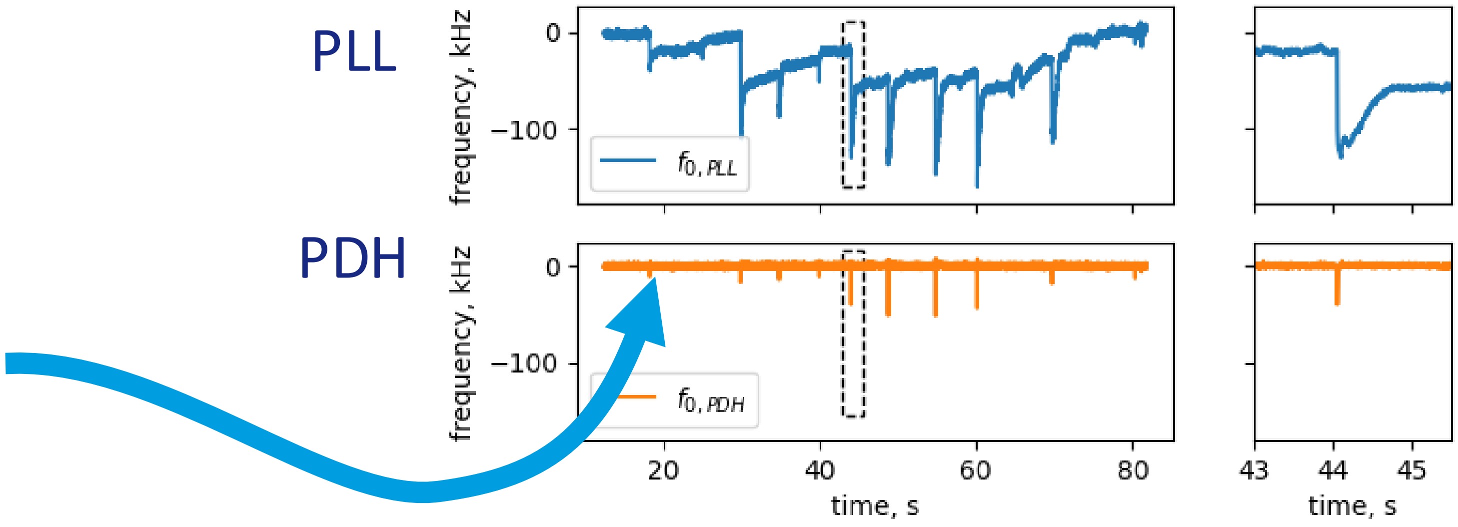
Lock a PLL

Simultaneously, acquire PDH data

Disturb the resonator by tapping the cables

PLL sees frequency jumps, and return drifts

PDH-corrected frequency is constant!



Measuring a resonator more accurately

When parasitics confound a PLL

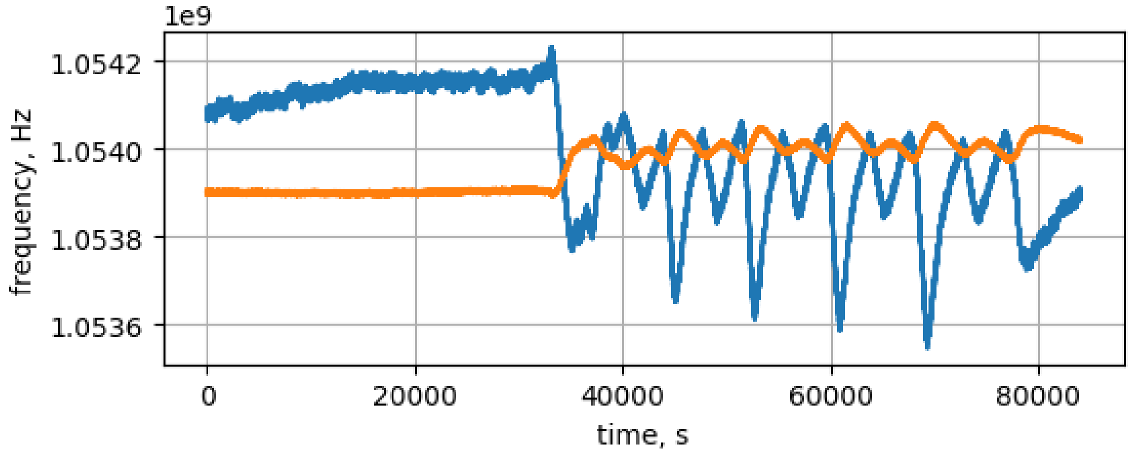
Run overnight, undisturbed

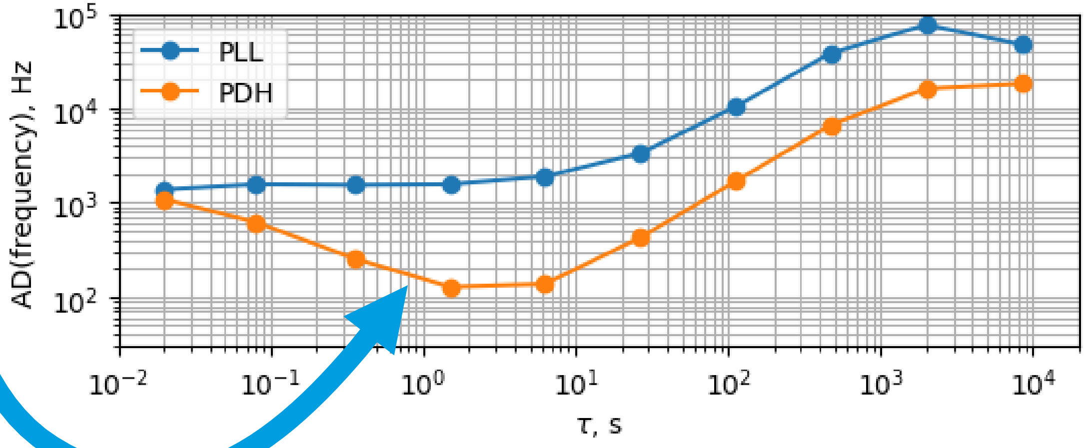
Record PLL frequency & PDH correction

Variation likely due to temperature, HVAC

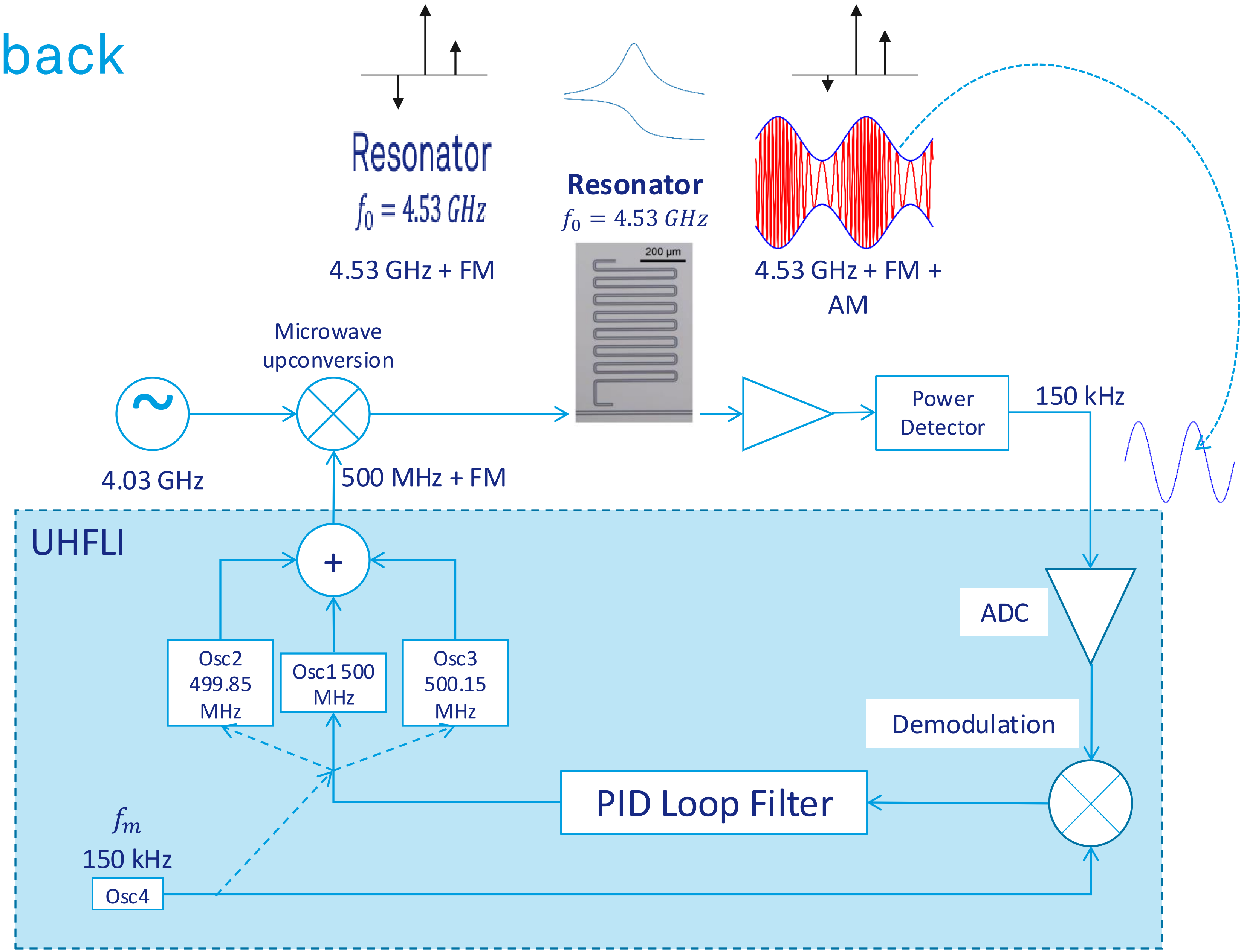
PDH-corrected shows much less variation

Allan deviation 10x smaller at mid-frequencies

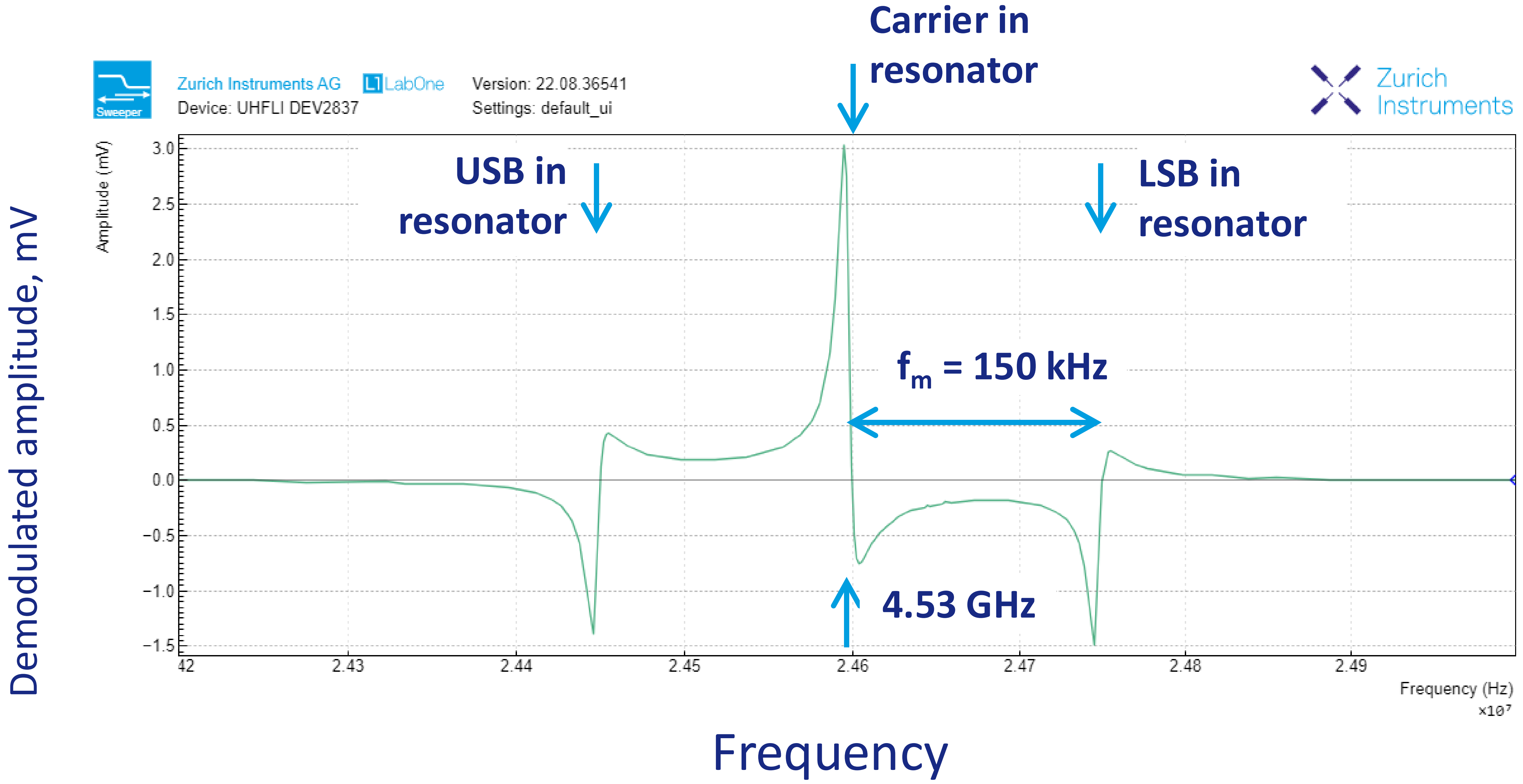




PDH feedback



PDH Error Signal

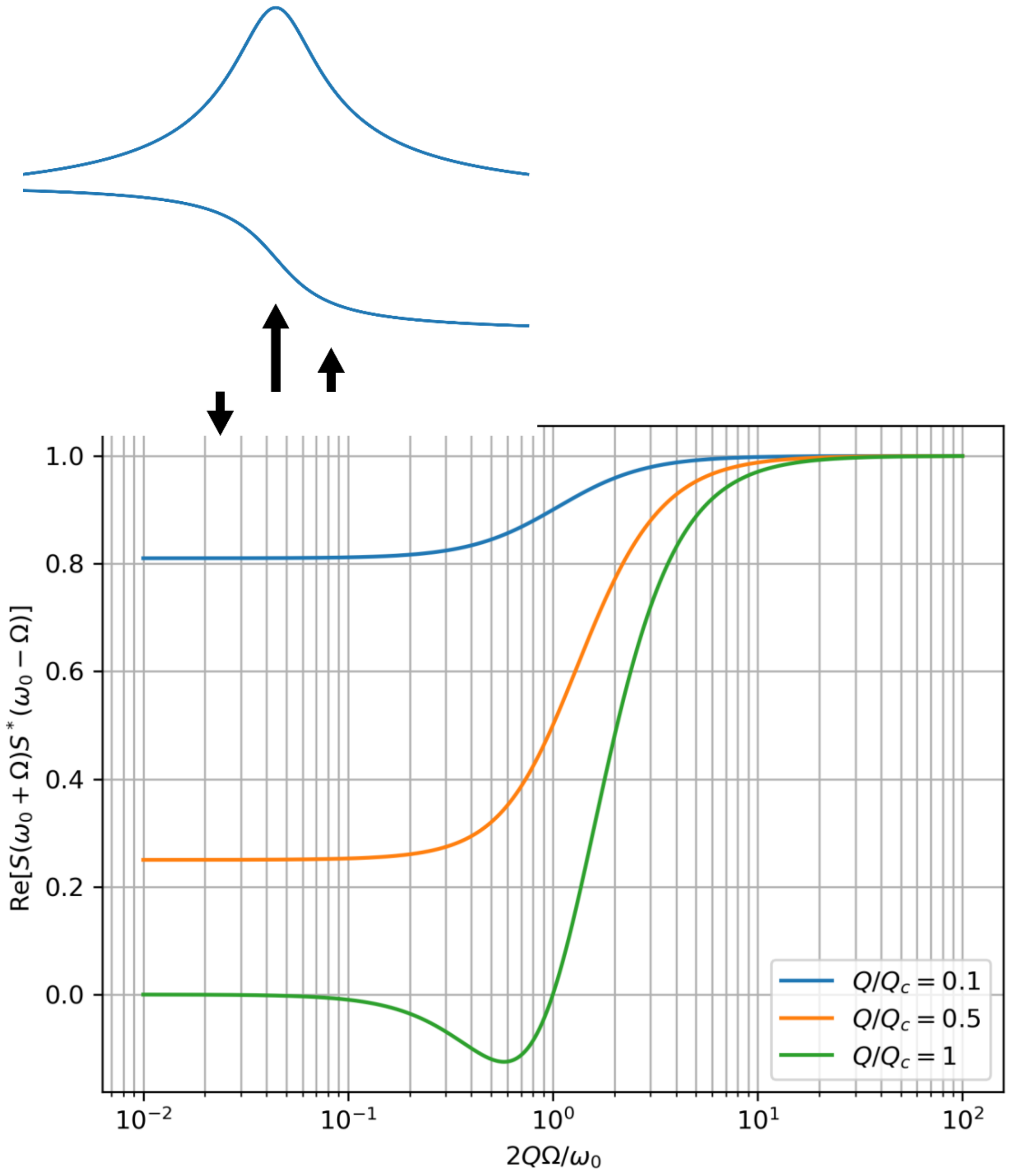


Q measurements with PDH

Q-Signal:

$$2\,P_0 G_{net} J_1^2(\beta) Re[S(\omega_0+\Omega)S^*(\omega_0-\Omega)]\cos(2\Omega t)$$

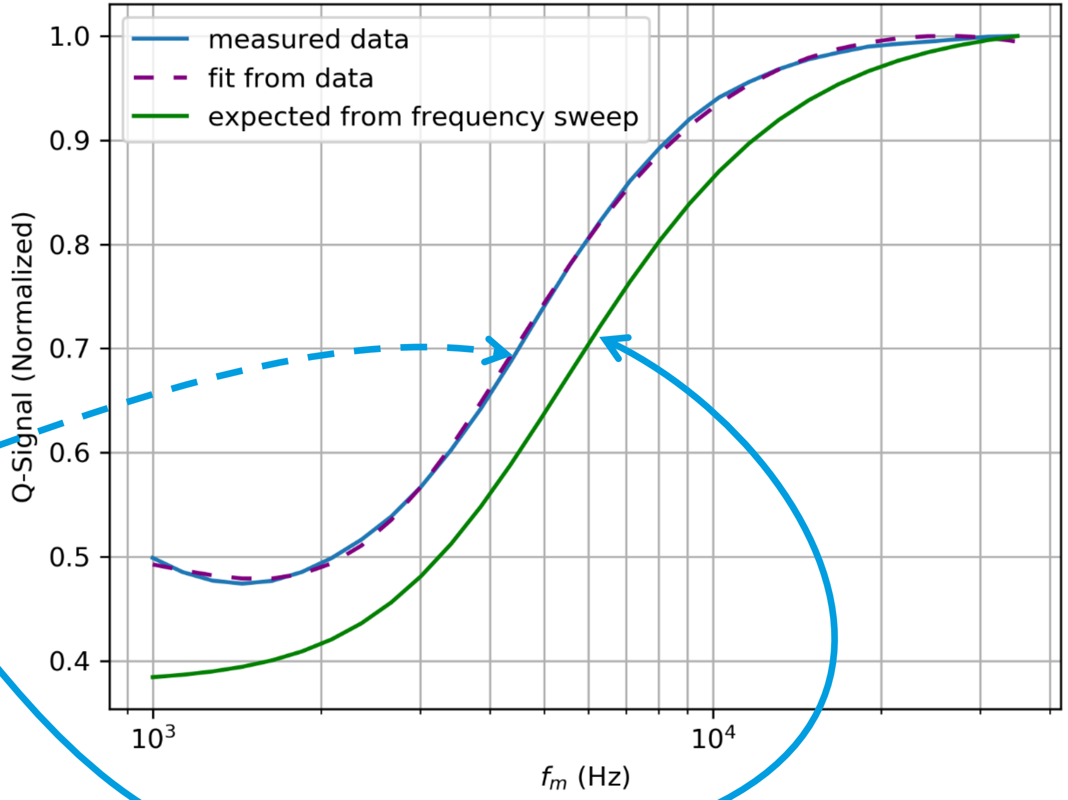
- Strong sensitivity to Q when modulating frequency on order of a linewidth
- System gain calibrated by large modulation frequency signal
- Rapid low-power Q measurements possible with knowledge of power independent parameters Q_c and asymmetry ϕ



Preliminary Q measurements with PDH

Coplanar waveguide resonator
10 mK
Power = -100 dBm

PDH measurement	Frequency sweep
f_0 = 4.530599 GHz	f_0 = 4.530596 GHz
Q = 818000	Q = 576000
Δf = 5.5 kHz	Δf = 7.8 kHz



Summary

Increase Signal-to-Noise Ratio by better understanding your measurement system

Lock-in amplifiers:

- Used in a wide variety of applications
- Extract a periodic signal buried in noise
- Digital electronics allows advanced signal processing and functionality, such as a Phase-Locked Loop.

Pound-Drever-Hall resonance sensing

- Improved accuracy with respect to parasitics

Get in touch

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